AMAP Arctic Climate Change Update 2021: **Key Trends and Impacts**

AMAP
Arctic Monitoring and Assessment Programme (AMAP)

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Dedication

In memory of two great scientists and friends

This report is dedicated to two outstanding scientists who both played a significant role in the seminal Arctic Monitoring and Assessment Programme (AMAP) *Snow, Water, Ice and Permafrost in the Arctic (SWIPA): Climate Change and the Cryosphere* assessment report in 2011.

Konrad ‘Koni’ Steffen was lost on 8 August, 2020 in a crevasse on the Greenland Ice Sheet. Koni was a leader in the climate community but first and foremost he was a pioneer in climate applications of satellite remote sensing and field observations in the Arctic, especially regarding the Greenland Ice Sheet. His work laid the foundation for a generation of scientists that made the ice sheet their real or virtual laboratory. Koni supported and communicated science at high levels, for example, leading World Climate Research Programme panels. Koni will be missed and never forgotten.

David Barber passed away unexpectedly on 15 April, 2022. David was one of Canada’s most influential Arctic researchers, and was instrumental in the development of many large international multidisciplinary networks for Arctic research that raised the profile of Arctic science across Canada. By doing so, David created opportunities for countless students, professors and research staff working collectively to better understand the rapidly changing Arctic, and its impacts on people and habitats in the Arctic and beyond. David was a gifted speaker who could express complex scientific ideas in terms that policy-makers, media and the public could easily understand. His extraordinary ability and contributions benefited many national and international programs. In addition to his work on the 2011 SWIPA assessment report, David had an important role in the follow-up 2017 SWIPA report as coordinating lead author of the sea ice chapter and making extensive use of this assessment report in his teaching materials. David enjoyed research in its entirety, and had looked forward to many more years of ‘discovery’. He has touched the lives of so many people, and he will be greatly missed.

Contents

Preface

This report presents the findings of the *Arctic Climate Change Update 2021: Key Trends and Impacts* prepared by the Arctic Monitoring and Assessment Programme (AMAP). This report is a follow-up to the *Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2017* assessment, which focused mainly on physical changes in the Arctic and its cryosphere, with some material on ecosystem changes. The present report updates information in the 2017 report and focuses on several topics that have emerged as 'climate issues of concern'. These include an expanded and updated suite of Arctic climate indicators, the most recent projections of Arctic climate change, extreme events and thresholds, Arctic/mid-latitude linkages, climate change impacts on Arctic ecosystems and ecosystem feedbacks, and societal implications of Arctic climate change. This report is not an assessment report *per se,* but was identified from the start as an interim report between the SWIPA 2017 report and the planned assessments on climate impacts on Arctic ecosystems and ecosystem feedbacks to climate as well as a broader assessment of societal implications of climate change, both intended for production in 2023–2025.

Although the initial intention of this 2021 report was to serve as an interim report between larger, more in-depth assessments of aspects of climate change prepared on a scale of every five or six years, the rapidity and scale of climate-related changes in the Arctic subsequently resulted in AMAP Heads of Delegation deciding that AMAP should produce shorter, more timely climate update reports on a biennial basis. These biennial reports should highlight key climate issues of concern as well as provide updates of past assessments when needed. Accordingly, this 2021 report is the first in a series of climate update reports.

The preparation of this report was coordinated by the AMAP Climate Expert Group (CEG). The CEG maintains an overview of climate issues and the coordination of climate-related activities and reports, ensuring that AMAP maintains momentum on climate work and can provide information on climate issues on a regular basis.

The 2021 report was prepared between 2019 and 2021 by an international group of over 60 scientists, experts and knowledgeable members of the Arctic Indigenous communities. Lead authors were selected by an open nomination process coordinated by AMAP and several national and international organizations. A similar process was used to select international experts who independently reviewed this report. A team of coordinating lead authors for the seven chapters was responsible for scientific oversight and coordination of all work related to the preparation of this report. Documentation available on the website www.amap.no includes listings of the comments received from the peer reviewers and how they were addressed.

Information contained in this report is fully referenced and based mainly on research and monitoring efforts published since 2016 (i.e., since the SWIPA 2017 report was undertaken). It includes peer-reviewed material accepted for publication up until October 2020, and in some cases later. Unpublished monitoring information, including both *in situ* and satellite observations with well-established national and international standards and quality assurance / quality control protocols, is also included. All such references have been collected and are available upon request (at cost of reproduction) from the AMAP Secretariat. Care has been taken to ensure that no critical probability statements are based on these materials.

Access to reliable and up-to-date information is essential for the development of science-based decision-making regarding ongoing changes in the Arctic and their global implications. Accordingly, this report formed the basis for a product containing more action-orientated conclusions and recommendations, namely, the *AMAP Climate Change Update 2021: Key Trends and Impacts Summary for Policy-makers.* This report was available for the Arctic Council Ministerial Meeting in May 2021. The lead authors have confirmed that this Summary for Policy-makers accurately and fully reflects their scientific report. The present report constitutes the fully-referenced scientific basis for all statements made in the Summary for Policy-makers. These reports are available from the AMAP Secretariat and on the AMAP website www.amap.no.

AMAP would like to express its appreciation to all experts who have contributed their time, effort, and data to this report, with particular gratitude to the chapter lead authors and members of the Climate Expert Group who coordinated the production of this report. Thanks are also due to the many referees and reviewers who contributed to the peer-review process and provided valuable comments that helped to ensure the quality of the report. A list of the main contributors is included at the start of each chapter. The list is not comprehensive. Specifically, it does not include the many national institutes, laboratories and organizations, and their staff, which have been involved in the various countries. Apologies, and no lesser thanks, are given to any individuals unintentionally omitted from the list.

The support of the Arctic countries and non-Arctic countries implementing research and monitoring in the Arctic is vital to the success of AMAP. The AMAP work is essentially based on ongoing activities within these countries, and the countries also provide the necessary support for most of the experts involved in the preparation of the AMAP assessments and reports. In particular, AMAP would like to thank Canada, the Kingdom of Denmark, and the Norwegian Ministry of Foreign Affairs for their financial support to this work, and to sponsors of programs and projects that have delivered data for use in this report. The AMAP Working Group is pleased to present its report to the Arctic Council and the international science community.

John E. Walsh (Chair, AMAP Climate Expert Group)

Anders Turesson (AMAP Chair, May 2021)

Rolf Rødven (AMAP Executive Secretary)

Tromsø, August 2021

Disclaimer: The views expressed in this peer-reviewed report are the responsibility of the authors of the report and do not necessarily reflect the views of the Arctic Council, its members or its observers.

1. Introduction

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1.1 The 2021 update report

This report by the Arctic Monitoring and Assessment Programme (AMAP) presents an update of findings in relation to various issues selected from the outcome of AMAP's most recent full assessment of Arctic climate change, *Snow, Water, Ice and Permafrost in the Arctic* (*SWIPA*) *2017* (AMAP, 2017a). The SWIPA 2017 report presented trends in observations for Arctic climate change and concurrent changes to the Arctic cryosphere during the 2010–2016 period. The SWIPA 2017 assessment had two additional aims, namely to:

- Update, synthesize and assess current knowledge on Arctic climate development and changes in the cryosphere since 2010.
- Establish pan-Arctic projections of future changes in the Arctic cryosphere as a baseline for, among others, the regional Arctic change assessments performed under the Arctic Council initiative *Adaptation Actions for a Changing Arctic* (AACA).

SWIPA 2017 focused mainly on physical changes in the Arctic and its cryosphere; however, it also included a section on ecosystem change. In addition, contemporary and possible future effects of climate change and other drivers of change in Arctic ecosystems, ecosystem services and human wellbeing were assessed in the AACA work.

The present report updates information in the 2017 report and focuses on several topics that have emerged as 'climate issues of concern'. These issues include an expanded and updated suite of Arctic climate indicators, the most recent projections of Arctic climate change, extreme events and thresholds, Arctic/mid-latitude linkages, climate change impacts on Arctic ecosystems and ecosystem feedbacks, and societal implications of Arctic climate change. This report is not an assessment report *per se*, but was identified from the start as an interim report between the SWIPA 2017 report and the assessment reports proposed for 2023-2025. It was subsequently decided that AMAP should prepare biennial climate update reports to highlight key issues of concern or provide updates on past assessments. Accordingly, this 2021 report represents the first in a new series of shorter, more timely updates on key climate issues of concern. These reports will be in addition to the less frequent, but more in-depth assessment reports.

1.2 Previous AMAP climate assessments

Mandated by the Arctic Council to monitor and assess the state of the Arctic environment and climate, AMAP produced its first assessment of Arctic climate change and its impacts as part of a comprehensive State of the Arctic Environment Report (AMAP, 1997, 1998). The findings of the 1998 assessment led the Arctic Council to initiate an independent and comprehensive assessment of Arctic climate change and its impacts – the Arctic Climate Impact Assessment (ACIA). This was undertaken by AMAP in cooperation with the Arctic Council Working Group on the Conservation of Arctic Flora and Fauna (CAFF) and the International Arctic Science Committee (IASC). The resulting *Arctic Climate Impact Assessment* (ACIA, 2005) and its derivative *Impacts of a Warming Arctic* (ACIA, 2004) documented Arctic-wide warming and ongoing changes in Arctic snow, water and ice conditions that were impacting Arctic ecosystems and human living conditions. It also highlighted the potential global impacts of Arctic climate change. These reports showed that the Arctic was now warming rapidly, that impacts of the changing climate were already apparent, that much larger changes were projected, and that Arctic warming and its consequences have worldwide implications (ACIA, 2004, 2005).

Focusing on climate-related changes in the Arctic cryosphere, AMAP published its third Arctic climate assessment in 2011: *Snow, Water, Ice and Permafrost in the Arctic (SWIPA): Climate Change and the Cryosphere* (AMAP, 2011). This was followed by the fourth Arctic climate assessment: a follow-up *Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2017* report (AMAP, 2017a), as noted above. These changes in the cryosphere and the freshwater system were found to cause fundamental changes in the Arctic ecosystems, which will have important implications for Arctic livelihoods and living conditions. The two SWIPA assessments highlighted regional and global-scale climatic feedbacks caused by changes in the Arctic cryosphere and the cascading climate change impacts, while recognizing that climate change is not the only driver of change in the Arctic.

As a parallel activity to SWIPA 2017, three regional reports were prepared under the *Adaptation Actions for a Changing Arctic* project to provide information on adaptation actions that could be taken based on assessments of drivers of change and resultant impacts. The three regions were the Barents area (AMAP, 2017b), the Baffin Bay / Davis Strait region (AMAP, 2018), and the Beaufort-Chukchi-Bering region (AMAP, 2017c).

1.3 Follow-up to SWIPA 2017

After the completion of the SWIPA 2017 assessment, AMAP held a series of three workshops to build on the outcome of the assessment and develop a plan for the future climate work within AMAP. The first part of this plan was to prepare immediate follow-up scientific papers on several key issues identified in the SWIPA 2017 report, particularly by preparing scientific peer-reviewed articles that could be published in time for their use in the preparation of upcoming Intergovernmental Panel on Climate Change (IPCC) reports.

Four scientific papers were prepared and submitted (Box et al., 2018, 2019; Overland et al., 2018; Walsh et al., 2020). The three papers from 2018 and 2019 were available for use and were cited in the IPCC *Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC)* report (IPCC, 2019), which also made use of several AMAP assessment reports (AMAP, 2015, 2017a,b,c,d, 2018).

However, based on the outcome and recommendations of the three workshops, it was clear that the scope of further AMAP climate work needed to be broadened beyond the recent focus on the cryosphere to review a wider range of impacts of climate change in the Arctic. This particularly concerned a need for a much broader and stronger focus on the impacts on Arctic ecosystems and ecosystem feedbacks to the climate system, as well as the impacts of the many climate-related changes on Arctic societies and livelihoods. In addition, several issues were identified for more detailed follow-up work, namely, extreme events and thresholds in the Arctic, Arctic/mid-latitude weather linkages, and an evaluation of the performance of the Coupled Model Intercomparison Project phase 6 (CMIP6) models for projections of key Arctic climate parameters.

As a result of these recommendations and outcomes, AMAP decided that an interim 'climate issues of concern' report should be prepared for 2021. This report should contain chapters based on the scientific papers that were under preparation on Arctic extremes and Arctic/mid-latitude weather connections as well as the outcome of the CMIP6 modeling evaluation. In addition, the report should include an update on the time series of key climate indicators as well as on the impacts of climate change on Arctic marine and terrestrial ecosystems, including connections to the coast, and associated feedbacks of these changes to the Arctic. The latter issue will be covered in greater detail in a joint AMAP/CAFF project to assess climate-related impacts on ecosystems and associated feedbacks; this project will prepare a series of products for publication in the period 2023–2025. Similarly, an initial consideration of societal impacts was agreed as a contribution to the 2021 report, as a first step to a broader consideration of this issue in an assessment in the period 2023–2025.

To maintain an overview of these issues and coordinate the preparation of this and future climate reports, AMAP reconstituted its Climate Expert Group in 2019; this had been held in abeyance during the years of the two SWIPA assessment activities. The reconstitution of the Climate Expert Group and its preparation of the 2021 report also serve to enable AMAP to maintain momentum on climate work and provide information on climate issues on a regular basis, particularly in relation to the more recent decision to prepare biennial climate update reports.

1.4 Geographical delineation

The geographical delineation of the Arctic as used in the SWIPA assessment and in this report is based on that adopted by AMAP (Figure 1.1). The 'AMAP area' essentially includes the terrestrial and marine areas north of the Arctic Circle (66°32'N), and north of 62°N in Asia and 60°N in North America, modified to include the marine areas north of the Aleutian Islands chain, Hudson Bay, and parts of the North Atlantic Ocean including the Labrador Sea. However, for certain chapters there has been some deviation from this delineation depending on the topic covered.

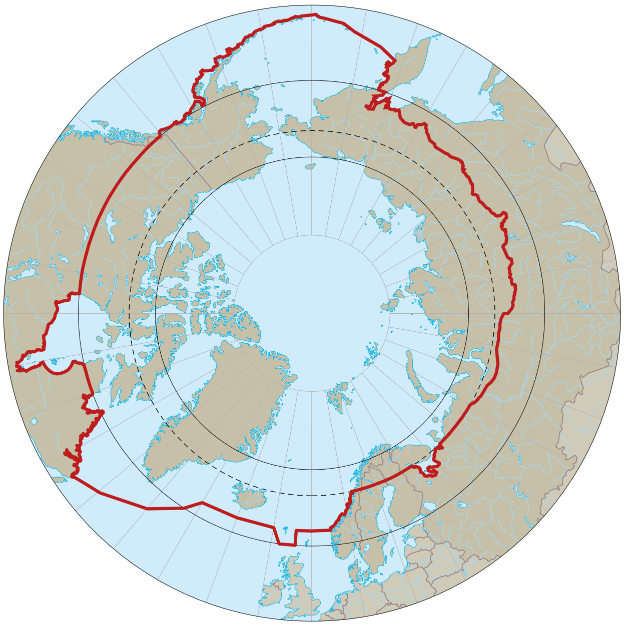

Figure 1.1 The Arctic, as defined by AMAP and as used in this report.

1.5 The process background

Preparation of the 2021 report involved over 50 scientists and experts from Arctic and non-Arctic countries. All were nominated by countries and relevant international bodies and selected on the basis of scientific qualifications by appointed convening lead authors. These experts were charged with compiling and evaluating information from Arctic monitoring networks, published literature, and recent national and international research activities.

Each chapter was drafted by experts covering relevant expertise from different scientific disciplines and geographical areas. A lead authors group, comprising the convening lead authors for each chapter, was responsible for the organization and overall accuracy of the assessment.

An important source of input for the report was a three-day workshop held virtually during 20–23 April 2020. This workshop was organized by the AMAP Secretariat and the co-leads of the Climate Expert Group. It was open to the full Climate Expert Group and invitees. Among the more than 50 participants were representatives from Canada, the Kingdom of Denmark, Finland, Iceland, Italy, Norway, the Russian Federation, Sweden, and the United States, as well as the Arctic Athabascan Council, the Inuit Circumpolar Council Canada, the North Atlantic Marine Mammal Commission, and the AMAP Secretariat. The workshop provided a forum for cross-chapter coordination and discussion of key messages of the 2021 report, as well as for obtaining additional contributing authors for the report.

This assessment report is fully referenced and peer reviewed. The assessment is based on the peer-reviewed scientific literature

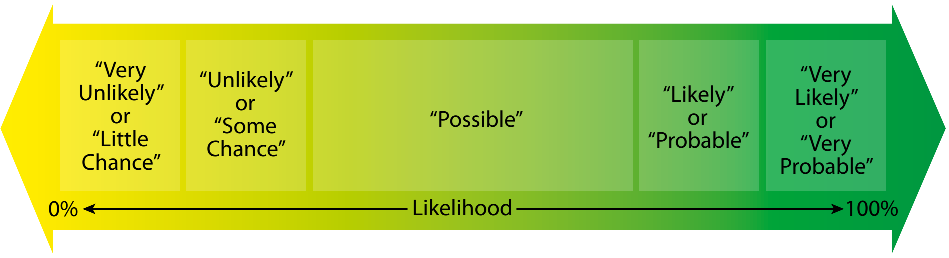

Figure 1.2 Five-tier lexicon describing the likelihood of expected change.

or on new results obtained using well-documented models and observational methods. The peer-reviewed observations, methods, and studies used in the assessment in many cases include contributions from Indigenous, traditional and local knowledge; it is recognized that this approach does not necessarily capture all relevant knowledge held by Indigenous and local communities.

Chapter authors have followed recommendations to promote the use of common terminology as far as possible. This included use of terminology associated with probability statements where discussion of future events and conditions need to take into account the likelihood that these conditions or events will occur. To ensure consistency of the summarized material, the procedures used by ACIA and the two SWIPA reports (as refined from those of the IPCC) were used throughout this report (see Figure 1.2). Statements regarding the likelihood that particular events or conditions will occur reflect expert evaluation of peer-reviewed results, typically from multiple lines of evidence.

The statements and assessments presented in this report were subject to a comprehensive review process, which involved national experts that contributed data and information to the assessment. These national experts verified that the interpretation of their data was correct and acceptable to the primary sources. A rule-based, independent international peer review process was established by AMAP to secure and document the integrity of the process (see the Preface for further details of the review process). Documentation of the results of the peer-review process applied to this report is available on the AMAP website: www.amap.no

1.6 What will readers find within each chapter?

The following six chapters present syntheses of current knowledge on six topics that are directly relevant to a rapidly changing Arctic climate. Because knowledge on these topics is rapidly evolving, they were chosen as foci of this report.

Chapter 2 presents updates on a suite of Arctic climate indicators, including air temperature, precipitation, permafrost temperature, terrestrial snow cover, river ice and river discharge, tundra greenness, wildfire, and sea ice and land ice. While many of these indicators were introduced in the 2017 SWIPA report, the list has been expanded to include additional metrics, thereby enabling the most comprehensive synthesis to date of indicators of Arctic climate change. Because they encompass many components of the Arctic system, they provide the foundation for assessments of ongoing Arctic change.

Chapter 3 presents updated simulation results from the state-of-the-art climate models. The models are the ones that participated in CMIP6. Nearly three dozen models were evaluated for their historical simulations and future runs under several Shared Socioeconomic Pathways (SSPs). This study shows that CMIP6 models are able to capture the general features of the present-day Arctic climatology, spatial variability, and historical linear trends in several variables investigated, such as: surface air temperature, sea-ice concentration, sea-ice extent, Northern Hemisphere spring snow extent, and sea-surface salinity and freshwater content in the upper 250 m of the Arctic Ocean. Compared with the Coupled Model Intercomparison Project phase 5 (CMIP5) models, CMIP6 models show a certain degree of improvement. Models project that the global warming will continue under all but the lowest scenario, and the amplified Arctic warming will continue as well, with the strongest warming projected to occur in the winter. Arctic sea ice (cover and thickness) and Northern Hemisphere snow extent are projected to decline under all scenarios. An ice-free summer Arctic is projected to occur under all but the lowest scenario. Depending on the models, the first ice-free date could be as early as the 2040s (SSP5-8.5). The Pacific Arctic is projected to become fresher, and the Atlantic Arctic is projected to become saltier based on the analysis of sea-surface salinity and the freshwater content in the upper 250 m. The probability of an ice-free Arctic summer is an order of magnitude smaller (10 times) under 1.5°C global warming, a scenario consistent with the Paris Agreement, compared to 2.0°C global warming based on CanESM2 stabilization runs.

Chapter 4 was motivated by the fact that the greatest impacts of climate change on ecosystems, wildlife and humans often arise from extreme events rather than changes in climate averages. However, there has been little attempt to synthesize information on extreme events in the Arctic. This chapter reviews work on thirteen types of Arctic extreme event, addressing the evidence for variations and changes based on analyses of recent historical data, as well as projected changes based primarily on studies utilizing global climate models. The chapter also points out associated thresholds to the extent that they are known. The survey of extreme weather and climate events includes temperature, precipitation, snow, freezing rain, atmospheric blocking, cyclones, and wind. The survey also includes cryospheric and biophysical impacts: sea-ice rapid loss events, Greenland Ice Sheet melt, floods, drought, coastal erosion and wildfire. Temperature, sea-ice loss events, and Greenland Ice Sheet melt events rank at the high end of the spectra of evidence for change and confidence in future change, while event types such as drought, inland flooding and cyclones rank at the lower end. Research priorities identified on the basis of this review include further work on thresholds, especially thresholds relevant to impacts on ecosystems and humans. Particular needs are the identification of impact-relevant thresholds and the likelihood of their exceedance in the future.

In Chapter 5, the rapidly evolving state of research on Arctic/mid-latitude linkages is reviewed. These linkages extend to extreme events in both the Arctic and middle latitudes, and have been the subject of intensive research by the climate modeling and diagnostics communities in recent years. Chapter 5 notes that pronounced changes in the Arctic (temperature increases, sea-ice and snow loss, polar vortex shifts) are adding potential drivers of anomalous weather in the mid-latitudes that affect billions of people. Examples include stalled severe weather events, persistent hot-dry extremes/drought, and cold air outbreaks. Mid-latitude impacts are on a weather event time scale (weeks) rather than on seasonal averages.

The report's final two chapters set the stage for AMAP's upcoming studies on ecosystems and societal implications of climate change in the Arctic.

Chapter 6 investigates Arctic climate-ecosystem impacts and feedbacks, based on the current climate and cryosphere observational basis and state-of-the-art models presented in Chapter 3. The chapter extends beyond previous assessments to provide an update and analysis of the most current scientific knowledge regarding the impacts of climate change on Arctic terrestrial and marine ecosystems and their feedbacks to climate. Whereas climate impacts on Arctic ecosystems are widespread and span all trophic levels, ecosystem feedbacks to the climate system are inherent to the biogeochemical cycling of greenhouse gases and exchanges of heat and water. In this context, Chapter 6 focuses on ecosystem processes and components that influence the biogeochemical cycling of greenhouse gases and surface energy exchanges. The chapter highlights fundamental and widespread ecosystem changes, altering the productivity, seasonality, distribution and interactions of species in terrestrial, coastal, and marine ecosystems. Extreme events exacerbate the transitions and changes already under way from climate warming and sea-ice changes, triggering further impacts. The Arctic gateways that connect the Arctic Ocean to the Pacific and Atlantic oceans are experiencing major ecosystem shifts. In addition, coastal ecosystems and communities are increasingly vulnerable to combined effects of climate change and extreme events. Long-term monitoring, conservation and protection of unique ecosystems are important tools for adaptation in the rapidly changing Arctic.

Chapter 7 presents a set of societal impacts of climate change on Arctic livelihoods and communities. This work is limited to a synthesis of peer-reviewed literature in the two categories of (i) livelihoods and economies and (ii) impacts from cryosphere change and extreme events. Indigenous livelihoods were found to be particularly impacted by reduced access to traditional food and increased hazards when traveling on frozen land and water. Wildlife populations have declined in parts of the Arctic, and the taste and quality of berries and meat have been impacted by a changing climate. Storage capacity of traditional food in winter has also been jeopardized by warmer temperatures and water in ice cellars. Saami reindeer pastoralism has been particularly affected by rain-on-snow events and extreme snowfall, resulting in losses during winter and late spring. On average, however, earlier snowmelt and green-up has been beneficial for calf production in most years. Loss of land is limiting the opportunity of Saami reindeer herders to adapt to changing conditions, such as adverse weather and predators. There is an increase in ocean-related activities. Marine fisheries are moving northward tracking the reduction of sea ice, aquaculture has expanded in the Atlantic Ocean, tourism boomed prior to Covid-19 restrictions and access to oil, gas and minerals has increased in areas previously covered by ice. Coastal communities have to some extent benefitted through increased economic development and employment, but costs to the environment and traditional users are also evident. Arctic communities have been exposed to impacts that have resulted in fatalities, relocation of settlements, or high costs for society. These impacts include those related to wildfire, permafrost thaw, coastal erosion, flooding, storms, landslides and avalanches. Remote communities with poor infrastructure have been particularly vulnerable to disasters. Some disaster costs can also be ascribed to lack of facilities, proper engineering, maintenance, and poor disaster management. Future assessments need to be more integrated across disciplines to address compound and cascading impacts, including interactions between changing climate, ecosystems and society. There is further need for documentation of impacts that are experienced in northern society but not necessarily studied by social scientists. Future assessments should include an authentic co-production process with respectful engagement of Indigenous People and local communities.

1.7 Influence of Covid-19

1.7.1 Impact of Covid-19 on the production of this report

The preparation of this report coincided with the Covid-19 pandemic. While chapter topics and lead authors had been identified prior to the onset of Covid restrictions in March 2020, the preparation of this report was notably impacted by the pandemic. In-person workshops for the solicitation of broader input for the cross-chapter coordination of content, and for the distillation of key findings have been hallmarks of past AMAP reports and assessments. The pandemic precluded this component of the report preparation. The alternative was the virtual format, which was utilized for both regular author meetings and the larger workshop for input solicitation. Challenges of this format included the multiple time zones of the participants in Europe, North America (including Alaska) and Japan, and the logistics of organizing an online workshop with parallel sessions for breakout groups. The pandemic also eliminated the possibility of additional meetings, including in-person gathering of Indigenous stakeholders or representatives of AMAP's Permanent Participants, from whom input would have been highly desirable for Chapters 4 (extreme events and thresholds), 6 (ecosystems) and 7 (societal implications).

In addition to these identifiable direct effects on the preparation of the report, the Covid pandemic had broader effects on the authors responsible for the individual chapters and the AMAP Secretariat tasked with the overall coordination of the report. Changes in working arrangements, unavailability of support staff, and the additional family responsibilities of many authors resulted in a general loss of efficiency and greater levels of stress in meeting the timeline of the report. While the report's final delivery and publication are within a few months of the original timeline, the constraints imposed by the pandemic clearly narrowed the options for soliciting input and for the scope of the report.

1.7.2 Initial estimate of impact of Covid-19 on scientific observations and fieldwork in the Arctic

The Covid-19 pandemic had notable impacts on the Arctic observations that are at the core of any evaluation of Arctic change. Travel restrictions as well as the closure of many Arctic communities and research sites interrupted many routine monitoring activities and resulted in the postponement of field programs throughout the Arctic. In some cases, the interruptions will result in data gaps in long-term records. In other cases, the data may be recoverable but their input to data banks may be delayed. Examples of lost data include measurements with data loggers powered by batteries having lifetimes of about a year; in these situations, the two-year interval between site visits by investigators will cause data gaps in the second year. In cases where ocean cruises or site-specific terrestrial measurements had been planned for 2020, postponing or cancelling field measurements will represent an irretrievable loss of data or other local information.

1.7.3 Other implications of the Covid-19 pandemic in the Arctic

One of the most notable impacts of the Covid-19 pandemic has been the isolation of Arctic communities. Travel restrictions affect not only access to communities by scientists, but also the ability of community members to travel outside their local areas for participation in meetings and other forms of engagement. At a time when the importance of co-producing knowledge is increasingly recognized, the timing of the Covid travel restrictions is especially unfortunate. Other broader impacts of Covid-19 include the addition of another stressor in communities that are already subject to multiple stressors, for example, climate change, contaminants, socio-economic challenges, healthcare limitations, and threats to culture. Multiple stressors on Arctic communities were recognized in AMAP's Adaptation Actions for a Changing Arctic reports, and the Covid-19 pandemic serves as a reminder that the impact assessments of climate and environmental change in the Arctic must be placed within a broader framework of stressors, some of which (such as Covid) cannot be foreseen.

References

ACIA, 2004. Impacts of a Warming Arctic: Arctic Climate Impact Assessment. 140 pp. Cambridge University Press.

ACIA, 2005. Arctic Climate Impact Assessment: Scientific Report. 1042 pp. Cambridge University Press.

AMAP, 1997. Arctic Pollution Issues: a State of the Arctic Environment Report. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway.

AMAP, 1998. The AMAP Assessment Report: Arctic Pollution Issues. Arctic Monitoring and Assessment Programme, (AMAP), Oslo, Norway.

AMAP, 2011. Snow, Water, Ice and Permafrost in the Arctic (SWIPA): Climate Change and the Cryosphere. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway.

AMAP, 2015. AMAP Assessment 2015: Temporal Trends in Persistent Organic Pollutants in the Arctic. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway, vi+71 pp.

AMAP, 2017a. Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2017. Arctic Monitoring and Assessment Programme, Oslo, Norway. xiv + 269pp.

AMAP, 2017b. Adaptation Actions for a Changing Arctic: Perspectives from the Barents Area. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway, xiv + 267pp.

AMAP, 2017c. Adaptation Actions for a Changing Arctic: Perspectives from the Bering – Chukchi – Beaufort Region. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway, xiv + 255pp.

AMAP, 2017d. AMAP Assessment 2016: Chemicals of Emerging Arctic Concern. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway, xvi+353 pp.

AMAP, 2018. Adaptation Actions for a Changing Arctic: Perspectives from the Baffin Bay/Davis Strait Region. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway, xvi + 254pp.

Box, J.E., W.T. Colgan, B. Wouters, D.O. Burgess, S. O'Neel, L.I. Thomson and S.H. Mernild, 2018. Global sea-level contribution from Arctic land ice: 1971–2017. Environmental Research Letters, ERL-105795, doi: 10.1088/1748-9326/aaf2ed.

Box, J.E., W.T. Colgan, R. Brown, M. Wang, J. Overland, J. Walsh, U. Bhatt, T. Christensen, N. Schmidt, M. Lund, F.-J. Parmentier, E. Euskirchen, V. Romanovsky, R. Corell, W. Meier, B. Wouters, S. Mernild, J. Mård, J. Pawlak and M. Olsen, 2019. Key Indicators of Arctic Climate Change: 1971–2017. Environmental Research Letters, ERL-106063, doi: 10.1088/1748-9326/aafc1b.

IPCC, 2019. IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Pörtner, H.-O., D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N.M. Weyer (eds.). Intergovernmental Panel on Climate Change (IPCC).

Overland, J., E. Dunlea, J.E. Box, R. Corell, M. Forsius, V. Kattsov, M. Skovgård Olsen, J. Pawlak, L.-O. Reiersen and M. Wang, 2018. The urgency of Arctic change. Polar Science, 21:6-13.

Walsh, J.E., T.J. Ballinger, E.S. Euskirchen, E. Hanna, J. Mård, J.E. Overland, H. Tangen and T. Vihma, 2020. Extreme weather and climate events in northern areas. Earth Science Reviews, 209:193324, doi: 10.1016/j.earscirev.2020.103324.

2. Recent developments in Arctic climate observational indicators

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Key findings

- *Key observational indicators of Arctic climate, most spanning a 49-year period (1971–2019), demonstrate clear and statistically significant trends.*
- *The increase in Arctic average near-surface air temperature between 1971 and 2019 was three times higher than the global average during that period, with warming most pronounced over the Arctic Ocean and during the freeze-up season (October through May).*
- *Precipitation in the Arctic increased from 1971 to 2019, driven by a 25% increase in rainfall.*
- *Permafrost is thawing across the Arctic with rates of warming at colder permafrost sites higher this century than at any time on record.*
- *Arctic snow-covered area in May and June has declined by 21% since 1971, and ice cover on most northern rivers has decreased in thickness and duration.*
- *Arctic river discharge to the Arctic Ocean increased by 8% (~187 km^3/y) between 1971 and 2019, about an average of 2400 km^3/y.*
- *Arctic tundra greenness increased by 10% in the 38 years between 1982 and 2019 and correlates with year-to-year melt season air temperatures.*
- *Increased boreal forest and tundra wildfire is promoted by Arctic climate warming with Arctic wildfire an increasing source of carbon emissions into the atmosphere.*
- *Arctic sea-ice area and thickness have declined by 43% in the period of satellite observations, continuous from 1979.*
- *Ice losses from Arctic glaciated areas accounted for most of the world's land-ice loss in the 1971 to 2019 period.*
- *The Arctic physical climate is clearly trending away from its 20th century state and into an unprecedented state, with implications within and beyond the Arctic.*

2.1 Introduction

This chapter distills a list of 'key climate signals' from a collection of more than 10 observational Arctic climate indicator series. The temporal coverage is here focused on the 49-year period between 1971 and 2019. By starting the survey in 1971, the available records encompass the pronounced Arctic warming that began after the mid-1980s (Overland et al., 2004; Przybylak and Wyszyński, 2020). Those datasets beginning after the mid-1980s should be viewed on the basis that they would not reflect the absence of a clear anthropogenic trend at the start of the record. In this chapter, use of the term 'change' is interchangeable with the term 'trend' or 'total increase/decrease' and refers to the magnitude of linear trends assessed by standard least squares regression (Chatterjee and Hadi, 2006) equal to the regression temporal slope multiplied by the time duration. Statistical 'confidence' is measured as 1-p after a Student's two-tailed T-test. Regional averages are obtained from gridded data using land/ocean masks.

The chapter provides new insights relative to the SWIPA 2017 update (AMAP, 2017) and its observational indicators follow-on article (Box et al., 2019). Each section reports knowledge gaps and recommendations for future efforts.

In terms of linkage with other chapters, for the topic of future Arctic climate, see Chapter 3 *Model assessment and future of the Arctic*. Chapter 5 explores *Arctic/mid-latitude weather connectivity*. Cascading impacts of the trends reported here on human populations and ecosystems receive attention in Chapter 6 *Arctic climate and ecosystem linkages: impacts and feedbacks* and Chapter 7 *Impacts of climate change and climate extremes on Arctic livelihoods and communities.*

2.2 Air temperature

Air temperature is an excellent climate indicator because it locally integrates the surface and atmospheric energy budgets, including horizontal heat transport. Increasing air temperatures (this section) and precipitation (Section 2.3) are drivers of change in various components of the Arctic climate system, such as river discharge or glacier mass balance (Box et al., 2019).

2.2.1 New insights

Key climate signals:

- Arctic (north of 65°N) near-surface air temperatures have warmed three times as fast as the globe, with annual averages increasing by 3.1°C in the 49 years between 1971 and 2019.
- Largest air temperature trends occur over the Arctic Ocean during the freeze-up season (October through May) with warming peaking at +10.7°C over the northeastern Barents Sea and averaging +3.9°C over the Arctic Ocean.

- Annually, the Arctic Ocean warming trend from 1971 to 2019 averages 2.9°C and peaks at 7.5°C over the northeastern Barents Sea.
- An acceleration of Arctic warming has occurred since 2005, especially for the Arctic Ocean, linked to increases in the number and duration of winter warm events accompanied by increased moisture intrusions.

2.2.1.1 Air temperature validation

Here, near-surface (2 m above ground) air temperature records are examined. The first begins in the 19th century and includes an interpolation to more realistically represent the sparsely-instrumented Arctic Ocean (Cowtan and Way, 2014). The second is the EU Copernicus ERA5 monthly reanalysis, here spanning the period 1971–2019 (Copernicus, 2020). ERA5 is an atmospheric model constrained by observations via data assimilation and provides air temperature and precipitation estimates on a global 31-km grid. Biases are evident in the ERA5 temperature data; for example, over Arctic sea ice, the ERA5 2-m air temperature data exhibit a warm bias of ~1.8°C at -25°C that increases to ~8°C below -40°C (Wang et al., 2019) that appears to be the result of missing representation of the snow layer on top of the sea ice (Batrak and Müller, 2019). A freeze-up season warm bias of 0.5°C to 1.5°C is confirmed here for island meteorological stations on High Arctic islands in the vicinity of Svalbard and to the east north of Siberia. Elsewhere, the terrestrial station bias pattern is spatially variable, which is likely to reflect complex factors such as topographic error resulting from smoothing in the ERA5 grid. Regarding the validation of trends, with monthly-averaged meteorological station air temperatures (GISTEMP Team, 2020), there is an insignificant (-0.5°C) ERA5 cold bias for the period July through February. Regarding 1971–2019 trends, an insignificant (+0.5°C) bias is evident in January through April. Otherwise, ERA5 agreement with observed air temperature is excellent (average errors are under 0.3°C).

2.2.1.2 Changes in air temperature

Arctic annual air temperatures have increased more than 1°C above pre-21st century levels in the instrumental HadCRUT4 record that begins in the late 1800s (Brohan et al., 2006; Cowtan and Way, 2014). According to these data, Arctic annual near-surface air temperatures have increased 3.3 times as fast as the global pattern for 1971 to 2019.

An abrupt ~1.5°C average air temperature increase is observed from 2005 onward (Figure 2.1), followed by a 1.3 times higher warming rate for the Arctic north of 65°N. For the Arctic Ocean, the air temperature increase is 1.6 times larger than in the 1971–2005 period. The shift is attributable to an increase in the number and duration of winter warm events over the central Arctic Ocean after 2004 (Graham et al., 2017b). The winter storms are accompanied by increased atmospheric moisture and heat intrusions above the Arctic Ocean (Boisvert and Stroeve, 2015; Park et al., 2015; Woods and Caballero, 2016; Graham et al., 2017a).

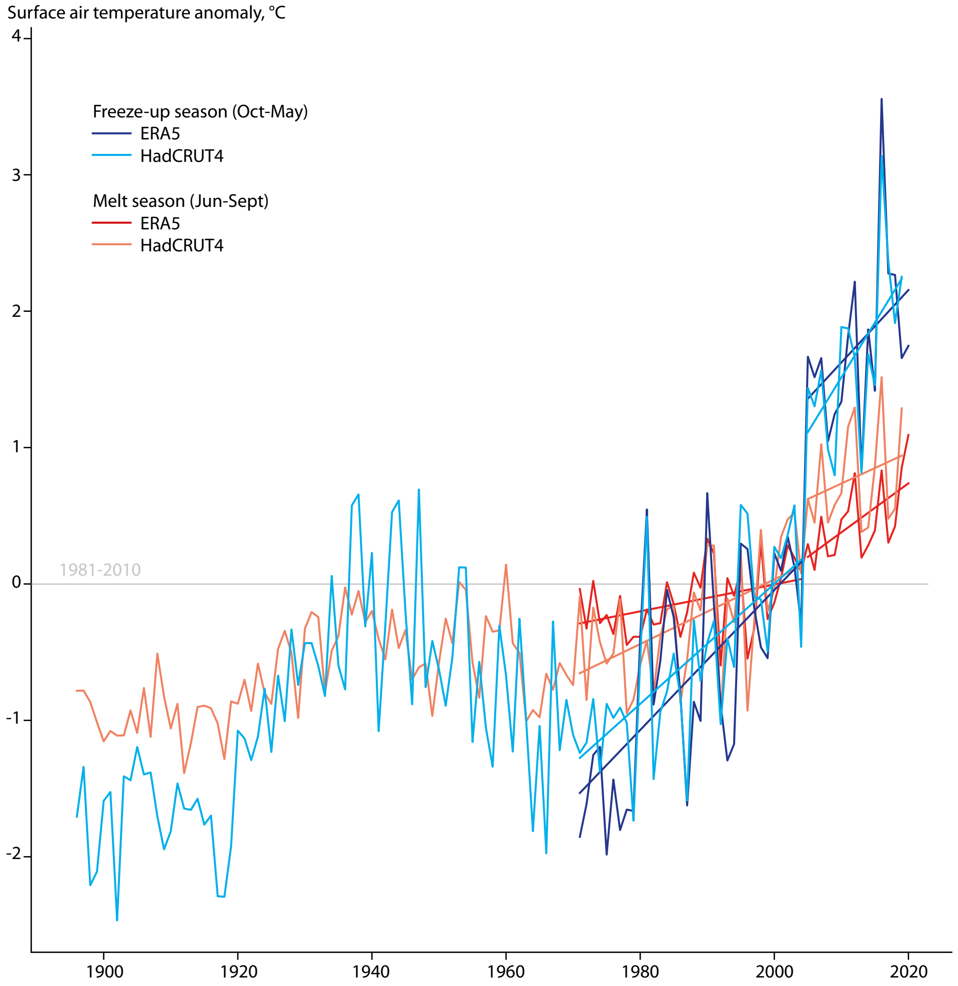


Figure 2.1 Arctic (north of 65°N) annual near-surface air temperature anomalies 1896–2019 from HadCRUT4 data after Cowtan and Way (2014) and from ERA5 1971–2019. The annual time series pattern (not shown) has a very similar pattern.

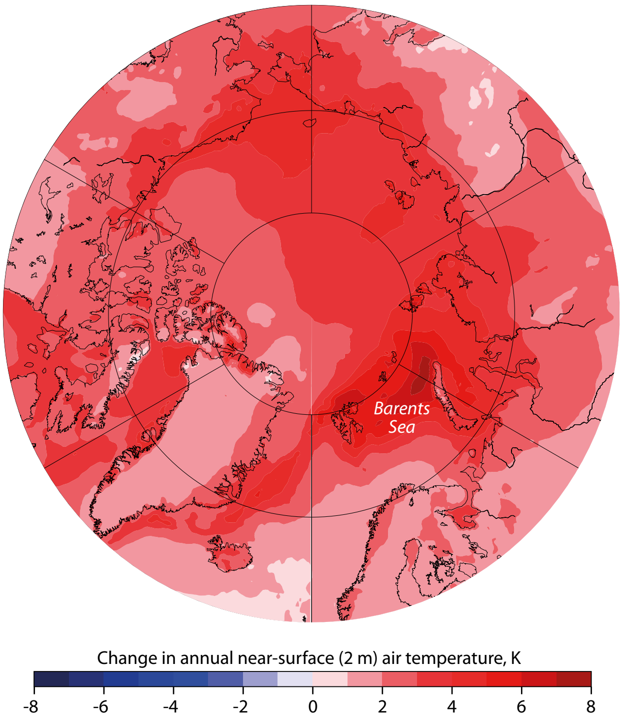


Figure 2.2 Arctic near-surface air temperature trends for the 49-year period 1971–2019. The trend metric is the linear regression temporal slope multiplied by the timespan in years. Data source: ERA5.

For the melt season (June through September), there is less agreement between ERA5 and HadCRUT4 in trend magnitude before 2005, with ERA5 lacking less extreme low temperature anomalies. And during the melt season, the absolute temperature anomaly is more uncertain. If ERA5 data are taken as providing an accurate trend, the melt season 2019 increase above the 1981–2010 baseline is +0.6±0.2°C. The HadCRUT4 data yield +0.9±0.4°C. Annually, the 2019 increase above the 1981–2010 baseline is the same for the ERA5 and HadCRUT4 data: +1.8±0.4°C. If the 1896–1900 baseline is taken, the annual warming is +3.2±0.6°C according to the HadCRUT4 data.

Annually, the Arctic Ocean near-surface atmospheric warming averages 2.9°C and peaks at 7.5°C over the northeastern Barents Sea (Figure 2.2), higher than anywhere else in the Arctic.

Arctic air temperature increases are strongest during the October through May freeze-up season (Figures 2.1 and 2.3). The largest regional air temperature trend 1971–2019 is over the Arctic Ocean during the freeze-up season, with warming peaking at +10.7°C over the northeastern Barents Sea (Figure 2.3 left) and averaging +3.9°C over the Arctic Ocean. Later freeze-up of sea ice (Markus et al., 2009; Johansson et al., 2020) and advection of moisture into the Arctic (Zhang et al., 2013; Neff et al., 2014) are key contributors to the rise in freeze-up season air temperatures confirmed by instrumental records (Graham et al., 2017b). The annual pattern is very similar to that of the freeze-up season due to the higher freeze-up season trends and larger fraction of the year covered by the freeze-up season. The June through September ‘melt season’ trend is of lower magnitude for several reasons, including: an increase in low clouds (Walsh et al., 2011) that reduce surface cooling (Zhang et al., 2001); an increase in humidity at the surface (Vihma et al., 2016) and in the mid-troposphere (Serreze et al., 2012); the melt process absorbs sensible heat and the melt season atmospheric circulation is less vigorous than in the freeze-up season (Serreze et al., 1993). The ‘melt season’ temperature increase peaks within 200 km of the Arctic Ocean shoreline, especially over the ocean (Figure 2.3 right).

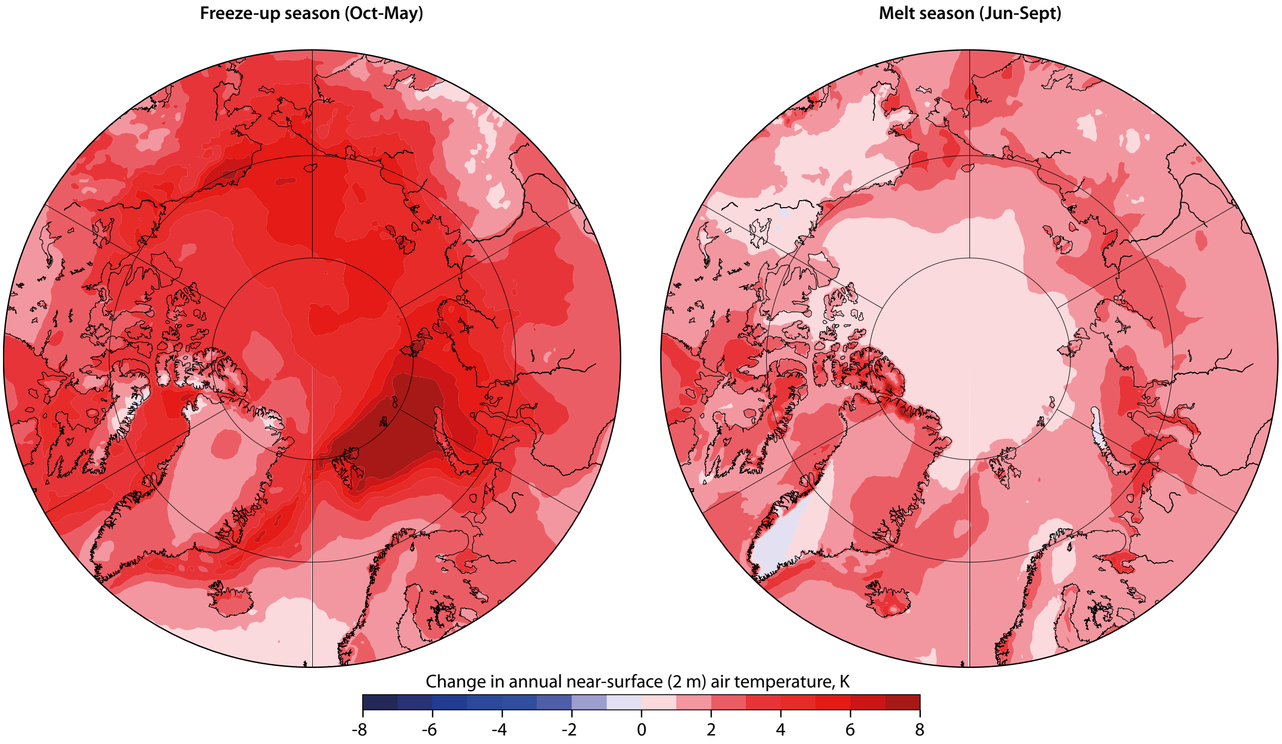


Figure 2.3 Arctic near-surface air temperature trends for the 49-year period 1971–2019 for the freeze-up season (October through May) and ‘melt season’ (June through September). The trend metric is the linear regression temporal slope multiplied by the timespan in years. Data source: ERA5.

2.2.2 Knowledge gaps and recommendations

While near-surface air temperature is a powerful climate indicator, more insight is gained from analyzing individual components of the surface energy budget, that is, the balance of the turbulent latent and sensible heat fluxes with upward and downward solar and infrared radiation fluxes. Further, analyzing heat and moisture transport can complement the study of the surface energy budget.

2.3 Precipitation

2.3.1 New insights

Key climate signals:

- Arctic total precipitation is increasing, by 9% in the 1971–2019 period according to the ERA5 dataset, driven by a 25% rainfall increase. There is no net overall Arctic snowfall trend.
- At the regional scale, total precipitation trends are evident in areas of elevated terrain along the southeastern coasts of Greenland and Iceland, across the northern North Atlantic and the Barents Sea, in the vicinity of Svalbard and along the southern Alaskan coast.

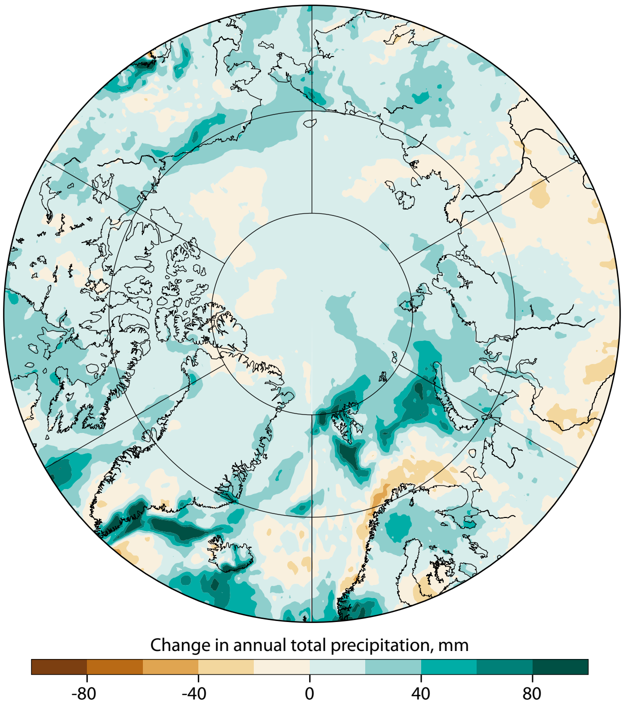


Figure 2.4 Arctic total precipitation trends for the 49-year period 1971–2019. The trend metric is the linear regression temporal slope multiplied by the timespan in years. Data source: ERA5.

While there is considerable uncertainty in Arctic precipitation rates owing to sparse observations, uncertain adjustments for gauge undercatch and in reanalysis datasets (Rawlins et al., 2010; Rapaić et al., 2015), the small (1.5–2.0% per decade) increase in annual precipitation is consistent with the estimated temperature sensitivity of Arctic precipitation of +4.5% for each °C of warming (Bintanja and Selten, 2014). ERA-Interim reanalysis data (Screen and Simmonds, 2012) and a later intercomparison of eight atmospheric reanalysis datasets found no overall trend for total precipitation over the Arctic Ocean, but an increase in rainfall (Boisvert et al., 2018). In another reanalysis intercomparison, Barrett et al. (2020) found that the ERA5 dataset, used here, captures the spatial and seasonal patterns of Arctic precipitation. ERA5 precipitation accuracy was evaluated for central Arctic Ocean sea ice by

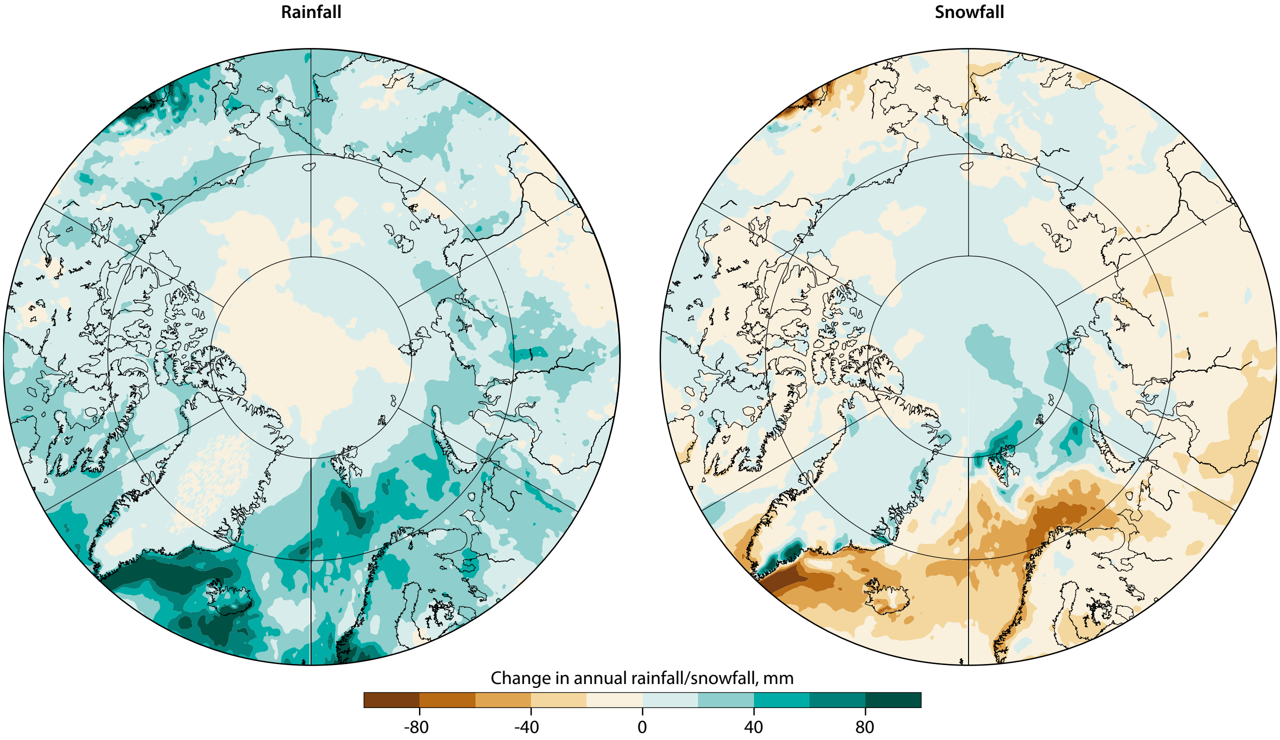


Figure 2.5 Arctic rainfall trends (left) and snowfall trends (right) for the 49-year period 1971–2019. The trend metric is the linear regression temporal slope multiplied by the timespan in years. Data source: ERA5.

Wang et al. (2019) who found general agreement with in-situ observations at drifting buoys.

The ERA5 observational reanalysis dataset (Copernicus, 2020), analyzed here, indicates an overall Arctic precipitation increase of 9% in the past 49 years (1971–2019) (Figure 2.4). The largest precipitation increase north of 65°N is during the freeze-up season from October through May (when temperature increases are greatest), especially along the southeastern coasts of Greenland and Iceland, across the northern North Atlantic and the Barents Sea and in the vicinity of Svalbard.

According to the ERA5 data, Arctic total precipitation is increasing, by 9% in the 1971–2019 period, driven by a 25% rainfall increase. There is no net overall Arctic snowfall trend. The greatest rainfall increase is across the North Atlantic, especially along the mountainous Norwegian and Icelandic coasts (Figure 2.5). There is a similar rainfall increase along the southern Alaskan coast. In contrast to the changing rainfall patterns, decreasing snowfall is evident across the Arctic, with the exception of increases along southeastern Greenland, Svalbard and the northern Barents Sea (Figure 2.5). Decreasing Arctic snowfall, especially over the North Atlantic, is partially at the expense of increasing rainfall simply due to a warming climate, see for example, Førland et al. (2020), consistent with modeling (Bintanja and Andry, 2017; Bintanja, 2018). The decreasing snowfall is consistent with independent observations documenting decreasing snow-covered area and snow mass (see Section 2.5).

2.3.2 Knowledge gaps and recommendations

While solid and liquid precipitation estimates are available from atmospheric reanalyses beginning well before present, their quality for the Arctic region remains poorly established. Some high-quality long-term in-situ precipitation records are available in the Arctic: in Arctic Alaska via the U.S. Climate Reference Network (e.g., Utqiaġvik, Dead Horse, Ivotuk, Toolik) (Diamond et al., 2012). For Canadian networks, automated precipitation gauges were introduced in the early 2000s (Mekis et al., 2018) which may suffer in quality from less human oversight. It would help in-situ data users for data to be published with undercatch-corrections in addition to the raw data, and for the data to be accompanied by correction details and metadata.

2.4 Permafrost temperature

2.4.1 New insights

Key climate signals:

- Arctic permafrost has warmed 2–3°C since the 1970s accompanied by increases in active layer thickness and landscape changes such as coastline erosion and thaw slumping.
- At the lowest permafrost temperature sites, the 21st century warming rates have been the greatest on record.

Permafrost includes earth materials having a temperature that remains below freezing (0°C) for two or more years and underlies extensive areas of the Arctic landscape. Permafrost influences landscape stability, hydrological systems and ecosystems (Box et al., 2019). Warming and thawing of permafrost have important implications for infrastructure integrity and carbon sources and sinks (Romanovsky et al., 2017).

2.4.1.1 Borehole temperature increases

Permafrost temperatures in the upper 30 m of land surface have been measured in boreholes across the Arctic over the past five decades within the framework of the Global Terrestrial Network for Permafrost (GTN-P) as part of the Global Climate Observing System of the World Meteorological Organization (Noetzli et al., 2020). Figure 2.6 illustrates annual permafrost temperatures for 19 sites across the Arctic.

Permafrost warming rates vary regionally (Biskaborn et al., 2019; Romanovsky et al., 2020). For example, the Alert sites (BH1, BH2, BH5) have accelerated warming after 1999 while the Alaskan sites (e.g., Deadhorse) have a more constant warming rate. With the exception of Iskoras, Urengoy15-06, Bolvansky56, Wrigley and Norman Wells where the 2000–2019 warming is relatively small (under 0.3°C), the sites have an average (± standard deviation) warming of 1.0±0.6°C over this period (Figure 2.7). The longest record, from Deadhorse, exhibits warming of 3.5°C 20 m below the surface from 1971 to 2019 (Figure 2.6).

Permafrost temperature trends at the (lower temperature) Arctic tundra sites are much greater than the trends at the (higher temperature) forested sites where permafrost temperatures are close to 0°C (Figure 2.7). At the higher temperature sites, permafrost thawing offsets warming due to latent heat release from melting ground ice (Romanovsky et al., 2017).

In Svalbard and the Nordic countries, permafrost temperatures increased to their highest levels in both ‘cold’ and ‘warm’ permafrost (Isaksen et al., 2007; Christiansen et al., 2010; Hanssen-Bauer et al., 2019). At Iskoras, northern Norway, latent heat exchanges from melting ground ice dominate the ground temperature series and at 20 m depth, ground temperatures have now risen to 0°C (Noetzli et al., 2020).

Observations from Zackenberg Research Station, NE Greenland demonstrate increasing ground temperatures in the permafrost zone that are strongest during the freeze-up season, as is also the case for near-surface air temperature trends (Christensen et al., 2020). The 1.3-m depth Zackenberg observations indicate a 1.3°C warming in the 20 years from 1999 to 2019. The 18.3 m temperatures since 2012 (see Figure 2.6) also indicate warming.

2.4.1.2 Active layer trends and permafrost thaw

Active layer thickness (ALT), the thickness of the seasonally thawed layer, is determined by mechanical probing at 88 sites in Alaska, Russia and the Nordic countries and by use of thaw tubes at 25 sites in northwestern Canada. In northwestern North America, there has been an ALT increase since the mid-1990s in the Alaskan interior with new record high values in 2019 (Duchesne et al., 2020; Romanovsky et al., 2020). However, there is no long-term trend on the North Slope of Alaska nor in the Mackenzie Valley although an increase in ALT has been observed over the past decade (Romanovsky et al., 2020).

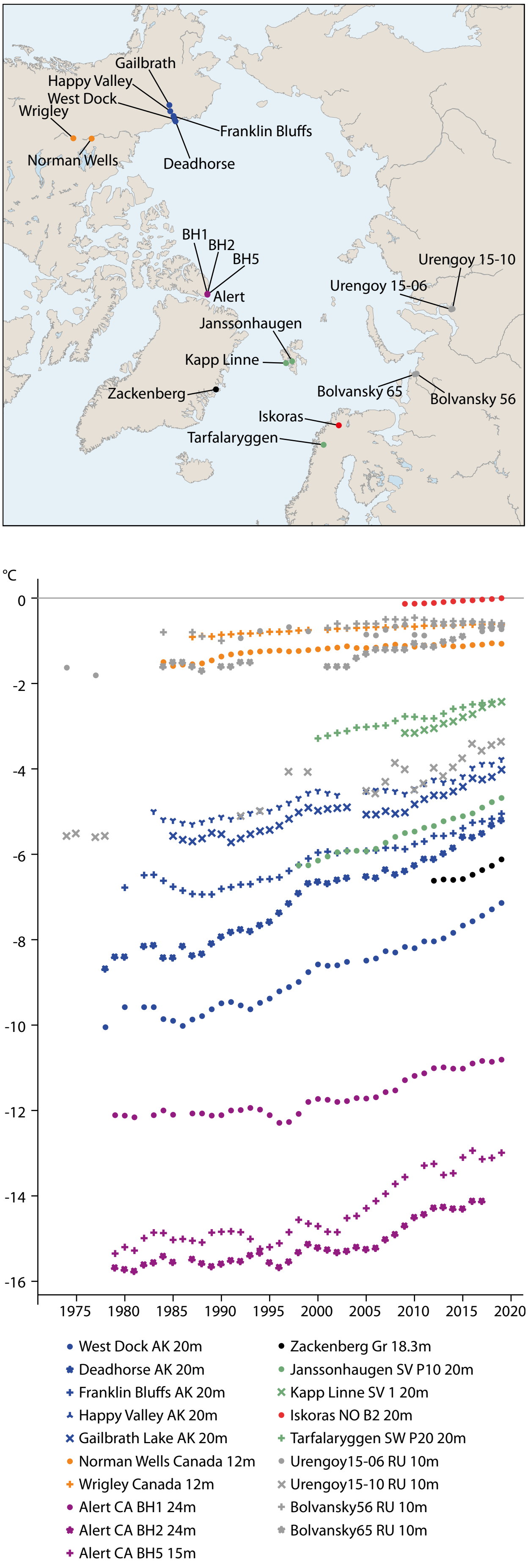


Figure 2.6 Permafrost temperature records for nineteen Arctic locations.

ALT has generally increased since the 1990s for Svalbard and Greenland sites (Romanovsky et al., 2020). A general increase in ALT over the past two decades has been observed at sites across Russia, with the increase becoming less in the past 10 years (Abramov et al., 2019; Vasiliev et al., 2020). ALT at sites underlain by ice-rich permafrost may show little variation due to both the energy required for phase change and the surface subsidence that accompanies melting of ground ice (Streletskiy et al., 2017; Abramov et al., 2019; O'Neill et al., 2019; Vasiliev et al., 2020). Subsidence in the tundra landscapes of Alaska since 2003 ranges from 0.4 to 1.0 cm/y (Streletskiy et al., 2017) and in the Mackenzie Delta, subsidence between 1991 and 2016 ranged from 0.2 to 0.8 cm/y with a 5 to 38 cm loss of permafrost (O'Neill et al., 2019).

In addition to the gradual subsidence that occurs as ice-rich permafrost thaws, several recent studies provide other evidence of trends in permafrost conditions throughout the Arctic. This includes documentation of loss of permafrost mounds, collapse of lithalsas and palsas, increases in thermokarst pond size, coastal erosion (Figure 2.8), melting of ice wedges and intensification of thaw slumping (e.g., Rachold et al., 2000; Mars and Houseknecht, 2007; Liljedahl et al., 2016; Borge et al., 2017; Jolivel and Allard, 2017; Mamet et al., 2017; Nitze et al., 2017; Fraser et al., 2018; Swanson and Nolan, 2018; Derksen et al., 2019; Farquharson et al., 2019; Jones et al., 2019; Lewkowicz and Way, 2019).

2.4.2 Knowledge gaps and recommendations

Since permafrost is a subsurface phenomenon, long-term trends in permafrost condition are conventionally determined from in-situ measurements. Although these measurements are generally of high quality and provide enough information to determine general trends, the distribution of sites is uneven and the monitoring network has spatial gaps such as in the central Canadian Arctic or central Siberia. The remoteness of many monitoring sites also presents logistical challenges including accessibility, and can result in gaps in the record. Expanding the monitoring network is recommended, as is co-location with other monitoring networks including meteorological and other cryosphere networks (e.g., snow), to address logistical challenges as well as to provide the information required to attribute the changes in permafrost condition. Analysis of remotely sensed imagery has been utilized to detect landscape change that may be related to changes in permafrost condition, including thermokarst processes, as previously discussed. Greater integration of remote sensing and in-situ observations is required, as is research into the use of new satellite products to enhance permafrost monitoring and apply results from point-based field measurements to the broader spatial domain.

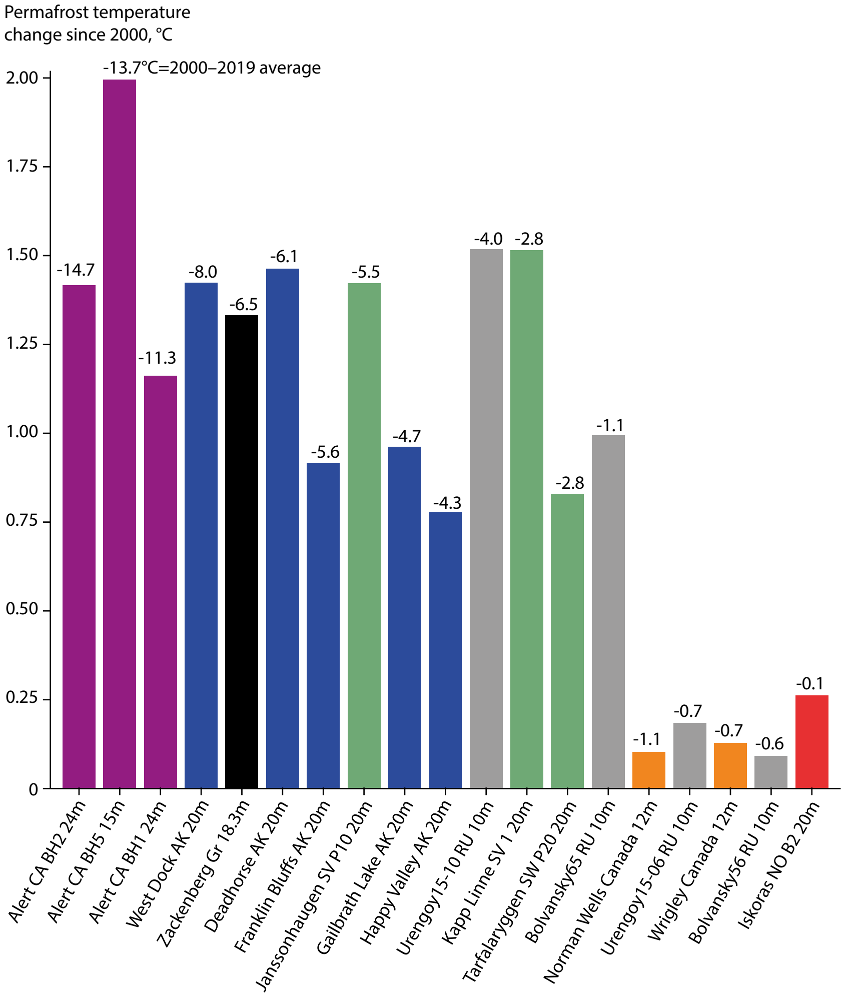


Figure 2.7 Permafrost warming trends for the period 2000–2019 ranked from lowest to highest average temperature (left to right). Average permafrost temperature since 2000 appears above the bar. The trend metric is the linear regression temporal slope multiplied by the timespan in years. Bar colors indicate regions (see Figure 2.6).


Alexander Oboimov, Ivan Mizin/WWF Russia

Figure 2.8 Coastline erosion is observed at some locations to exceed 30 m/y, and is 5 m/y on average. The image shows an abandoned meteorological station on Vise (Wiese) Island falling into the Kara Sea (Gertcyk, 2016).

2.5 Terrestrial snow cover

2.5.1 New insights

Key climate signals:

- Arctic spring (May through June) snow-cover extent decreased by 21% over the 1971–2019 period. A bigger decrease (-25%) is evident over the larger Eurasian area than across North America (-17%).
- Reduced spring snow cover is a major contributor to the amplified warming across the Arctic.

All Arctic land areas are covered with snow in winter, so the transition seasons of autumn and spring are particularly sensitive to the impact of warming. Changes in seasonal snow exert important influences on the surface energy budget (Flanner et al., 2011; Euskirchen et al., 2016), the ground thermal regime and hence carbon fluxes (Natali et al., 2019), and the Arctic freshwater budget (Déry et al., 2016). Changes in snow cover have consequences for terrestrial and aquatic ecosystems, human community health and wellbeing, transportation and infrastructure (Meredith et al., 2019).

Combining multiple snow products is helpful to form a robust analysis given a large spread among datasets (Mudryk et al., 2015; Krinner et al., 2018). Averaging to create multi-product ensembles produces the best statistical agreement with reference snow survey data (Mortimer et al., 2020). Five independent snow analyses were combined to determine trends in snow extent and snow-water equivalent (SWE) across Arctic land areas north of 60°N:

- Dataset 1: Output from the Modern-Era Retrospective Analysis for Research and Applications version 2 (MERRA-2) (Gelaro et al., 2017)
- Dataset 2: Snow accumulation determined by a simple temperature index model (after Brown et al., 2003) driven by the ERA-Interim reanalysis data
- Dataset 3: The Crocus physical snowpack model driven by the ERA-Interim reanalysis data (Brun et al., 2013)

- Dataset 4: The European Space Agency GlobSnow combination of satellite passive microwave data and climate station snow depth observations (Takala et al., 2011)
- Dataset 5: The NOAA snow chart Climate Data Record (Estilow et al., 2015) derived primarily from optical satellite imagery.

Monthly totals of Arctic snow mass were calculated directly from gridded SWE values in datasets 1 to 4 by summing over land north of 60°N. Gridded snow-cover fraction (SCF) is available directly from dataset 5 and is estimated for datasets 1 to 4 by applying a 4-mm threshold to daily gridded SWE and averaging to obtain monthly gridded SCF. Arctic snow-cover extent is calculated by summing monthly SCF over land north of 60°N. For both snow-cover extent and snow mass, the variability-adjusted anomalies from each dataset are averaged as described by Mudryk et al. (2020a) and added to the best-estimate climatology of each metric; considered here to be the NOAA Arctic snow-cover extent climatology, the dataset average snow mass climatology, and the dataset mean snow-cover duration climatology.

Consistent with recent assessments, it is clear that spring snow-cover extent has declined across Arctic land areas (Callaghan et al., 2011; Brown et al., 2017; Meredith et al., 2019). The trend over the 1971–2019 period using the average of products listed above is a 21% reduction for May through June (Figure 2.9). Downward trends over this period are stronger across the Eurasian Arctic (-25%) than the smaller North American Arctic area (-17%).

Arctic autumn snow-cover extent trends are difficult to assess owing to an increasing trend in the NOAA snow chart data record (dataset 5) not replicated in the other datasets (Brown and Derksen, 2013). Analysis of Northern Hemisphere data shows evidence of decreasing autumn snow-cover extent but this does not emerge strongly until November and December when the Arctic is already completely snow-covered each year (Mudryk et al., 2020a).

Trends for snow mass in March (the approximate timing of peak accumulation for land areas north of 40° N) exhibit long-term reductions across North America and Eurasia between 1981 and 2013 (Pulliainen et al., 2020). For the region north of 60° N for April (higher snow mass in April than March for the Arctic), decreasing trends are evident for North America and Eurasia. The metric for statistical confidence (1-p) is higher in North America (0.969) than Eurasia (0.899), in part due to very heavy snow years in Eurasia in four of the last five years of the record (Figure 2.10).

2.5.2 Knowledge gaps and recommendations

The selection of hemispheric gridded snow-cover datasets available for trend analyses continues to evolve from year to year as some products fail to be updated, some transition to updated versions, and entirely new datasets emerge. Consequently, multi-decadal trends in snow-cover variables are subject to differences based on the time period, region, datasets considered, and statistical approaches in multi-dataset trend analysis. While differences in trend magnitude between

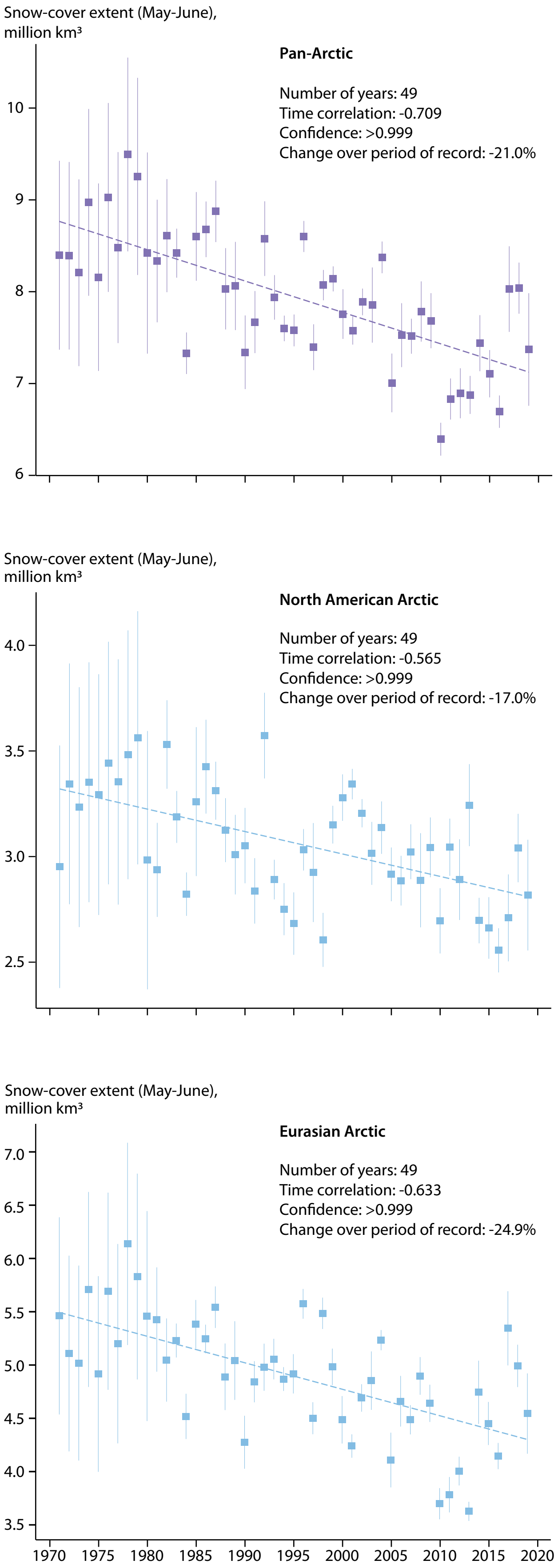


Figure 2.9 Time series of pan-Arctic, North American Arctic and Eurasian Arctic snow-cover extent for May through June. The trend metric is the linear regression temporal slope multiplied by the timespan in years divided by the multi-year average, expressed as a percentage. Symbols indicate multi-dataset average; whiskers indicate 95% confidence range.

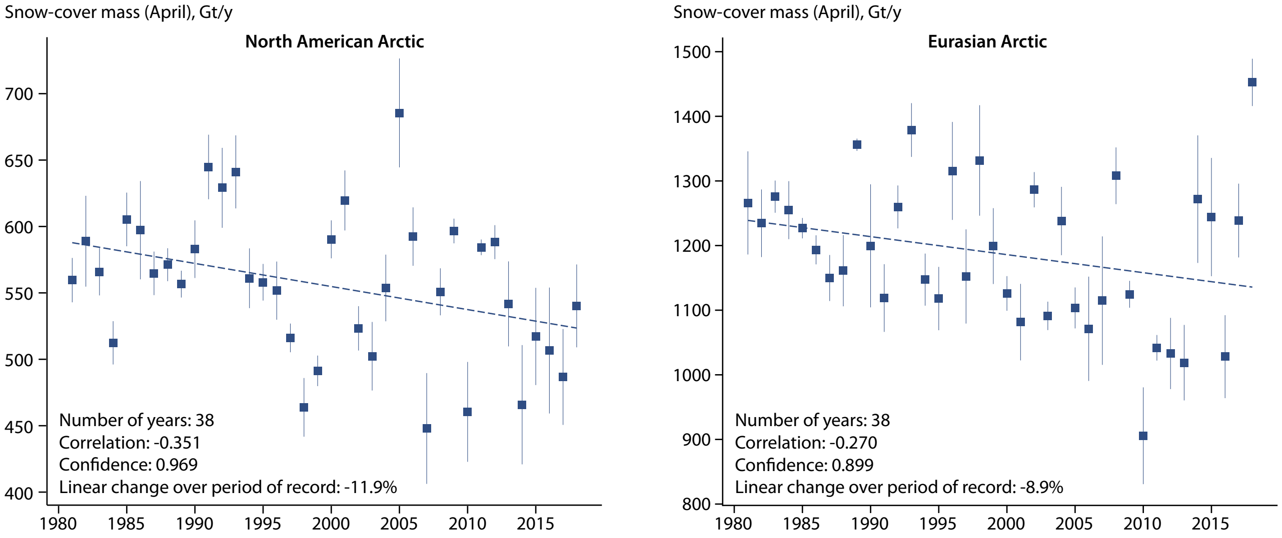


Figure 2.10 Trends in April snow-cover mass for North America and Eurasia, i.e. north of 60° N. The trend metric is the linear regression temporal slope multiplied by the timespan in years. Symbols indicate a multi-dataset average; whiskers indicate 95% confidence range.

studies and assessments in recent years are considerable (Meredith et al., 2019; Mudryk et al., 2020a,b), community-wide efforts continue to focus on producing more robust and up-to-date time series for climate analysis. Nonetheless, the overall patterns of declining Arctic spring snow cover remain. Further work is necessary to better understand autumn trends, and to continue to refine multi-dataset analyses.

High variability is evident in the snow mass time series, reflecting the interplay between temperature and precipitation within and between seasons. The complexity of Arctic precipitation change, combined with few surface measurements, highlights the need to produce new precipitation records by properly correcting and curating existing gauge measurements, sparse as they may be (e.g., Stuefer et al., 2020), and developing new remote-sensing and reanalysis-derived precipitation estimates.

Given the coarse spatial resolution of current snow mass products, they are not sensitive to factors such as increased shrub cover (Mekonnen et al., 2021), which may play a role in changes to snow accumulation and redistribution at the landscape scale. It is unclear how changes in vegetation and snow cover will increase or decrease ground moisture content. Shrubification of the Arctic modifies snow layer heat conduction with opposite effects on the thermal conductivity from compaction and ice-layer development. Across tundra regions in winter, insulation of the underlying soil by snow cover is a key factor driving winter carbon losses from northern permafrost (Natali et al., 2019). The impact of snow-cover stratigraphic properties (and how these have changed or may change in the future) on soil insulation and hence carbon flux is poorly understood.

Observational records clearly show that snow cover, permafrost (temperature, active layer thickness), and disturbance regimes (thermokarst, wildfire) are changing, with concurrent changes in hydrology including surface water and groundwater (Meredith et al., 2019). A process-based understanding of the net effect of these changes on hydrological connectivity and river discharge remains elusive, and requires further integrated research between the snow, permafrost, and hydrological communities.

Finally, as recently assessed by Meredith et al. (2019), changes in the Arctic terrestrial cryosphere (including snow) impact ecosystems, food and water security, and the built environment, thereby affecting the livelihood, health and cultural identity of Arctic residents. These risks will be exacerbated by the future changes (with associated impacts) projected for snow across the Arctic by climate models (see Chapter 3).

2.6 River ice

2.6.1 New insights

Key climate signals:

- Arctic river ice is freezing up later and breaking up earlier.
- A decrease in ice thickness is observed for most northern rivers leading to increased base flow and a reduction in the risk of ice-jam floods.
- Trends in river ice for the Siberian and North American Arctic rivers are similar.

River ice is critical for northern hydrology and climate. For example, the magnitude and timing of hydrological extremes (low flows and floods) are mostly controlled by the dynamics of river ice freeze-up and break-up dates (Beltaos and Prowse, 2009; Yang et al., 2021). Analyses of historical data (Yang et al., 2002, 2021; Shiklomanov and Lammers, 2014) and model studies (Park et al., 2016) clearly show widespread decreases in river-ice thickness and duration due to climate warming across the northern regions. The regulation of reservoirs on large Siberian rivers and corresponding increase in winter runoff and stream velocity could also affect changes in river-ice thickness and timing (Shiklomanov et al., 2021) and water temperature (Liu et al., no date). Changes in ice-jam flooding may have major benefits for communities and infrastructure along the river margins, but could also alter the ecology of deltaic riparian and coastal marine ecosystems (Rokaya et al., 2018). Reductions in river-ice thickness and duration influence transportation opportunities in remote regions.

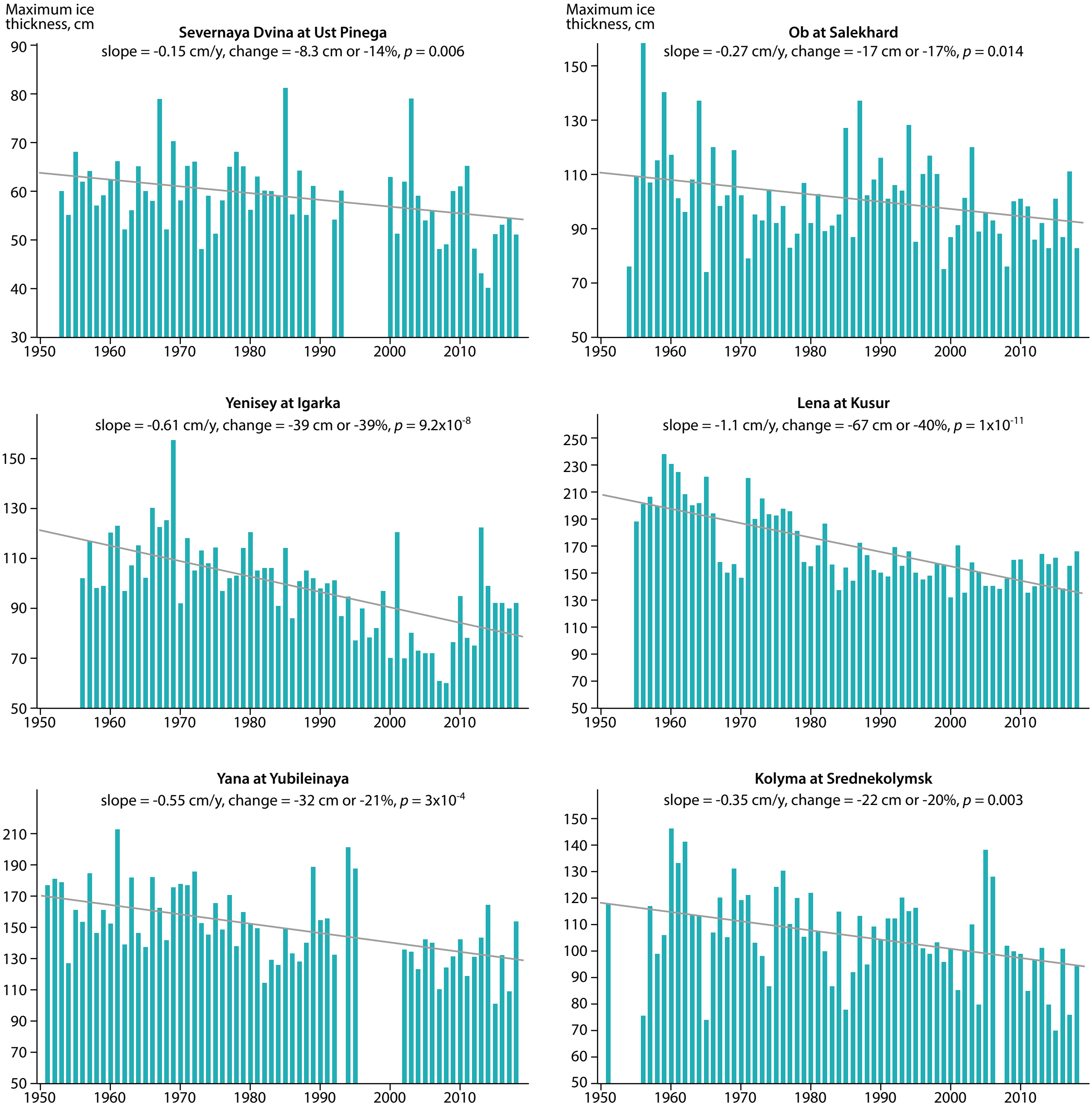


Figure 2.11 Maximum winter ice thickness for six major Arctic Russian rivers for the period 1955 to 2018. Multiple trend metrics are presented: the annual linear regression-derived slope, the change equal to the slope multiplied by the number of years, the percentage equal to the change divided by the number of years, expressed as a percentage and the p-statistic which describes the probability that the trend is a false-positive. Linear trend in river-ice thickness is shown as a solid line (updated from Shiklomanov and Lammers, 2014).

Goulding et al. (2009) examined hydrometric controls of river-ice break-up on the Mackenzie River Delta, at the Arctic Red River Hydrometric Station, for the period 1974 to 2006, and found generally lower ice thickness from the 1990s onward. Lacroix et al. (2005) found a general trend towards earlier break-up dates across Canada, especially between 1961 and 1990. Lesack et al. (2014) related the earlier break-up on the Mackenzie River to changes in the timing of water-level maxima in the central delta and break-up temperatures, as rising winter temperatures weakly correlated to trends in break-up dates and water-level maxima. In addition to trends in the associated break-up temperature, water-level peaks and break-up date, Lesack et al. (2014) observed substantial decreases in river-ice snow cover during 1986 to 2012 relative to 1957 to 1985. Freeze-up patterns were more spatially complex. Moderate to strong correlations exist between river-ice break-up dates and the spring 0°C isotherm for 62–100% of northern sites. This relationship is less strong for autumn, when only 20–75% of freeze-up dates correlate (Beltaos and Prowse, 2009).

Changes in river-ice thickness and timing have been observed over the past few decades on large Russian rivers flowing into the Arctic Ocean. Shiklomanov and Lammers (2014) examined the responses of river-ice regimes in river gauges of six major Russian Arctic rivers (Severnaya Dvina, Ob, Yenisey, Lena, Yana, Kolyma) to a warming climate. They reported a statistically significant decreasing trend from the 1950s to 2018 in maximum ice thickness for all six rivers (Figure 2.11). The largest decrease in ice thickness was observed for the Lena River at Kusur; a decrease of 67 cm

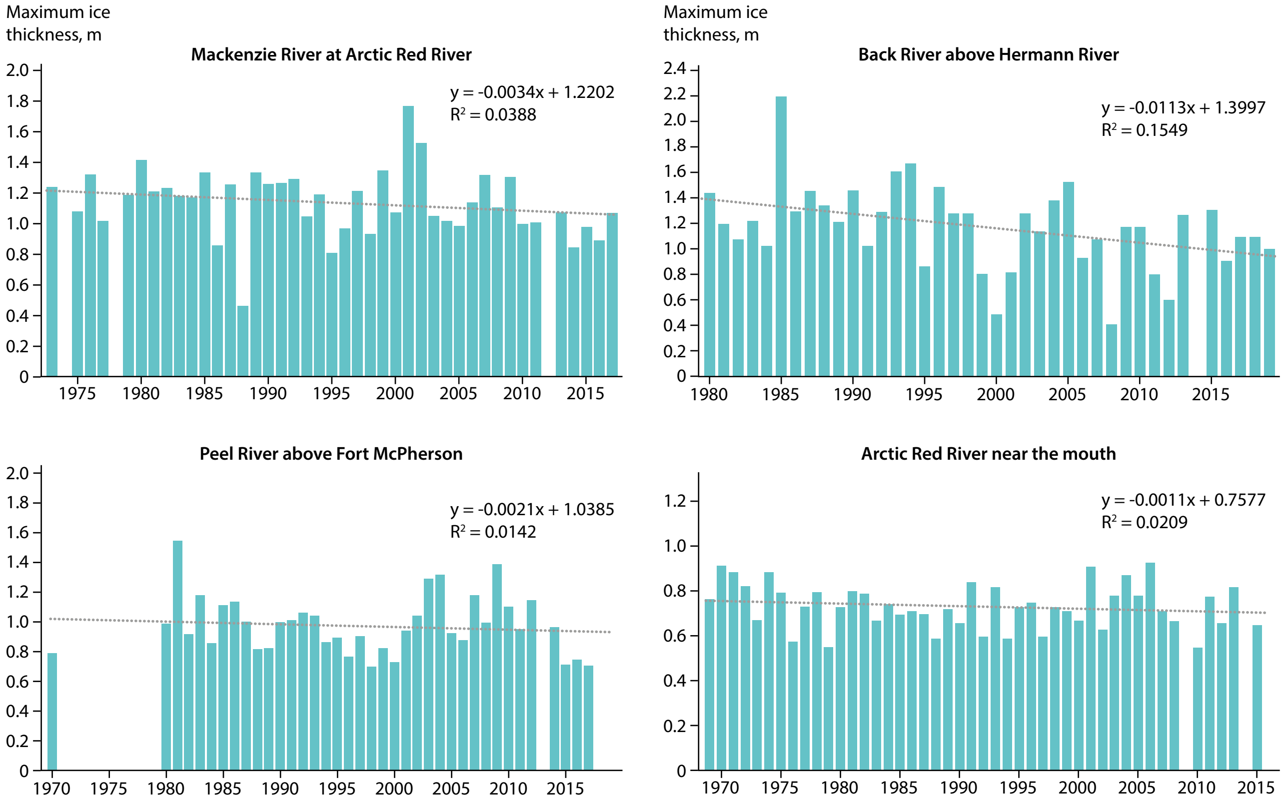


Figure 2.12 Maximum river-ice thickness and trend at four sites in northern Canada. The trend metric is the linear regression temporal slope multiplied by the timespan in years.

between 1955 and 2018, representing a 40% reduction. The other five rivers also demonstrated a significant decrease in ice thickness over the same period, ranging from 8 cm or 14% for Severnaya Dvina at Ust Pinega to 39 cm or 39% for Yenisey River at Igarka (Figure 2.11). Yang et al. (2002) found a negative relation between stream flow and ice thickness for the Lena river at the Kusur station during November to April. This relationship suggests that winter climate warming produces more runoff and less river ice. The greatest decreases in maximum river ice were observed in the Lena and Yenisey rivers where winter flows have significantly increased due to reservoir regulation, with potential effects on river-ice regime. The timing of ice events has also significantly changed for the six major Russian Arctic rivers (Table 2.1).

For each of the six rivers, the latest dates of ice formation and the earliest dates of ice break-up have been observed since 1990. The data show a pattern of decreasing ice season duration from about 230–260 days in east Siberia (Lena, Yana, Kolyma) to approximately 170–190 days in the European north (Severnaya Dvina). From 1955 to 2018, there was an appreciable decrease in the length of the river-ice season, from 7 days for Yenisey and Yana to 18 days for Ob (Table 2.1), resulting from later ice formation and earlier ice disappearance (Shiklomanov and Lammers, 2014). All rivers show a trend towards later ice formation and earlier ice disappearance in the last 15 to 20 years. This corresponds to the period of greatest warming in the Arctic.

Table 2.1 Changes in river-ice phenology for the six major Arctic Russian rivers over the period 1955 to 2018 based on linear trends. Significant trends ($p<0.05$) are shown in bold font.

River	Change in start of ice events, days	Change in end of ice events, days	Change in duration of ice events, days
Severnaya Dvina	+5.3	**-7.0**	**-12.4**
Ob	**+13.0**	**-4.9**	**-18.0**
Yenisey	+2.6	**-5.5**	**-7.4**
Lena	**+4.5**	**-4.1**	**-8.6**
Yana	**+6.6**	-1.6	**-7.5**
Kolyma	**+9.6**	-1.7	**-11.1**

Table 2.2 River-ice break-up dates and (advancing) trend at ten sites along the Yukon River, 1980–2020.

Sites	Early season	Mid-season	Late season	Trend, days
Dawson	22 April	03 May	15 May	7
Eagle	24 April	03 May	17 May	8
Circle	29 April	07 May	24 May	8
Fort Yukon	30 April	10 May	23 May	10
Tanana	29 April	07 May	23 May	8
Ruby	02 May	08 May	25 May	8
Galena	02 May	10 May	25 May	8
Kaltag	01 May	11 May	29 May	10
Holy Cross	26 April	13 May	28 May	9
Emmonak	03 May	19 May	03 June	13

For northern Canada, long-term river-ice thickness data between 1969/1970 and 2018/2019 show variation and change in ice conditions over time (Figure 2.12). There is generally a weak trend of thinning ice cover in the winter season, about 10–15 cm for the Mackenzie, Arctic Red, and Peel rivers, and 40 cm for the Back River along the Arctic coast. Observations by the U.S. National Weather Service in Alaska (Anon, no date a) also demonstrate changes in river-ice regimes, including the timing/date of ice break-up advancing across the Yukon watershed between 1980 and 2020 by about 7 to 13 days, particularly in the downstream regions (Table 2.2).

2.6.2 Knowledge gaps and recommendations

Regular in-situ observations are valuable to monitor the ongoing changes in river-ice features across the North. The Russian networks, mostly manual, have 10-day observations of river-ice thickness since the 1950s. The Russian data are not freely accessible to the scientific community, excluding a long-term dataset covering the period to the early 1990s (Vuglinsky, 2000). Thus, it is recommended to create a contemporary dataset of in-situ river-ice data based on these observations to better understand responses of river ice to climate change and to provide ground-truth information for validation of remote sensing products. Despite the importance of river-ice data for Arctic hydrology/ecosystem studies and northern communities, there are few comprehensive observational records of river ice in North America because most remote gauges are automated and unable to provide such information. Environment and Climate Change Canada (ECCC) has made great efforts during the past 20 years to compile, archive and extract river-ice-related information from available hydrometric records and create the Canadian River Ice Database (CRID) (Yang et al., 2002; Rham et al., no date). This holds almost 73,000 recorded values from a subset of 196 stations throughout Canada, many located in the Arctic. It is recommended to develop remote sensing approaches (Cooley and Pavelsky, 2016) and new instrumentation to improve observations of river-ice conditions across the northern regions. Currently, lack of long-term and consistent records limits understanding of river-ice changes.

River ice is an important component of water storage. Yet, it seems impossible to use local observations to determine the ice volume over large northern basins. Fortunately, recent developments in modeling and remote sensing provide opportunities to quantify river-ice phenology and estimate river-ice volume. There is, however, a need to enhance remote sensing techniques and data to study river-ice processes in the northern regions and to improve hydrological models for better simulation of water cycle elements, including water temperature and ice dynamics. More effort is also required on river ice and lake ice data and model integrations, for example, to combine the ECCC river-ice dataset (Yang et al., 2002; Rham et al., no date) with the coupled hydrological and biogeochemical model CHANGE (Park et al., 2016) over northern regions. The modeling efforts will allow further testing of model physics and validation of river-ice simulations over large Arctic watersheds.

2.7 River discharge

2.7.1 New insights

Key climate signals:

- Arctic river discharge to the Arctic Ocean increased by 8% (187 km^3/y) between 1971 and 2019, about an average of 2400 km^3/y.

Arctic rivers are central to the Arctic freshwater circulation, contributing a significant amount of freshwater and energy from land to the ocean. River discharge is the main contributor of freshwater input to the Arctic Ocean (Haine et al., 2015), as the Arctic Ocean basin (1% of global ocean volume) receives more than 10% of global river flows (Aagaard and Carmack, 1989; McClelland et al., 2012).

Various estimates of freshwater discharge into the Arctic Ocean, using different methods and for different drainage areas, has shown good consistency in long-term mean discharge with concurrent trends of overall increasing flows (McClelland et al., 2006; Dyurgerov et al., 2010). Earlier estimates showed an overall increasing discharge from the large Eurasian rivers (Peterson et al., 2002; Shiklomanov and Lammers, 2014), but decreasing discharge from North American rivers (Déry and Wood, 2005). More recent estimates benefiting from longer records show that the North American rivers are now following the Eurasian trend (Déry et al., 2009; Ge et al., 2013; Rood et al., 2017; Durocher et al., 2019; Shiklomanov et al., 2021).

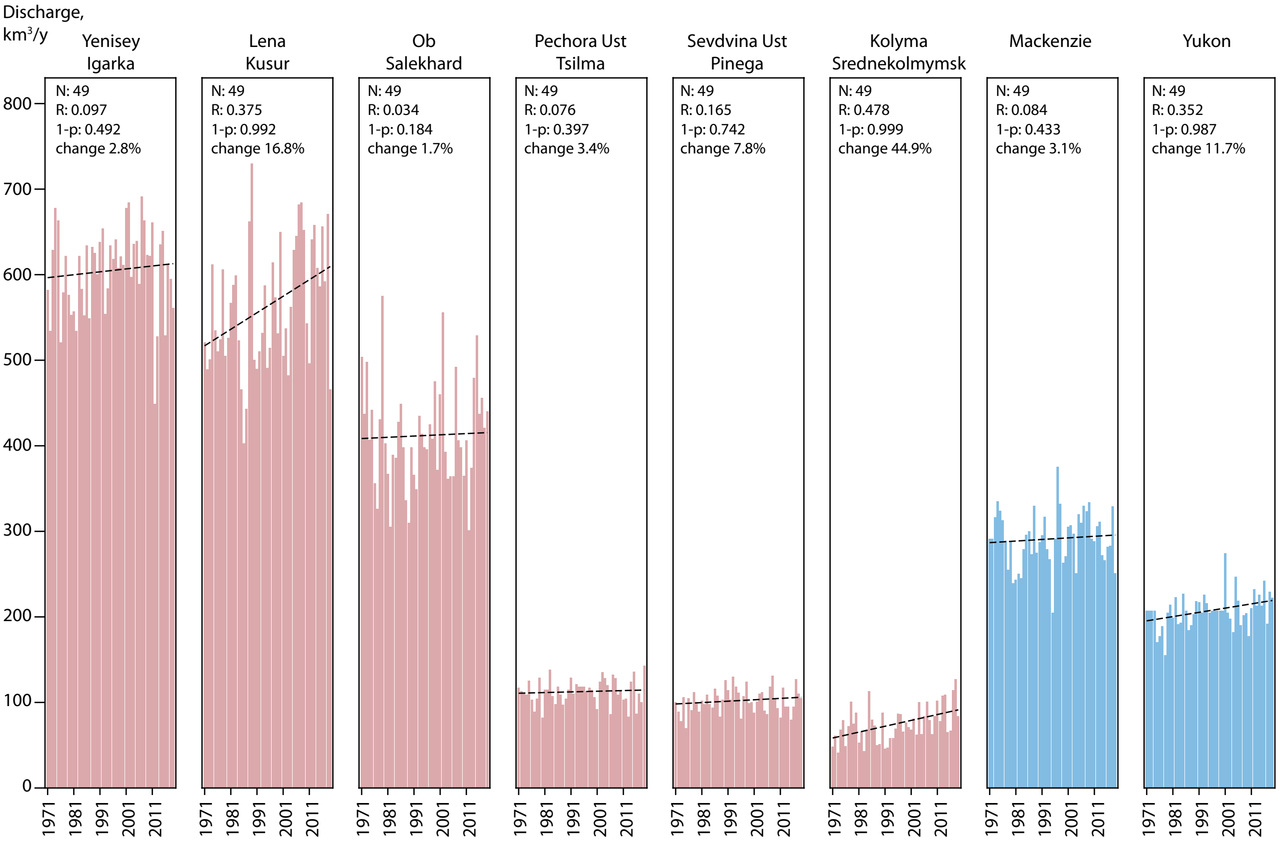
Mean annual discharge and trends are assessed for eight major rivers (Yukon, Mackenzie, Ob, Yenisey, Lena, Kolyma, Pechora, Severnaya Dvina) that together cover approximately 60% of the pan-Arctic drainage basin and produce around 60% of the Arctic Ocean river influx (Figure 2.13).

River discharge for the eight major Arctic rivers for the 49-year period 1971 through 2019 (Figure 2.13) shows an overall increase of 7.8% (+186.7 km^3/y), about an average of 2394 km^3/y. The mean annual discharge data were extracted from the Global Runoff Data Centre (GRDC; Anon, no date b) and the Arctic Great Rivers Observatory (ArcticGRO; Shiklomanov et al., no date). Minor mismatches are evident between the GRDC and ArcticGRO datasets, with the exception of ~15% average higher GRDC discharge for Pechora (Oksino, GRDC no. 6970700) for 2007 to 2014, Severnaya Dvina (Ust Pinega, GRDC no. 6970250) in 2008 and 2014, and Yenisey (Igarka, GRDC no. 2909150) from 1999 to 2006. Overlapping GRDC and ArcticGRO data are averaged by year to minimize the mismatch.

2.7.2 Knowledge gaps and recommendations

Projections using global climate models suggest that river discharge will continue to increase over much of the Arctic, with increases of up to 25–50% (Bring et al., 2017 and references therein). However, there are uncertainties as to where the greatest discharge trends are projected to occur, and where monitoring therefore needs to be strengthened. Bring et al. (2017) identified particular sites for increased

Figure 2.13 Watersheds of the eight major rivers together covering approximately 60% of the pan-Arctic drainage basin. The red dots on the graphic to the left show the location of the discharge monitoring stations (Holmes et al., 2019) on which the charts below showing the relative magnitude and trends in discharge for 1971–2019 are based. The number of years (N) and trend metrics appear at the top of each chart. Data are from the Global Runoff Data Centre (GRDC) and Arctic Great Rivers Observatory (ArcticGRO) and Shiklomanov (pers. comm., 2021). Data for 2019–2020 for the Mackenzie and Yukon rivers are provisional and come from ArcticGRO. The trend metric is the linear regression temporal slope multiplied by the timespan in years divided by the multi-year average, expressed as a percentage.



monitoring in central and eastern Siberia, Alaska and central Canada, where higher trends are projected. For hydroclimatic analysis, to understand changes in Arctic river discharge, it is necessary to account for human impact on the seasonal discharge regime and temporal changes (Yang et al., 2021). Satellite retrievals of sea surface salinity are valuable to link river discharge with the Arctic freshwater system. Thus, there is much potential in using remote sensing data to increase understanding of variability in the Arctic freshwater system.

2.8 Tundra greenness

2.8.1 New insights

Key climate signals:

- Arctic tundra greenness increased by 10% in the 38-year period 1982–2019. The greenness correlates significantly with melt season air temperature, suggesting continued greening with projected climate warming, despite some regions instead exhibiting 'browning', such as the Canadian Arctic Archipelago, southwestern Alaska, and parts of northwestern Siberia.

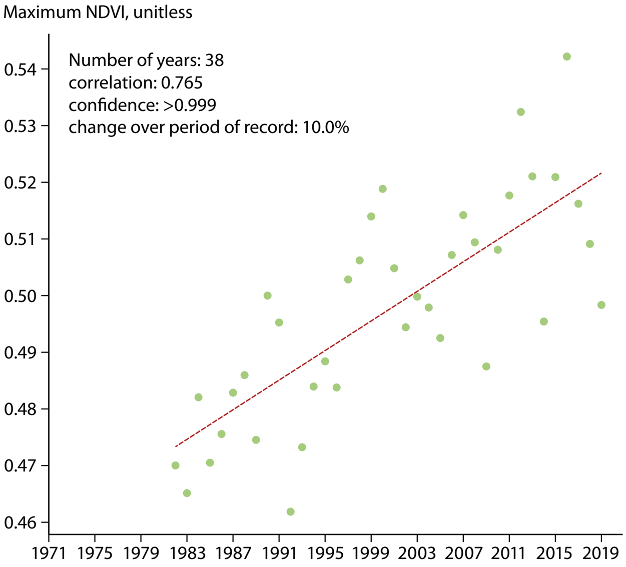


Figure 2.14 Time series of pan-Arctic tundra greenness according to the annual maximum satellite-derived normalized difference vegetation index (NDVI) (after Pinzon and Tucker, 2014). The trend metric is the linear regression temporal slope multiplied by the timespan in years divided by the multi-year average, expressed as a percentage.

Arctic tundra greenness (after Pinzon and Tucker, 2014) is updated here through 2019, producing a 38-year record since 1982. The data cover the pan-Arctic tundra region, with a regional split between North America and Eurasia. Arctic tundra greenness increased by 10% between 1982 and 2019 (Figure 2.14).

Arctic tundra greening has been attributed to summer warming (Berner et al., 2020). Comparing the North American and Eurasian normalized difference vegetation index (NDVI) time series with melt season (June through September) near-surface air temperature from the ERA5 dataset (Copernicus, 2020) shows for $\mathrm{NDVI_{max}}$ a slightly higher correlation (0.687, confidence >0.999) for North America than for Eurasia (correlation = 0.605, confidence >0.999). This difference in correlation could be attributed to sea ice retreating earlier along the Eurasian coast and that Eurasia is warmer and wetter than North America. The average Eurasian NDVI is higher, so it has less to increase to reach a maximum value of 1. The North America NDVI is lower on average and the sea ice is still retreating. So the NDVI has a stronger increase. The significant correlation suggests the likelihood for continued Arctic tundra greening with projected climate warming, despite some regions exhibiting an opposite 'browning', such as across the Canadian Arctic Archipelago, southwestern Alaska, and parts of northwestern Siberia.

For non-forested Arctic landscapes, the greenness trend is strongest for the Alaskan North Slope, while a browning trend is evident for the Canadian Arctic Archipelago and the Yukon-Kuskokwim Delta in southwest Alaska (Figure 2.15). High spatial variability in tundra greenness is recognized as arising from complex interactions among the vegetation, atmosphere, sea ice, seasonal snow cover, ground (soils, permafrost, topography), disturbance processes, and herbivores of the Arctic system (e.g., Frost et al., 2019; Myers-Smith et al., 2020).

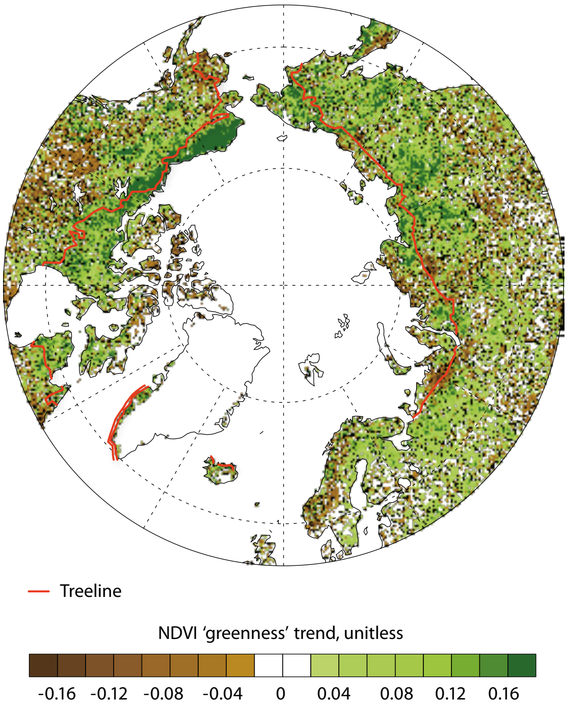


Figure 2.15 Trend in Arctic and northern land surface vegetation greenness for the period 1982–2019 (after Bhatt pers. comm.). The trend metric is the linear regression temporal slope multiplied by the timespan in years.

2.8.2 Knowledge gaps and recommendations

The research community needs to develop a framework to ensure a continuous record of measurements for Arctic remotely sensed indicator series such as NDVI. This framework should describe a process to combine the past record with data from new sensors to provide a long-term consistent time series that ensures continuous monitoring of the Arctic. The Advanced Very-High-Resolution Radiometer (AVHRR) NDVI time series has reached a critical point as some in the community are moving to using the MODIS sensor only, which is available from 2000, and disregarding the AVHRR record that extends back to 1982. The MODIS record is soon being extended, so record homogeneity will be an ongoing issue. Inaction risks a serious lapse in critical environmental information. This highlights the need to combine datasets from past sensors with those of the present and to prepare for future sensors, focused on the goal of maintaining as consistent a record of vegetation productivity as possible.

2.9 Wildfire

2.9.1 New insights

Key climate signals:

- Increased boreal forest and tundra wildfire is promoted by Arctic climate warming via increased lightning ignition, higher air temperatures, reduced snow cover, increased surface dryness and a longer fire season.
- Arctic wildfires are an increasing source of carbon emissions to the atmosphere.

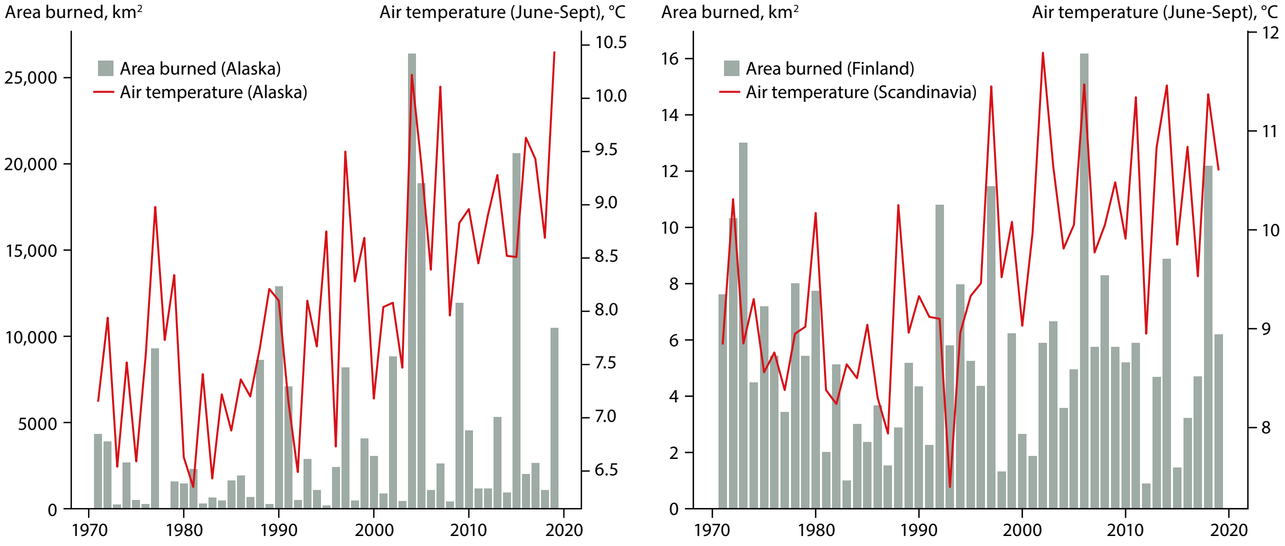


Figure 2.16 Some peak fire years correspond with extremely high melt-season (Jun–Sept) near-surface air temperatures, after NCEP NCAR Reanalysis (Kalnay et al., 1996). Finland burned area data are from Vanha-Majamaa (pers. comm.).

Fire season length is increasing over large areas of North America, especially in June through August (Masrur et al., 2018) and in the eastern Canada Hudson Bay lowlands, consistent with an earlier fire-season start and later fire-season end (Jain et al., 2017). Tundra wildfire occurrence has a clustered (Masrur et al., 2018) and temporally sporadic, non-linear character, making trend definition a challenge. During the 2006–2017 decade, Kirchmeier-Young et al. (2017) found that the combined effect of anthropogenic and natural forcing is estimated to have made western Canadian extreme fire risk events 1.5 to 6 times more likely than for climate with natural forcing alone. Earlier snowmelt, exposing the land surface to elevated evapotranspiration, results in drier ground conditions that in turn promote the spread of boreal fires (Kim et al., 2020). For Alaska and Finland, most of the peak burned-area years correspond with extremely high melt-season near-surface air temperatures (Figure 2.16).

Fire-induced permafrost degradation is well-documented in boreal forests (Brown et al., 2016; Potter and Hugny, 2020; Yoshikawa et al., 2002). Arctic tundra fires promote permafrost thaw subsidence (Jones et al., 2015). In the Sakha Republic of Yakutia, Siberia, a region extending from the Arctic Ocean coast to several hundred kilometers south of the Arctic Circle, one of the most fire-prone regions of Russia (World Meteorological Organization, 2020), data from the period 1996–2018 exhibit statistically significant increases in fire activity, driven by warming and anthropogenic alteration (Kirillina et al., 2020).

Wildfires in Siberia in summer 2019 were such that the government declared a state of emergency (Anon, 2019). "A less snowy winter and insufficient soil moisture are factors that create the conditions for the transition of landscape fires to settlements", an expert told The Siberian Times. He also said that unusually hot weather was combining with strong winds to fan the flames. Similarly in 2020, air temperatures across northern Siberia set records in June, contributing to some of the worst wildfires in the region (Farge and Soldatkin, 2020). According to Farge and Soldatkin, (2020), the World Meteorological Organization is seeking to confirm whether a record Russian reading of more than 100°F (38°C) in Siberia is also the highest temperature ever recorded north of the Arctic Circle. Their report also quotes the Russian forestry agency as saying that, "as of July 6, there were 246 forest fires covering 140,073 hectares and an emergency situation has been declared in seven regions". Also, that the EU is reported to have said that "Wildfire carbon dioxide emissions from the region last month were an estimated 59 megatonnes, compared with 53 megatonnes last year". Farge and Soldatkin (2020) also state that "In total, last year [2019], wildfires in the Arctic Circle produced more than 170 megatonnes of emissions". Tundra fire is a considerable source of carbon emissions, not only from the vegetation layer but from ancient soil carbon that can be released rapidly by wildfire (Mack et al., 2011).

2.9.2 Knowledge gaps and recommendations

International coordination of burned area datasets appears lacking, although pan-Arctic burned area assessment could be achieved using the satellite remote sensing datasets that provide coverage from 1981 to present.

While laboratory observations indicate a temperature-driven soil carbon emission (Natali et al., 2019), further observation and modeling integration are needed to resolve whether permafrost carbon is a significant source of warming-driven carbon release to the atmosphere.

2.10 Sea ice

2.10.1 New insights

Key climate signals:

- Arctic sea-ice extent declined by 43% in the 41-year period of record between 1979 and 2019.
- Over the past 30 years, snow depth on sea ice declined by over a third in the western Arctic, due to delayed autumn freeze-up.

2.10.1.1 Sea-ice extent, thickness and export

Arctic sea-ice extent declined by 43% in the 41-year period of record between 1979 and 2019. The extent, area, age, and thickness of Arctic sea ice continue to remain at levels well below those of earlier decades (1970s to 1990s) albeit with substantial regional and interannual variability (Meredith et al., 2019; Perovich et al., 2020). Sea-ice extent during the seasonal minimum in September has been particularly low since 2007, a record low at that time. Sea-ice extent in 2012 set a new record low and several years have since been at or near 2007 levels. Overall, the trend in September sea-ice extent from 2007 to 2019 is flat, but these 13 years represent the 13 lowest Septembers in the 41-year sea-ice record and the 2007–2019 average is over 2 million km^2 (30%) below the average of the earlier years (1979–2006). Overall, the September trend is -12.9% (±2.2%) per decade. Trends are smaller in other months, particularly during winter, but all months show trends of decreasing extent with statistical significance above 95%. These estimates are based on passive microwave sensor data published by the National Snow and Ice Data Center (NSIDC) Sea Ice Index (Fetterer et al., 2017). Several other sea-ice extent products exist from groups such as the EUMETSAT Satellite Application Facility on Ocean and Sea Ice (OSI SAF). They have constant biases between estimates from the various products, up to 1 million km^2, due to different sensitivities to the ice edge, as well as quality-control factors (Comiso et al., 2017; Meier and Scott Stewart, 2019), meaning that the trends largely agree. Uncertainties in extent from a single product are on the order of 50,000 km^2 or 0.5–1.0%, resulting in even smaller long-term trend uncertainties (Meier and Scott Stewart, 2019).

Regionally, sea-ice extent and area are declining across the Arctic in all months, except for the Bering Sea in winter. However, during the 2017–2018 and 2018–2019 winters, the Bering Sea had record or near-record low winter sea-ice extents with much of the sea nearly devoid of ice for much of the year (Thoman et al., 2020).

With lower sea-ice extents, the summer open-water season has increased, with earlier melt onset and retreat of ice and later freeze-up and advance (Stroeve et al., 2016; Peng et al., 2018; Bliss et al., 2019). The open-water period has increased by up to 10 days per decade in some regions.

The sea-ice cover also continues a trend towards younger and thinner ice. In winter, old ice (>4 years old), which represented the thickest thermodynamically grown ice, constituted about one third of the Arctic Ocean region in the mid-1980s, but by 2019 represented only about 1% of the region (Perovich et al., 2020; Tschudi et al., 2020). First-year ice comprised about 35% of the Arctic Ocean ice cover in the mid-1980s, but now ~60% of the region is first-year ice.

Sea-ice thickness data have historically been less comprehensive spatially and temporally, but more complete fields have become available in the past decade with the launch of the European Space Agency (ESA) CryoSat-2 radar altimeter in 2010 and the National Aeronautics and Space Administration (NASA) ICESat-2 laser altimeter in 2018 (Kwok et al., 2019; Petty et al., 2020). Combining these records along with sparser early satellite data (from ICESat) and submarine sonar data shows a thinning in average sea-ice thickness of 50% or more since the 1970s (Kwok, 2018). However, the thinning has stabilized in recent years (since 2012), characterized by high interannual variability (Ricker et al., 2017; Perovich et al., 2019). Data on sea-ice thickness is less complete and uncertainties are higher than for sea-ice extent; however, a substantial trend toward a thinner ice cover is evident.

Spreen et al. (2020) estimated that sea-ice export out of the Arctic Ocean through Fram Strait between 1992 and 2014 declined by an average of 2400 ± 640 km^3, 27 ± 2% per decade. They also estimated that 14% of the total Arctic sea-ice volume is exported each year through Fram Strait, leaving most of the remainder to be ablated, consistent with declining sea-ice thickness (Figure 2.17).

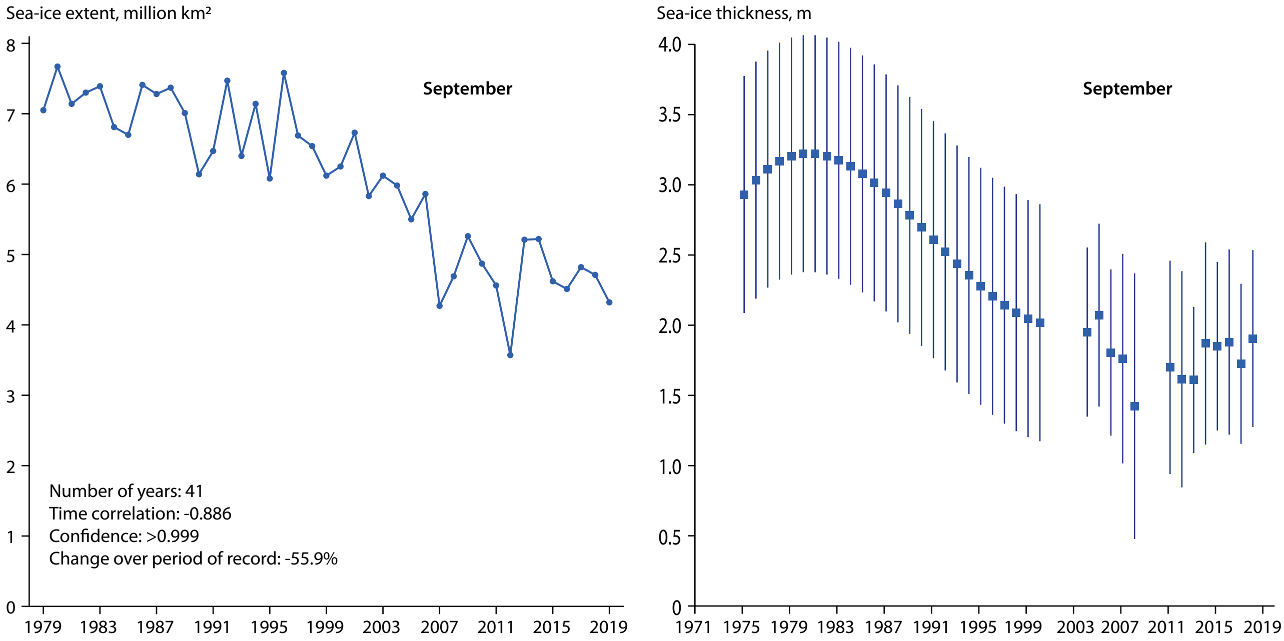


Figure 2.17 September Arctic sea-ice extent and sea-ice thickness from regression analysis of the submarine record for the period before 2001 (Rothrock et al., 1999) and from satellite altimetry for the period after 2003 (Kwok et al., 2019; Petty et al., 2020).

2.10.1.2 Snow on sea ice

The snow cover on Arctic sea ice plays a critical role for the evolution of sea ice (Webster et al., 2018), the lower atmosphere over sea ice (Batrak and Müller, 2019) and, owing especially to its optical properties, the marine ecosystem (e.g., Fernández-Méndez et al., 2018). See also Section 6.2.3.1 in Chapter 6. During autumn and winter, the overlying snow cover insulates the sea ice from the atmosphere, reducing heat transfer and thereby slowing ice growth. In spring, the high albedo of snow reflects incoming solar radiation and serves to delay melt onset. The snow also acts as a sea-ice melt buffer in that it needs to melt away before ice melt can progress. However, snow melt on sea ice can result in the formation of melt ponds and their lower albedo can enhance melt during summer.

Data from different observations show trends for the last half century of a thinning snow cover in the western Arctic (Webster et al., 2014, 2018). In the western Arctic overall, the snow has thinned by 37% (±29%), while in the Beaufort/Chukchi seas, the thinning is by 56% (±33%). This decrease is largely due to a delayed freeze-up where any early snow-season snow falls onto the open ocean and does not accumulate on the sea ice. In the Atlantic sector, thick snow has been observed in some years since the 1970s (Rösel et al., 2018). However, there are still gaps in observations and understanding of the snow cover on Arctic sea ice (Gerland et al., 2019). This knowledge gap also affects satellite retrieval of, for example, sea-ice thickness (Nandan et al., 2017, 2020).

With the thinning of the Arctic sea-ice cover the conditions for snow-ice formation, prevalent in the Antarctic sea-ice zone, may become more favorable especially in the Atlantic sector of the Arctic Ocean (Granskog et al., 2017; Merkouriadi et al., 2020). Therefore, the seasonal Arctic ice pack might become more resembling of its Antarctic counterpart. Recent advances in satellite remote sensing may fill some of the observational gaps on snow depth on sea ice (Kwok et al., 2020; Rostosky et al., 2020). However, satellite altimetry still widely uses a snow-on-sea ice climatology (Warren et al., 1999) which is likely to be outdated in the current Arctic (Rösel et al., 2018; Perovich et al., 2019).

2.10.2 Knowledge gaps and recommendations

Gerland et al. (2019) presented an analysis of sea-ice knowledge gaps. While sea-ice extent and concentration are well-observed by the long-term time series from passive microwave instruments, uncertainties in trends are still an issue because data from several sensors must be stitched together for the long-term record. Intercalibration between simultaneously operating sensors is used to intercalibrate across satellite transitions. But these transition periods were sometimes short (a few weeks to a few months) and not optimal for obtaining the best possible intercalibration. There is also concern over the aging of the current passive microwave sensors, all of which are at least nine years old, well past their nominal mission lifetimes of three to five years. If the older sensors fail before replacements are launched and with overlap for intercalibration, then there will be a gap that will need to be filled with less complete and less consistent data. This will reduce the confidence in sea-ice extent trends going forward.

Sea-ice extent is an imperfect measure of the ice cover because it does not account for variation in concentration within the ice pack. Moreover, sea-ice extent has a gap in satellite coverage near the pole over which no data are collected; this gap has varied in size over the record, so it is not feasible to get consistent sea-ice concentration and area information from the gap regions. For extent, the 'pole hole' can be assumed to be ice-covered. Another factor is that sea-ice concentration retrievals by passive microwave instruments are biased in summer due to surface melt, leading to inconsistencies in sea-ice concentration and area estimates. Extent is less affected by these biases.

Remote sensing of sea-ice thickness has increased considerably over recent years with the launch of CryoSat-2 and ICESat-2. However, coverage is still somewhat sparse, leading to at best monthly composites that include spatial interpolation of gaps and higher uncertainty in transition seasons in regions with relatively thin ice cover. There is also much uncertainty in interpreting the altimeter observations and converting to sea-ice thickness estimates (Nandan et al., 2017, 2020). The radar altimeter from CryoSat-2 is generally assumed to penetrate snow and retrieve a signal from the snow-ice interface. However, depending on the character of the snow, this assumption may not always be valid (King et al., 2018). Both CryoSat-2 and ICESat-2 require knowledge of snow density, salinity and depth on sea ice to accurately convert from the raw elevation estimates to sea-ice thickness. This is more of an issue for the ICESat-2 laser altimeter, which generally reflects off the top of the snow surface. So snow depth must be subtracted to get the sea-ice freeboard. Data on snow are very sparse and generally not available coincidently with the altimeter observations. Observations from NASA's Operation IceBridge have helped characterize the snow cover and its relation to sea-ice freeboard and thickness observations (Farrell et al., 2012; King et al., 2018; Nandan et al., 2020), but extending this to basin-wide ICESat-2 and CryoSat-2 estimates remains a challenge.

Beyond physical properties of the ice cover, there are substantial gaps in terms of the interaction of sea ice with the environment. There are still substantial uncertainties as to how declining sea ice and the transition toward a thinner, seasonal ice cover will affect thermodynamics (e.g., radiative, sensible, and latent fluxes) and dynamics (e.g., transport) in the Arctic. For example, long-range transport of sediments and nutrients is inhibited by increased summer ice loss (Krumpen et al., 2019; DeRepentigny et al., 2020). How the changing sea ice affects biogeochemical cycles in the Arctic is also not well known. The Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC), a year-long field experiment around a ship frozen in the sea ice from October 2019 to October 2020, will yield valuable insights into these processes and help fill some of these critical gaps (e.g., Krumpen et al., 2020).

2.11 Land ice

2.11.1 New insights

Key climate signals:

- The Arctic remains the largest regional source of global sea-level rise.
- The rate of sea-level contribution from the loss of Arctic land ice has been increasing.
- The Antarctic sea-level contribution has had a larger relative increase, but remains lower than that from Greenland and the Arctic as a whole.

The water balance (also referred to as the mass balance) of glaciated areas represents a balance between mass input, mainly from snowfall, and mass loss to the ocean, in the form of meltwater runoff or iceberg calving. Box et al. (2018) computed the annual mass balance for Arctic glaciers and ice caps from the early 1960s, and the Greenland Ice Sheet since 1971, through a combination of ground survey data from the World Glacier Monitoring Service (WGMS, 2020) and satellite gravimetry data beginning in 2002. The 49-year record (1971 to 2019) indicates a pattern of increasing land-ice loss, with the largest sea-level contributions from Greenland, Alaska and Arctic Canada (Figure 2.18).

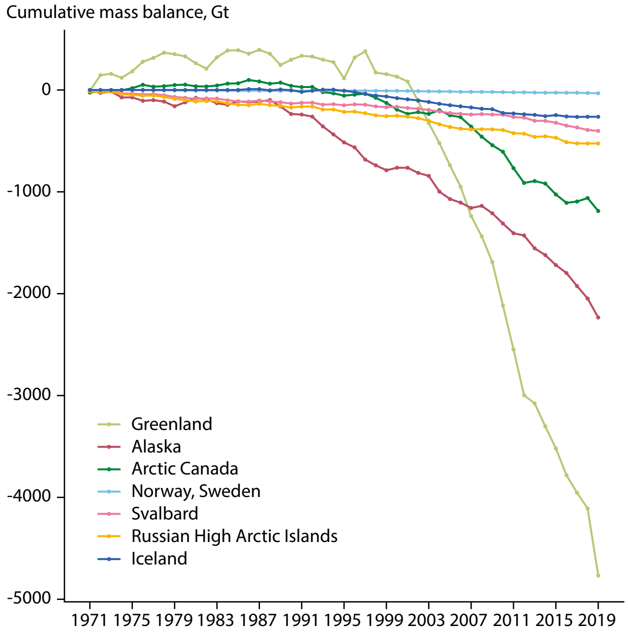


Figure 2.18 Cumulative mass balance of Arctic land ice since 1971.

2.11.1.1 Arctic regional and global comparison

The rate of sea-level contribution from the loss of Arctic land ice has increased for all regions in each successive decade since the 1970s, indicating an acceleration of sea-level contribution (Figure 2.19). For Greenland, 2012 and 2019 brought record mass loss, increasing annual eustatic sea-level rise by 1.5 mm each year (Tedesco et al., 2013; Sasgen et al., 2020). Similarly, for Alaska and Arctic Canada, glacier melt rates are observed to have accelerated since 2005, driven by surface melting (Sharp et al., 2011; O'Neel et al., 2019). Studies have also documented accelerated glacier mass loss for the Russian Arctic (2010–2017) (Sommer et al., no date) and across Svalbard (Morris et al., 2020; Noël et al., 2020; Schuler et al., 2020).

Variation in the sea-level contribution of Arctic land ice is caused by year-to-year variations in persistent weather patterns associated with the Arctic Oscillation (AO), which is closely related to the North Atlantic Oscillation (NAO). NAO extremes lead to high and low extremes in surface melting and the rate of mass loss from Greenland (Box et al., 2012; Hanna et al., 2015; McLeod and Mote, 2016; Bevis et al., 2019; Tedesco and Fettweis, 2020). Regression of annual Greenland mass balance here with June through August average NAO data (NOAA, 2020) yields a correlation coefficient of 0.73 confirming the NAO influence. Nonetheless, the acceleration exceeds the NAO effect.

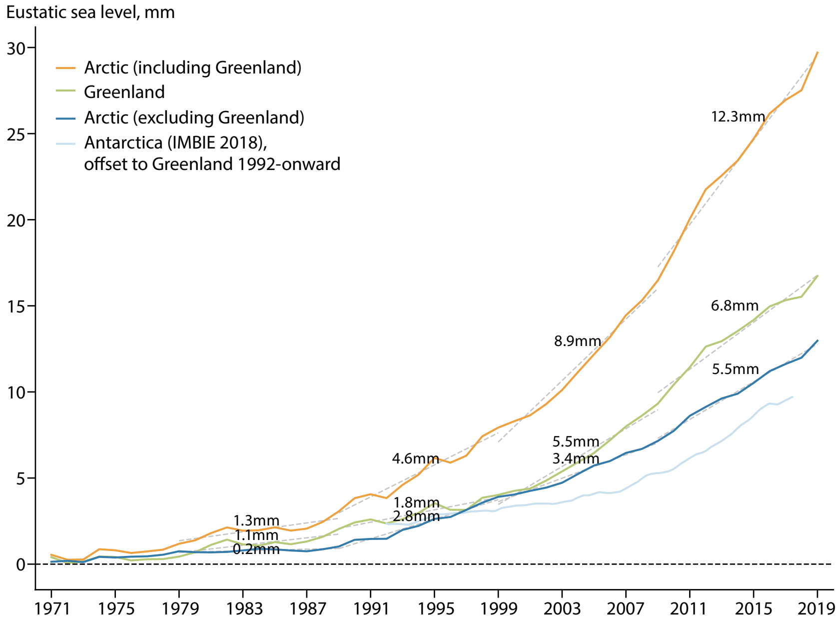


Figure 2.19 Arctic and Antarctic land-ice contributions to sea level. Dashed regression fit lines are included for the past four decades together with a number showing the respective decadal rate of sea-level contribution. Antarctic data from Shepherd et al. (2019) are illustrated to contextualize the relatively large Arctic contributions to sea-level rise. IMBIE: Ice sheet Mass Balance Inter-comparison Exercise.

2.11.2 Knowledge gaps and recommendations

There is growing activity from a combination of ground and remotely sensed observations, and modeling, to address the relatively weak constraint on snowfall accumulation that drives glacier mass input and buffers extreme surface melting.

Observations are increasingly being brought into modeling systems for increased constraint and thus realism. Thus, it serves this effort to facilitate observations being more readily obtained through, for example, open data portals.

References

Personal communications

Bhatt, U.S., Department of Atmospheric Sciences, Geophysical Institute, University of Alaska Fairbanks.

Shiklomanov, A., University of New Hampshire, Earth Systems Research Center, Durham, NH, USA.

Vanha-Majamaa, I., Natural Resource Institute Finland (LUKE), Helsinki, Finland.

Main references

Aagaard, K. and E,C. Carmack, 1989. The role of sea ice and other fresh water in the Arctic circulation. Journal of Geophysical Research, 94:14485-14498.

Abramov, A., S. Davydov, A. Ivashchenko, D. Karelin, A. Kholodov, G. Kraev, A. Lupachev, A. Maslakov, V. Ostroumov, E. Rivkina, D. Shmelev, V. Sorokovikov, O. Tregubov, A. Veremeeva, D. Zamolodchikov and S. Zimov, 2019. Two decades of active layer thickness monitoring in northeastern Asia. Polar Geography, DOI: 10.1080/1088937X.2019.1648581.

AMAP, 2017. Snow, Water, Ice and Permafrost in the Arctic (SWIPA), 2017. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway.

Anon, no date a. US National Weather Service river ice breakup status. Online: www.weather.gov/aprfc/breakup

Anon, no date b. Global Runoff Database (GRDC). www.bafg.de/GRDC/EN/Home/homepage_node.html

Anon, 2019. Russia declares emergency over huge wildfires in Siberia, Deutsche Welle, 30th July. www.dw.com/en/russia-declares-emergency-over-huge-wildfires-in-siberia/a-49817454

Barrett, A.P., J.C. Stroeve and M.C. Serreze, 2020. Arctic Ocean precipitation from atmospheric reanalyses and comparisons with North Pole drifting station records. Journal of Geophysical Research: Oceans, 125: doi:10.1029/2019jc015415

Batrak, Y. and M. Müller, 2019. On the warm bias in atmospheric reanalyses induced by the missing snow over Arctic sea-ice. Nature Communications, 10:4170. doi:10.1038/s41467-019-11975-3

Beltaos, S. and T. Prowse, 2009. River-ice hydrology in a shrinking cryosphere. Hydrological Processes, 23:122-144.

Berner, L.T., R. Massey, P. Jantz, B.C. Forbes, M. Macias-Fauria, I. Myers-Smith, T. Kumpula, G. Gauthier, L. Andreu-Hayles, B.V. Gaglioti, P. Burns, P. Zetterberg, R. D'Arrigo and S.J. Goetz, 2020. Summer warming explains widespread but not uniform greening in the Arctic tundra biome. Nature Communications, 11:4621. doi:10.1038/s41467-020-18479-5

Bevis, M., C. Harig, S.A. Khan, A. Brown, F.J. Simons, M. Willis, X. Fettweis, M.R. van den Broeke, F.B. Madsen, E. Kendrick, D.J. Caccamise, T. van Dam, P. Knudsen and T. Nylen, 2019. Accelerating changes in ice mass within Greenland, and the ice sheet's sensitivity to atmospheric forcing. Proceedings of the National Academy of Sciences, 116:1934-1939.

Bintanja, R., 2018. The impact of Arctic warming on increased rainfall. Scientific Reports, 8:16001. doi: 0.1038/s41598-018-34450-3

Bintanja, R. and O. Andry, 2017. Towards a rain-dominated Arctic. Nature Climate Change, 7:263-267.

Bintanja, R. and F.M. Selten, 2014. Future increases in Arctic precipitation linked to local evaporation and sea-ice retreat. Nature, 509:479-482.

Biskaborn, B.K., S.L. Smith, J. Noetzli, H. Matthes, G. Vieira, D.A. Streletskiy, P. Schoeneich, V.E. Romanovsky, A.G. Lewkowicz, A. Abramov, M. Allard, J. Boike, W.L. Cable, H.H. Christiansen, R. Delaloye, B. Diekmann, D. Drozdov, B. Etzelmüller, G. Grosse, M. Guglielmin, T. Ingeman-Nielsen, K. Isaksen, M. Ishikawa, M. Johansson, H. Johannsson, A. Joo, D. Kaverin, A. Kholodov, P. Konstantinov, T. Kröger, C. Lambiel, J.-P. Lanckman, D. Luo, G. Malkova, I. Meiklejohn, N. Moskalenko, M. Oliva, M. Phillips, M. Ramos, A.B.K. Sannel, D. Sergeev, C. Seybold, P. Skryabin, A. Vasiliev, Q. Wu, K. Yoshikawa, M. Zheleznyak and H. Lantuit, 2019. Permafrost is warming at a global scale. Nature Communications, 10:264. doi:10.1038/s41467-018-08240-4

Bliss, A.C., M. Steele, G. Peng, W.N. Meier and S. Dickinson, 2019. Regional variability of Arctic sea ice seasonal change climate indicators from a passive microwave climate data record. Environmental Research Letters, 14:045003. doi:10.1088/1748-9326/aafb84

Boisvert, L.N. and J.C. Stroeve, 2015. The Arctic is becoming warmer and wetter as revealed by the Atmospheric Infrared Sounder. Geophysical Research Letters, 42:4439-4446.

Boisvert, L.N., M.A. Webster, A.A. Petty, T. Markus, D.H. Bromwich and R.I. Cullather, 2018. Intercomparison of precipitation estimates over the Arctic Ocean and its peripheral seas from reanalyses. Journal of Climate, 31:8441-8462.

Borge, A.F., S. Westermann, I. Solheim and B. Etzelmüller, 2017. Strong degradation of palsas and peat plateaus in northern Norway during the last 60 years. The Cryosphere, 11:1-16.

Box, J.E., X. Fettweis, J.C. Stroeve, M. Tedesco, D.K. Hall and K. Steffen, 2012. Greenland ice sheet albedo feedback: thermodynamics and atmospheric drivers. The Cryosphere, 6:821-839.

Box, J.E., W.T. Colgan, B. Wouters, D.O. Burgess, S. O'Neel, L.I. Thomson and S.H. Mernild, 2018. Global sea-level contribution from Arctic land ice: 1971–2017. Environmental Research Letters, 13:125012.

Box, J.E., W.T. Colgan, T.R. Christensen, N.M. Schmidt, M. Lund, F.-J.W. Parmentier, R. Brown, U. Bhatt, E.S. Euskirchen, V.E. Romanovsky, J.E. Walsh, J.E. Overland, M. Wang, R.W. Corell, W.N. Meier, B. Wouters, S. Mernild, J. Mård, J. Pawlak and M.S. Olsen, 2019. Key indicators of Arctic climate change: 1971–2017. Environmental Research Letters, 14:045010.

Bring, A., A. Shiklomanov and R.B. Lammers, 2017. Pan-Arctic river discharge: Prioritizing monitoring of future climate change hot spots. Earth's Future, 5:72-92.

Brohan, P., J. Kennedy, I. Harris and S.F.B. Tett and P.D. Jones, 2006. Uncertainty estimates in regional and global observed temperature changes: A new data set from 1850. Journal of Geophysical Research, 111:D12106.

Brown, R.D. and C. Derksen, 2013. Is Eurasian October snow cover extent increasing?, Environmental Research Letters, 8(2), 024006, doi:10.1088/1748-9326/8/2/024006, 2013.

Brown, R. D., B. Brasnett and D. Robinson, 2003. Gridded North American monthly snow depth and snow water equivalent for GCM evaluation. Atmosphere-Ocean, 41:1-14.

Brown, D., M. Jorgenson, K. Kielland, D. Verbyla, A. Prakash and J. Koch, 2016. Landscape effects of wildfire on permafrost distribution in interior Alaska derived from remote sensing. Remote Sensing, 8:654, doi:10.3390/rs8080654

Brown, R., D. Vikhamar Schuler, O. Bulygina, C. Derksen, K. Luojus, L. Mudryk, L. Wang and D. Yang, 2017. Arctic terrestrial snow cover. In: Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2017. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway.

Brun, E., V. Vionnet, A. Boone, B. Decharme, Y. Peings, R. Valette, F. Karbou and S. Morin, 2013. Simulation of northern Eurasian local snow depth, mass, and density using a detailed snowpack model and meteorological reanalyses. Journal of Hydrometeorology, 14:203-219.

Callaghan, T.V., M. Johansson, R.D. Brown, P.Y. Groisman, N. Labba, V. Radionov, R.G. Barry, O.N. Bulygina, R.L.H. Essery, D.M. Frolov, V.N. Golubev, T.C. Grenfell, M.N. Petrushina, V.N. Razuvaev, D.A. Robinson, P. Romanov, D. Shindell, A.B. Shmakin, S.A. Sokratov, S. Warren and D. Yang, 2011. The changing face of Arctic snow cover: a synthesis of observed and projected changes. AMBIO, 40:17-31.

Chatterjee, S. and A.S. Hadi, 2006. Regression Analysis by Example. John Wiley & Sons.

Christensen, T.R., M. Lund, K. Skov, J. Abermann, E. López-Blanco, J. Scheller, M. Scheel, M. Jackowicz-Korczynski, K. Langley, M.J. Murphy and M. Mastepanov, 2020. Multiple ecosystem effects of extreme weather events in the Arctic. Ecosystems, 24: doi:10.1007/s10021-020-00507-6.

Christiansen, H.H., B. Etzelmüller, K. Isaksen, H. Juliussen, H. Farbrot, O. Humlum, M. Johansson, T. Ingeman-Nielsen, L. Kristensen, J. Hjort, P. Holmlund, A.B.K. Sannel, C. Sigsgaard, H.J. Åkerman, N. Foged, L.H. Blikra, M.A. Pernosky and R.S. Ødegård, 2010. The thermal state of permafrost in the Nordic area during the International Polar Year 2007-2009. Permafrost and Periglacial Processes, 21:156-181.

Comiso, J.C., W.N. Meier and R. Gersten, 2017. Variability and trends in the Arctic Sea ice cover: Results from different techniques. Journal of Geophysical Research: Oceans, 122:6883-6900.

Cooley, S.W. and T.M. Pavelsky, 2016. Spatial and temporal patterns in Arctic river ice breakup revealed by automated ice detection from MODIS imagery. Remote Sensing of Environment, 175:310-322.

Copernicus, 2020. Copernicus Climate Change Service (C3S): ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate. https://cds.climate.copernicus.eu Accessed May 2020.

Cowtan, K. and R.G. Way, 2014. Coverage bias in the HadCRUT4 temperature series and its impact on recent temperature trends. Quarterly Journal of the Royal Meteorological Society, 140:1935-1944.

DeRepentigny, P., A. Jahn, L.B. Tremblay, R. Newton and S. Pfirman, 2020. Increased transnational sea ice transport between neighboring Arctic states in the 21st century. Earth's Future, 8: doi:10.1029/2019ef001284.

Derksen, C., D. Burgess, C. Duguay, S. Howell, L. Mudryk, S. Smith, C. Thackeray and M. Kirchmeier-Young, 2019. Changes in Snow, Ice and Permafrost Across Canada. In: Canada's Changing Climate Report, pp. 194-260. Government of Canada, Ottawa.

Déry, S.J. and E.F. Wood, 2005. Decreasing river discharge in northern Canada. Geophysical Research Letters, 32: doi:10.1029/2005gl022845.

Déry, S.J., M.A. Hernández-Henríquez, J.E. Burford and E.F. Wood, 2009. Observational evidence of an intensifying hydrological cycle in northern Canada. Geophysical Research Letters, 36: doi:10.1029/2009gl038852.

Déry, S.J., T.A. Stadnyk, M.K. MacDonald and B. Gauli-Sharma, 2016. Recent trends and variability in river discharge across northern Canada. Hydrology and Earth System Sciences, 20:4801-4818.

Diamond, H.J., T.R. Karl, M.A. Palecki, C. Bruce Baker, J.E. Bell, R.D. Leeper, D.R. Easterling, J.H. Lawrimore, T.P. Meyers, M.R. Helfert, G. Goodge and P.W. Thorne, 2012. U.S. Climate Reference Network after one decade of operations: status and assessment. Bulletin of the American Meteorological Society, 94:485-498.

Duchesne, C., J. Chartrand and S.L. Smith, 2020. Report on 2018 field activities and collection of ground-thermal and active-layer data in the Mackenzie corridor, Northwest Territories. Geological Survey of Canada.

Durocher, M., A.I. Requena, D.H. Burn and J. Pellerin, 2019. Analysis of trends in annual streamflow to the Arctic Ocean. Hydrological Processes, 33:1143-1151.

Dyurgerov, M., A. Bring and G. Destouni, 2010. Integrated assessment of changes in freshwater inflow to the Arctic Ocean. Journal of Geophysical Research, 115: doi:10.1029/2009jd013060.

Estilow, T.W., A.H. Young and D.A. Robinson, 2015. A long-term Northern Hemisphere snow cover extent data record for climate studies and monitoring. Earth System Science Data, 7:137-142.

Euskirchen, E.S., A.P. Bennett, A.L. Breen, H. Genet, M.A. Lindgren, T.A. Kurkowski, A.D. McGuire and T.S. Rupp, 2016. Consequences of changes in vegetation and snow cover for climate feedbacks in Alaska and northwest Canada. Environmental Research Letters, 11:105003, doi:10.1088/1748-9326/11/10/105003.

Farge, E. and V. Soldatkin, 2020. Siberia temperatures hit record for June as wildfires spread. Reuters, 7th July. www.reuters.com/article/us-climate-change-arctic/siberian-temperatures-hit-june-record-fires-spread-eu-data-idUSKBN2480SA

Farquharson, L.M., V.E. Romanovsky, W.L. Cable, D.A. Walker, S.V. Kokelj and D. Nicolsky, 2019. Climate change drives widespread and rapid thermokarst development in very cold permafrost in the Canadian High Arctic. Geophysical Research Letters, 46:6681-6689.

Farrell, S.L., N. Kurtz, L.N. Connor, B.C. Elder, C. Leuschen, T. Markus, D.C. McAdoo, B. Panzer, J. Richter-Menge and J.G. Sonntag, 2012. A first assessment of icebridge snow and ice thickness data over Arctic sea ice. IEEE Transactions on Geoscience and Remote Sensing, 50:2098-2111.

Fernández-Méndez, M., L.M. Olsen, H.M. Kauko, A. Meyer, A. Rösel, I. Merkouriadi, C.J. Mundy, J.K. Ehn, A. Malin Johansson, P.M. Wagner, Å. Ervik, B.K. Sorrell, P. Duarte, A. Wold, H. Hop and P. Assmy, 2018. Algal hot spots in a changing Arctic Ocean: sea-ice ridges and the snow-ice interface. Frontiers in Marine Science, 5: doi:10.3389/fmars.2018.00075.

Fetterer, F., K. Knowles, W.N. Meier, M. Savoie and A.K. Windnagel, 2017. Sea Ice Index. Version 3. doi:10.7265/N5K072F8.

Flanner, M.G., K.M. Shell, M. Barlage, D.K. Perovich and M.A. Tschudi, 2011. Radiative forcing and albedo feedback from the Northern Hemisphere cryosphere between 1979 and 2008. Nature Geoscience, 4:151-155.

Førland, E.J., K. Isaksen, J. Lutz, I. Hanssen-Bauer, T.V. Schuler, A. Dobler, H.M. Gjelten and D. Vikhamar-Schuler, 2020. Measured and modeled historical precipitation trends for Svalbard. Journal of Hydrometeorology, 21:1279-1296.

Fraser, R., S. Kokelj, T. Lantz, M. McFarlane-Winchester, I. Olthof and D. Lacelle, 2018. Climate sensitivity of High Arctic permafrost terrain demonstrated by widespread ice-wedge thermokarst on Banks Island. Remote Sensing, 10:954, doi:10.3390/rs10060954.

Frost, G.V., U.S. Bhatt, H.E. Epstein, D.A. Walker, M.K. Raynolds, L.T. Berner, J.W. Bjerke, A.L. Breen, B.C. Forbes, S.J. Goetz, C.M. Iversen, M.J. Lara, M.J. Macander, G.K. Phoenix, A.V. Rocha, V.G. Salmon, P.E. Thornton, H. Tømmervik and S.D. Wullschleger, 2019. Tundra Greenness. Arctic Report Card 2019, NOAA.

Ge, S., D. Yang and D.L. Kane, 2013. Yukon River Basin long-term (1977-2006) hydrologic and climatic analysis. Hydrological Processes, 27:2475-2484.

Gelaro, R., W. McCarty, M.J. Suárez, R. Todling, A. Molod, L. Takacs, C.A. Randles, A. Darmenov, M.G. Bosilovich, R. Reichle, K. Wargan, L. Coy, R. Cullather, C. Draper, S. Akella, V. Buchard, A. Conaty, A.M. da Silva, W. Gu, G.-K. Kim, R. Koster, R. Lucchesi, D. Merkova, J.E. Nielsen, G. Partyka, S. Pawson, W. Putman, M. Rienecker, S.D. Schubert, M. Sienkiewicz and B. Zhao, 2017. The modern-era retrospective analysis for research and applications, Version 2 (MERRA-2). Journal of Climate, 30:5419-5454.

Gerland, S., D. Barber, W. Meier, C.J. Mundy, M. Holland, S. Kern, Z. Li, C. Michel, D.K. Perovich and T. Tamura, 2019. Essential gaps and uncertainties in the understanding of the roles and functions of Arctic sea ice. Environmental Research Letters, 14:043002, doi:10.1088/1748-9326/ab09b3

Gertcyk, O., 2016. Vanishing Arctic: how warming climate leaves remote permafrost islands on the precipice. Siberian Times, 30th September. https://siberiantimes.com/other/others/news/n0753-vanishing-arctic-how-warming-climate-leaves-remote-permafrost-islands-on-the-precipice

GISTEMP Team, 2020. GISS Surface Temperature Analysis (GISTEMP), version 4. Improvements in the GISTEMP uncertainty model. https://data.giss.nasa.gov/gistemp/ Accessed 30 October 2020.

Goulding, H.L., T.D. Prowse and B. Bonsal, 2009. Hydroclimatic controls on the occurrence of break-up and ice-jam flooding in the Mackenzie Delta, NWT, Canada. Journal of Hydrology, 379:251-267.

Graham, R.M., A. Rinke, L. Cohen, S.R. Hudson, V.P. Walden, M.A. Granskog, W. Dorn, M. Kayser and M. Maturilli, 2017a. A comparison of the two Arctic atmospheric winter states observed during N-ICE2015 and SHEBA. Journal of Geophysical Research: Atmospheres, 122:5716-5737.

Graham, R.M., L. Cohen, A.A. Petty, L.N. Boisvert, A. Rinke, S.R. Hudson, M. Nicolaus and M. Granskog, 2017b. Increasing frequency and duration of Arctic winter warming events. Geophysical Research Letters, 44:6974-6983.

Granskog, M.A., A. Rösel, P.A. Dodd, D. Divine, S. Gerland, T. Martma and M.J. Leng, 2017. Snow contribution to first-year and second-year Arctic sea ice mass balance north of Svalbard. Journal of Geophysical Research: Oceans, 122:2539-2549.

Haine, T.W.N., B. Curry, R. Gerdes, E. Hansen, M. Karcher, C. Lee, B. Rudels, G. Spreen, L. de Steur, K.D. Stewart and R. Woodgate, 2015. Arctic freshwater export: Status, mechanisms, and prospects. Global and Planetary Change, 125:13-35.

Hanna, E., T.E. Cropper, P.D. Jones, A.A. Scaife and R. Allan, 2015. Recent seasonal asymmetric changes in the NAO (a marked summer decline and increased winter variability) and associated changes in the AO and Greenland Blocking Index. International Journal of Climatology, 35:2540-2554.

Hanssen-Bauer, I., E. Førland, H. Hisdal, S. Mayer, A. Sandø and A. Sorteberg, 2019. Climate in Svalbard 2100 – a knowledge base for climate adaptation. www.miljodirektoratet.no/globalassets/publikasjoner/M1242/M1242.pdf

Holmes, R.M., A.I. Shiklomanov, A. Suslova, M. Tretiakov, J.W. McClelland, R.G.M. Spencer and S. Tank, 2019. River discharge. Bulletin of the American Meteorological Society, 100:S161-S163.

Isaksen, K., J.L. Sollid, P. Holmlund and C. Harris, 2007. Recent warming of mountain permafrost in Svalbard and Scandinavia. Journal of Geophysical Research, 112(F2), doi:10.1029/2006jf000522

Jain, P., X. Wang and M.D. Flannigan, 2017. Trend analysis of fire season length and extreme fire weather in North America between 1979 and 2015. International Journal of Wildland Fire, 26:1009, doi:10.1071/wf17008.

Johansson, A.M., A. Malin Johansson, E. Malnes, S. Gerland, A. Cristea, A.P. Doulgeris, D.V. Divine, O. Pavlova and T.R. Lauknes, 2020. Consistent ice and open water classification combining historical synthetic aperture radar satellite images from ERS-1/2, Envisat ASAR, RADARSAT-2 and Sentinel-1A/B. Annals of Glaciology, 61:1-11.

Jolivel, M. and M. Allard, 2017. Impact of permafrost thaw on the turbidity regime of a subarctic river: the Sheldrake River, Nunavik, Quebec. Arctic Science, 3:451-474.

Jones, B.M., G. Grosse, C.D. Arp, E. Miller, L. Liu, D.J. Hayes and C.F. Larsen, 2015. Recent Arctic tundra fire initiates widespread thermokarst development. Scientific Reports, 5:15865.

Jones, M.K.W., W.H. Pollard and B.M. Jones, 2019. Rapid initialization of retrogressive thaw slumps in the Canadian high Arctic and their response to climate and terrain factors. Environmental Research Letters, 14:055006, doi:10.1088/1748-9326/ab12fd.

Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, A. Leetmaa, R. Reynolds, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K.C. Mo, C. Ropelewski, J. Wang, R. Jenne and D. Joseph, 1996. The NCEP/NCAR 40-Year Reanalysis Project. Bulletin of the American Meteorological Society, 77:437-471.

Kim, J.-S., J.-S. Kug, S.-J. Jeong, H. Park and G. Schaepman-Strub, 2020. Extensive fires in southeastern Siberian permafrost linked to preceding Arctic Oscillation. Science Advances, 6:eaax3308, doi: 10.1126/sciadv.aax3308.

King, J., H. Skourup, S.M. Hvidegaard, A. Rösel, S. Gerland, G. Spreen, C. Polashenski, V. Helm and G.E. Liston, 2018. Comparison of freeboard retrieval and ice thickness calculation from ALS, ASIRAS, and CryoSat-2 in the Norwegian Arctic to field measurements made during the N-ICE2015 expedition. Journal of Geophysical Research: Oceans, 123:1123-1141.

Kirchmeier-Young, M.C., F.W. Zwiers, N.P. Gillett and A.J. Cannon, 2017. Attributing extreme fire risk in Western Canada to human emissions. Climatic Change, 144:365-379.

Kirillina, K., E.G. Shvetsov, V.V. Protopopova, L. Thiesmeyer and W. Yan, 2020. Consideration of anthropogenic factors in boreal forest fire regime changes during rapid socio-economic development: case study of forestry districts with increasing burnt area in the Sakha Republic, Russia. Environmental Research Letters, 15:035009, doi:10.1088/1748-9326/ab6c6e.

Krinner, G., C. Derksen, R. Essery, M. Flanner, S. Hagemann and 52 others, 2018. ESM-SnowMIP: assessing snow models and quantifying snow-related climate feedbacks. Geoscientific Model Development, 11:5027-5049.

Krumpen, T., H. Jakob Belter, A. Boetius, E. Damm, C. Haas, S. Hendricks, M. Nicolaus, E.-M. Nöthig, S. Paul, I. Peeken, R. Ricker and R. Stein, 2019. Arctic warming interrupts the Transpolar Drift and affects long-range transport of sea ice and ice-rafted matter. Scientific Reports, 9: doi:10.1038/s41598-019-41456-y.

Krumpen, T., F. Birrien, F. Kauker, T. Rackow, L. von Albedyll and 33 others, 2020. The MOSAiC ice floe: sediment-laden survivor from the Siberian shelf. The Cryosphere, 14:2173-2187.

Kwok, R., 2018. Arctic sea ice thickness, volume, and multiyear ice coverage: losses and coupled variability (1958–2018). Environmental Research Letters, 13:105005, doi:10.1088/1748-9326/aae3ec.

Kwok, R., T. Markus, N.T. Kurtz, A.A. Petty, T.A. Neumann, S.L. Farrell, G.F. Cunningham, D.W. Hancock, A. Ivanoff and J.T. Wimert, 2019. Surface height and sea ice freeboard of the Arctic Ocean from ICESat-2: characteristics and early results. Journal of Geophysical Research: Oceans, 124:6942-6959.

Kwok, R., S. Kacimi, M.A. Webster, N.T. Kurtz and A.A. Petty, 2020. Arctic snow depth and sea ice thickness from ICESat-2 and CryoSat-2 freeboards: a first examination. Journal of Geophysical Research: Oceans, 125: doi:10.1029/2019jc016008.

Lacroix, M.P., T.D. Prowse, B.R. Bonsal, C.R. Duguay and P. Menard, 2005. River ice trends in Canada. Committee on River Ice Processes and the Environment. http://cripe.ca/docs/proceedings/13/Lacroix-et-al-2005.pdf

Lesack, L.F.W., P. Marsh, F.E. Hicks and D.L. Forbes, 2014. Local spring warming drives earlier river-ice breakup in a large Arctic delta. Geophysical Research Letters, 41:1560-1567.

Lewkowicz, A.G. and R.G. Way, 2019. Extremes of summer climate trigger thousands of thermokarst landslides in a High Arctic environment. Nature Communications, 10: doi:10.1038/s41467-019-09314-7.

Liljedahl, A.K., J. Boike, R.P. Daanen, A.N. Fedorov, G.V. Frost, G. Grosse, L.D. Hinzman, Y. Iijma, J.C. Jorgenson, N. Matveyeva, M. Necsoiu, M.K. Raynolds, V.E. Romanovsky, J. Schulla, K.D. Tape, D.A. Walker, C.J. Wilson, H. Yabuki and D. Zona, 2016. Pan-Arctic ice-wedge degradation in warming permafrost and its influence on tundra hydrology. Nature Geoscience, 9:312-318.

Liu, B., D. Yang, B. Ye and S. Berezovskaya, no date. Long-term open-water season stream temperature variations and changes over Lena river basin in Siberia. Global and Planetary Change, 48:96-111.

Mack, M.C., M.S. Bret-Harte, T.N. Hollingsworth, R.R. Jandt, E.A.G. Schuur, G.R. Shaver and D. Verbyla, 2011. Carbon loss from an unprecedented Arctic tundra wildfire. Nature, 475:489-492.

Mamet, S.D., K.P. Chun, G.G.L. Kershaw, M.M. Loranty and G.P. Kershaw, 2017. Recent increases in permafrost thaw rates and areal loss of palsas in the western Northwest Territories, Canada. Permafrost and Periglacial Processes, 28:619-633.

Markus, T., J.C. Stroeve and J. Miller, 2009. Recent changes in Arctic sea ice melt onset, freezeup, and melt season length. Journal of Geophysical Research, 114: doi:10.1029/2009jc005436.

Mars, J.C. and D.W. Houseknecht, 2007. Quantitative remote sensing study indicates doubling of coastal erosion rate in past 50 yr along a segment of the Arctic coast of Alaska. Geology, 35:583, doi:10.1130/g23672a.1.

Masrur, A., A.N. Petrov and J. DeGroote, 2018. Circumpolar spatio-temporal patterns and contributing climatic factors of wildfire activity in the Arctic tundra from 2001–2015. Environmental Research Letters, 13:014019, doi:10.1088/1748-9326/aa9a76.

McClelland, J.W., S.J. Déry, B.J. Peterson, R.M. Holmes and E.F. Wood, 2006. A pan-arctic evaluation of changes in river discharge during the latter half of the 20th century. Geophysical Research Letters, 33: doi:10.1029/2006gl025753.

McClelland, J.W., R.M. Holmes, K.H. Dunton and R.W. Macdonald, 2012. The Arctic Ocean Estuary. Estuaries and Coasts, 35:353-368.

McLeod, J.T. and T.L. Mote, 2016. Linking interannual variability in extreme Greenland blocking episodes to the recent increase in summer melting across the Greenland ice sheet. International Journal of Climatology, 36:1484-1499.

Meier, W.N. and J. Scott Stewart, 2019. Assessing uncertainties in sea ice extent climate indicators. Environmental Research Letters, 14:035005, doi:10.1088/1748-9326/aaf52c.

Mekis, E., N. Donaldson, J. Reid, A. Zucconi, J. Hoover, Q. Li, R. Nitu and S. Melo, 2018. An overview of surface-based precipitation observations at Environment and Climate Change Canada. Atmosphere-Ocean, 56:71-95.

Mekonnen, Z.A., W.J Riley, L.T. Berner, N.J. Bouskill, M.S. Torn, G. Iwahana, A.L. Breen, I.H. Myers-Smith, M.G. Criado, Y. Liu, E.S. Euskirchen, S.J. Goetz, M.C. Mack and R.F. Grant, 2021. Arctic tundra shrubification: a review of mechanisms and impacts on ecosystem carbon balance. Environmental Research Letters, 16:053001.

Meredith, M., M.S. Sommerkorn, C.C. Derksen, A. Ekaykin, A. Hollowed, G. Kofinas, A. Mackintosh, J. Melbourne-Thomas, M.M.C. Muelbert, G. Ottersen, H. Pritchard and E.A.G. Schuur, 2019. Polar regions. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate.

Merkouriadi, I., G.E. Liston, R.M. Graham and M.A. Granskog, 2020. Quantifying the potential for snow-ice formation in the Arctic Ocean. Geophysical Research Letters, 47: doi:10.1029/2019gl085020.

Morris, A., G. Moholdt and L. Gray, 2020. Spread of Svalbard glacier mass loss to Barents Sea margins revealed by CryoSat-2. Journal of Geophysical Research: Earth Surface, 125: doi:10.1029/2019jf005357.

Mortimer, C., L. Mudryk, C. Derksen, K. Luojus, R. Brown, R. Kelly and M. Tedesco, 2020. Evaluation of long-term Northern Hemisphere snow water equivalent products. The Cryosphere, 14:1579-1594.

Mudryk, L.R., C. Derksen, P.J. Kushner and R. Brown, 2015. Characterization of Northern Hemisphere snow water equivalent datasets, 1981–2010. Journal of Climate, 28:8037-8051.

Mudryk, L., M. Santolaria-Otín, G. Krinner, M. Ménégoz, C. Derksen, C. Brutel-Vuilmet, M. Brady and R. Essery, 2020a. Historical Northern Hemisphere snow cover trends and projected changes in the CMIP6 multi-model ensemble. The Cryosphere, 14:2495-2514.

Mudryk, L.M., A. Elias Chereque, R. Brown, C. Derksen, K. Luojus and B. Decharme, 2020b. Terrestrial Snow Cover. Arctic Report Card 2020. https://doi.org/10.25923/p6ca-v923

Myers-Smith, I.H., J.T. Kerby, G.K. Phoenix, J.W. Bjerke, H.E. Epstein, J.J. Assmann, C. John, L. Andreu-Hayles, S. Angers-Blondin, P.S.A. Beck, L.T. Berner, U.S. Bhatt, A.D. Bjorkman, D. Blok, A. Bryn, C.T. Christiansen, J.H.C. Cornelissen, A.M. Cunliffe, S.C. Elmendorf, B.C. Forbes, S.J. Goetz, R.D. Hollister, R. de Jong, M.M. Loranty, M. Macias-Fauria, K. Maseyk, S. Normand, J. Olofsson, T.C. Parker, F.-J.W. Parmentier, E. Post, G. Schaepman-Strub, F. Stordal, P.F. Sullivan, H.J.D. Thomas, H. Tømmervik, R. Treharne, C.E. Tweedie, D.A. Walker, M. Wilmking and S. Wipf, 2020. Complexity revealed in the greening of the Arctic. Nature Climate Change, 10:106-117.

Nandan, V., T. Geldsetzer, J. Yackel, M. Mahmud, R. Scharien, S. Howell, J. King, R. Ricker and B. Else, 2017. Effect of snow salinity on CryoSat-2 Arctic first-year sea ice freeboard measurements. Geophysical Research Letters, 44:10,419-10,426.

Nandan, V., R.K. Scharien, T. Geldsetzer, R. Kwok, J.J. Yackel and M.S. Mahmud, 2020. Snow property controls on modeled ku-band altimeter estimates of first-year sea ice thickness: case studies from the Canadian and Norwegian Arctic. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 13:1082-1096.

Natali, S.M., J.D. Watts, B.M. Rogers, S. Potter, S.M. Ludwig, A.-K. Selbmann, P.F. Sullivan and 67 others, 2019. Large loss of CO_2 in winter observed across the northern permafrost region. Nature Climate Change, 9:852-857.

Neff, W., G.P. Compo, F. Martin Ralph and M.D. Shupe, 2014. Continental heat anomalies and the extreme melting of the Greenland ice surface in 2012 and 1889. Journal of Geophysical Research: Atmospheres, 119:6520-6536.

Nitze, I., G. Grosse, B. Jones, C. Arp, M. Ulrich, A. Fedorov and A. Veremeeva, 2017. Landsat-based trend analysis of lake dynamics across northern permafrost regions. Remote Sensing, 9:640. doi:10.3390/rs9070640.

NOAA, 2020. Monthly mean NAO index since January 1950. www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao.shtml Accessed 2021.

Noël, B., C.L. Jakobs, W.J.J. van Pelt, S. Lhermitte, B. Wouters, J. Kohler, J.O. Hagen, B. Luks, C.H. Reijmer, W.J. van de Berg and M.R. van den Broeke, 2020. Low elevation of Svalbard glaciers drives high mass loss variability. Nature Communications, 11:4597.

Noetzli, J., H.H. Christiansen, K. Isaksen, S. Smith, L. Zhao and D.A. Streletskiy, 2020. Permafrost thermal state. Bulletin of the American Meteorological Society, 101:S32-S36.

O'Neel, S., C. McNeil, L.C. Sass, C. Florentine, E.H. Baker, E. Peitzsch, D. McGrath, A.G. Fountain and D. Fagre, 2019. Reanalysis of the US Geological Survey Benchmark Glaciers: long-term insight into climate forcing of glacier mass balance. Journal of Glaciology, 65:850-866.

O'Neill, H.B., B.H. O'Neill, S.L. Smith and C. Duchesne, 2019. Long-term permafrost degradation and thermokarst subsidence in the Mackenzie Delta area indicated by thaw tube measurements. Cold Regions Engineering, doi:10.1061/9780784482599.074.

Overland, J.E., M.C. Spillane, D.B. Percival, M. Wang and H.O. Mofjeld, 2004. Seasonal and regional variation of pan-Arctic surface air temperature over the instrumental record. Journal of Climate, 17:3263-3282.

Park, D.-S.R., S. Lee and S.B. Feldstein, 2015. Attribution of the recent winter sea ice decline over the Atlantic Sector of the Arctic Ocean. Journal of Climate, 28:4027-4033.

Park, H., Y. Yoshikawa, K. Oshima, Y. Kim, T. Ngo-Duc, J.S. Kimball and D. Yang, 2016. Quantification of warming climate-induced changes in terrestrial Arctic river ice thickness and phenology. Journal of Climate, 29:1733-1754.

Peng, G., M. Steele, A. Bliss, W. Meier and S. Dickinson, 2018. Temporal means and variability of Arctic sea ice melt and freeze season climate indicators using a satellite climate data record. Remote Sensing, 10:1328, doi:10.3390/rs10091328.

Perovich, D., W. Meier, M. Tschudi, S. Farrell, S. Hendricks, S. Gerland, L. Kaleschke, R. Ricker, X. Tian-Kunze, M. Webster and K. Wood, 2019. Sea ice. In: Arctic Report Card 2019, NOAA.

Perovich, D., W. Meier, M. Tschudi, S. Hendricks, A.A. Petty, D. Divine, S. Farrell, S. Gerland, C. Haas, L. Kaleschke, O. Pavlova, R. Ricker, X. Tian-Kunze, M. Webster and K. Wood, 2020. Sea ice. In: Arctic Report Card.

Peterson, B.J., R.M. Holmes, J.W. McClelland, C.J. Vörösmarty, R.B. Lammers, A.I. Shiklomanov, I.A. Shiklomanov and S. Rahmstorf, 2002. Increasing river discharge to the Arctic Ocean. Science, 298:2171-2173.

Petty, A.A., N.T. Kurtz, R. Kwok, T. Markus and T.A. Neumann, 2020. Winter arctic sea ice thickness from ICESat-2 freeboards. Journal of Geophysical Research: Oceans, 125:e2019JC015764.

Pinzon, J. and C. Tucker, 2014. A non-stationary 1981–2012 AVHRR NDVI3g time series. Remote Sensing, 6:6929-6960.

Potter, C. and C. Hugny, 2020. Wildfire effects on permafrost and soil moisture in spruce forests of Interior Alaska. Journal of Forestry Research, 31:553-563.

Przybylak, R. and P. Wyszyński, 2020. Air temperature changes in the Arctic in the period 1951–2015 in the light of observational and reanalysis data. Theoretical and Applied Climatology, 139:75-94.

Pulliainen, J., K. Luojus, C. Derksen, L. Mudryk, J. Lemmetyinen, M. Salminen, J. Ikonen, M. Takala, J. Cohen, T. Smolander and J. Norberg, 2020. Publisher Correction: Patterns and trends of Northern Hemisphere snow mass from 1980 to 2018. Nature, 582:E18.

Rachold, V., M.N. Grigoriev, F.E. Are, S. Solomon, E. Reimnitz, H. Kassens and M. Antonow, 2000. Coastal erosion vs riverine sediment discharge in the Arctic Shelf seas. International Journal of Earth Sciences, 89:450-460.

Rapaić, M., R. Brown, M. Markovic and D. Chaumont, 2015. An evaluation of temperature and precipitation surface-based and reanalysis datasets for the Canadian Arctic, 1950–2010. Atmosphere-Ocean, 53:283-303.

Rawlins, M.A., M. Steele, M.M. Holland, J.C. Adam, J.E. Cherry, J.A. Francis, P.Y. Groisman, L.D. Hinzman, T.G. Huntington, D.L. Kane, J.S. Kimball, R. Kwok, R.B. Lammers, C.M. Lee, D.P. Lettenmaier, K.C. McDonald, E. Podest, J.W. Pundsack, B. Rudels, M.C. Serreze, A. Shiklomanov, Ø. Skagseth, T.J. Troy, C.J. Vörösmarty, M. Wensnahan, E.F. Wood, R. Woodgate, D. Yang, K. Zhang and T. Zhang, 2010. Analysis of the Arctic system for freshwater cycle intensification: observations and expectations. Journal of Climate, 23:5715-5737.

Rham, L. de, Y. Dibike, S. Beltaos, D. Peters, B. Bonsal and T. Prowse, no date. A Canadian river ice database from national hydrometric program archives. doi:10.5194/essd-2020-29.

Ricker, R., S. Hendricks, L. Kaleschke, X. Tian-Kunze, J. King and C. Haas, 2017. A weekly Arctic sea-ice thickness data record from merged CryoSat-2 and SMOS satellite data. The Cryosphere, 11:1607-1623.

Rokaya, P., S. Budhathoki and K.-E. Lindenschmidt, 2018. Trends in the timing and magnitude of ice-jam floods in Canada. Scientific Reports, 8:5834.

Romanovsky, V.E., K. Isaksen, D. Drozdov, O. Anisimov, A. Instanes, M. Leibman, A.D. McGuire, N. Shiklomanov, S. Smith and D. Walker, 2017. Changing permafrost and its impacts. In: Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2017, pp. 65-102. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway.

Romanovsky, V., S. Smith, K. Isaksen, K. Nyland, A. Kholodov, N. Shiklomanov, D. Streletskiy, L. Farquharson, D. Drozdov, G.V. Malkova and H.H. Christiansen, 2020. Terrestrial permafrost. Bulletin of the American Meteorological Society, 101:S265-S271.

Rood, S.B., S. Kaluthota, L.J. Philipsen, N.J. Rood and K.P. Zanewich, 2017. Increasing discharge from the Mackenzie River system to the Arctic Ocean. Hydrological Processes, 31:150-160.

Rösel, A., P. Itkin, J. King, D. Divine, C. Wang, M.A. Granskog, T. Krumpen and S. Gerland, 2018. Thin sea ice, thick snow, and widespread negative freeboard observed during N-ICE2015 north of Svalbard. Journal of Geophysical Research: Oceans, 123:1156-1176.

Rostosky, P., G. Spreen, S. Gerland, M. Huntemann and M. Mech, 2020. Modeling the microwave emission of snow on Arctic sea ice for estimating the uncertainty of satellite retrievals. Journal of Geophysical Research: Oceans, 125: doi:10.1029/2019jc015465.

Rothrock, D.A., Y. Yu and G.A. Maykut, 1999. Thinning of the Arctic sea-ice cover. Geophysical Research Letters, 26:3469-3472.

Sasgen, I., B. Wouters, A.S. Gardner, M.D. King, M. Tedesco, F.W. Landerer, C. Dahle, H. Save and X. Fettweis, 2020. Return to rapid ice loss in Greenland and record loss in 2019 detected by the GRACE-FO satellites. Communications Earth & Environment, 1: doi:10.1038/s43247-020-0010-1

Schuler, T.V., J. Kohler, N. Elagina, J.O.M. Hagen, A.J. Hodson, J.A. Jania, A.M. Kääb, B. Luks, J. Małecki, G. Moholdt, V.A. Pohjola, I. Sobota and W.J.J. Van Pelt, 2020. Reconciling Svalbard glacier mass balance. Frontiers in Earth Science, 8: doi:10.3389/feart.2020.00156

Screen, J.A. and I. Simmonds, 2012. Declining summer snowfall in the Arctic: causes, impacts and feedbacks. Climate Dynamics, 38:2243-2256.

Serreze, M.C., J.E. Box, R.G. Barry and J.E. Walsh, 1993. Characteristics of Arctic synoptic activity, 1952–1989. Meteorology and Atmospheric Physics, 51:147-164.

Serreze, M.C., A.P. Barrett and J. Stroeve, 2012. Recent changes in tropospheric water vapor over the Arctic as assessed from radiosondes and atmospheric reanalyses: changes in Arctic water vapor. Journal of Geophysical Research, 117: doi:10.1029/2011jd017421

Sharp, M., D.O. Burgess, J.G. Cogley, M. Ecclestone, C. Labine and G.J. Wolken, 2011. Extreme melt on Canada's Arctic ice caps in the 21st century. Geophysical Research Letters, 38: doi:10.1029/2011gl047381

Shepherd, A., F. Pattyn, T. Moon, I. Joughin, B. Smith and 75 others, 2019. Mass balance of the Greenland Ice Sheet from 1992 to 2018. Nature, 579:233-239.

Shiklomanov, A.I. and R.B. Lammers, 2014. River ice responses to a warming Arctic – recent evidence from Russian rivers. Environmental Research Letters, 9:035008, doi:10.1088/1748-9326/9/3/035008

Shiklomanov, A.I., R.M. Holmes, J.W. McClelland, S.E. Tank and R.G.M. Spencer, no date. Arctic Great Rivers Observatory, Discharge Dataset. https://arcticgreatrivers.org Accessed 2020.

Shiklomanov, A., S. Déry, M. Tretiakov, D. Yang, D. Magritsky, A. Georgiadi and W. Tang, 2021. River freshwater flux to the Arctic Ocean. In: Yang, D. and D.L. Kane (eds.), Arctic Hydrology, Permafrost and Ecosystems, pp. 703-738.

Sommer, C., T. Seehaus, A. Glazovsky and M.H. Braun, no date. Brief communication: Accelerated glacier mass loss in the Russian Arctic (2010–2017). The Cryosphere Discussions, doi:10.5194/tc-2020-358

Spreen, G., L. Steur, D. Divine, S. Gerland, E. Hansen and R. Kwok, 2020. Arctic sea ice volume export through Fram Strait from 1992 to 2014. Journal of Geophysical Research: Oceans, 125: doi:10.1029/2019jc016039

Streletskiy, D.A., N.I. Shiklomanov, J.D. Little, F.E. Nelson, J. Brown, K.E. Nyland and A.E. Klene, 2017. Thaw subsidence in undisturbed tundra landscapes, Barrow, Alaska, 1962-2015. Permafrost and Periglacial Processes, 28:566-572.

Stroeve, J.C., A.D. Crawford and S. Stammerjohn, 2016. Using timing of ice retreat to predict timing of fall freeze-up in the Arctic. Geophysical Research Letters, 43:6332-6340.

Stuefer, S.L., D.L. Kane and K.M. Dean, 2020. Snow water equivalent measurements in remote Arctic Alaska watersheds. Water Resources Research, 56: doi:10.1029/2019wr025621

Swanson, D. and M. Nolan, 2018. Growth of retrogressive thaw slumps in the Noatak Valley, Alaska, 2010–2016, measured by airborne photogrammetry. Remote Sensing, 10:983, doi:10.3390/rs10070983

Takala, M., K. Luojus, J. Pulliainen, C. Derksen, J. Lemmetyinen, J.-P. Kärnä, J. Koskinen and B. Bojkov, 2011. Estimating northern hemisphere snow water equivalent for climate research through assimilation of space-borne radiometer data and ground-based measurements. Remote Sensing of Environment, 115:3517-3529.

Tedesco, M. and X. Fettweis, 2020. Unprecedented atmospheric conditions (1948–2019) drive the 2019 exceptional melting season over the Greenland ice sheet. The Cryosphere, 14:1209-1223.

Tedesco, M., X. Fettweis, T. Mote, J. Wahr, P. Alexander, J.E. Box and B. Wouters, 2013. Evidence and analysis of 2012 Greenland records from spaceborne observations, a regional climate model and reanalysis data. The Cryosphere, 7:615-630.

Thoman, R.L., Jr., U.S. Bhatt, P.A. Bieniek, B.R. Brettschneider, M. Brubaker, S.L. Danielson, Z. Labe, R. Lader, W.N. Meier, G. Sheffield and J.E. Walsh, 2020. The record low Bering Sea ice extent in 2018: Context, impacts, and an assessment of the role of anthropogenic climate change. Bulletin of the American Meteorological Society, doi:10.1175/BAMS-D-19-0175.1

Tschudi, M.A., W.N. Meier and J. Scott Stewart, 2020. An enhancement to sea ice motion and age products at the National Snow and Ice Data Center (NSIDC). The Cryosphere, 14:1519-1536.

Vasiliev, A.A., D.S. Drozdov, A.G. Gravis, G.V. Malkova, K.E. Nyland and D.A. Streletskiy, 2020. Permafrost degradation in the Western Russian Arctic. Environmental Research Letters, 15:045001, doi:10.1088/1748-9326/ab6f12

Vihma, T., J. Screen, M. Tjernström, B. Newton, X. Zhang, V. Popova, C. Deser, M. Holland and T. Prowse, 2016. The atmospheric role in the Arctic water cycle: A review on processes, past and future changes, and their impacts. Journal of Geophysical Research, 121:586.

Vuglinsky, V., 2000. Russian River Ice Thickness and Duration. Version 1. doi:10.7265/N5J10129

Walsh, J.E., J.E. Overland, P.Y. Groisman and B. Rudolf, 2011. Arctic climate: recent variations. In: Snow, Water, Ice and Permafrost in the Arctic: Climate Change and the Cryosphere. pp. 2-1 – 2-13. Arctic Monitoring and Assessment Programme, Oslo, Norway.

Wang, C., R.M. Graham, K. Wang, S. Gerland and M.A. Granskog, 2019. Comparison of ERA5 and ERA-Interim near-surface air temperature, snowfall and precipitation over Arctic sea ice: effects on sea ice thermodynamics and evolution. The Cryosphere, 13:1661-1679.

Warren, S.G., I.G. Rigor, N. Untersteiner, V.F. Radionov, N.N. Bryazgin, Y.I. Aleksandrov and R. Colony, 1999. Snow depth on Arctic sea ice. Journal of Climate, 12:1814-1829.

Webster, M.A., I.G. Rigor, S.V. Nghiem, N.T. Kurtz, S.L. Farrell, D.K. Perovich and M. Sturm, 2014. Interdecadal changes in snow depth on Arctic sea ice. Journal of Geophysical Research: Oceans, 119:5395-5406.

Webster, M., S. Gerland, M. Holland, E. Hunke, R. Kwok, O. Lecomte, R. Massom, D. Perovich and M. Sturm, 2018. Snow in the changing sea-ice systems. Nature Climate Change, 8:946-953.

WGMS, 2020. Fluctuations of Glaciers Database. World Glacier Monitoring Service. doi:10.5904/wgms-fog-2020-08.

Woods, C. and R. Caballero, 2016. The role of moist intrusions in winter Arctic warming and sea ice decline. Journal of Climate, 29:4473-4485.

World Meteorological Organization, 2020. https://twitter.com/WMO/status/1275001460464418816?s=20

Yang, D., D.L. Kane, L.D. Hinzman, X. Zhang, T. Zhang and H. Ye, 2002. Siberia Lena River hydrologic regime and recent change. Journal of Geophysical Research: Atmospheres, 107:4694, doi:10.1029/2002jd002542

Yang, D., H. Park, T. Prowse, A. Shiklomanov and E. McLeod, 2021. River ice processes and changes across the northern regions. In: Yang D. and D.L. Kane (eds.), Arctic Hydrology, Permafrost and Ecosystems, pp. 379-406. Springer.

Yoshikawa, K., W.R. Bolton, V.E. Romanovsky, M. Fukuda and L.D. Hinzman, 2002. Impacts of wildfire on the permafrost in the boreal forests of Interior Alaska. Journal of Geophysical Research, 108: doi:10.1029/2001jd000438

Zhang, T., K. Stamnes and S.A. Bowling, 2001. Impact of the atmospheric thickness on the atmospheric downwelling longwave radiation and snowmelt under clear-sky conditions in the Arctic and subarctic. Journal of Climate, 14:920-939.

Zhang, X., J. He, J. Zhang, I. Polyakov, R. Gerdes, J. Inoue and P. Wu, 2013. Enhanced poleward moisture transport and amplified northern high-latitude wetting trend. Nature Climate Change, 3:47-51.

3. Model assessment and future of the Arctic

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Key findings

- *CMIP6 models are able to capture the general features of the present-day climatology, spatial variability, and historical linear trends in surface air temperature, sea-ice concentration, sea-ice extent, Northern Hemisphere spring snow extent, and ocean sea-surface salinity in the Arctic.*
- *A distinct improvement in the sea ice simulations is found in the CMIP6 models compared to the CMIP5 models.*
- *As global warming is projected to continue, so will the amplified Arctic warming and the strongest Arctic warming is projected to occur in winter. CMIP6 models project that annual mean surface air temperature in the Arctic will increase to 3.3–10.0°C above current levels (1981–2010) under a range of scenarios by the end of the 21st century.*
- *Although there is large inter-model spread in the simulated trends for snow extent, there is a single linear relationship between projected changes in spring snow extent and global surface air temperature, which is valid across all CMIP6 Shared Socioeconomic Pathways (SSPs).*
- *Arctic sea ice (cover and thickness) will continue to decline. An ice-free summer is projected to occur under the SSP2-4.5, SSP3-7.0, and SSP5-8.5 scenarios, but not the SSP1-2.6 scenario. Depending on the models, the first ice-free date could be as early as the 2040s (SSP5-8.5).*
- *A dipole pattern of linear trends in surface salinity/freshwater content (in the upper 250 m of the water column) is projected under all scenarios, with the Pacific Arctic becoming fresher and the Atlantic Arctic becoming more saline.*
- *The CanESM2 large ensemble simulations show that under stabilized global warming of 1.5°C, 2.0°C, and 3.0°C, the amplitude of Arctic mean warming remains fairly stable at roughly twice the global mean warming, while the September sea-ice extent remains fairly constant.*
- *The probability of an ice-free Arctic summer is an order of magnitude smaller under 1.5°C global warming, a scenario consistent with the Paris Agreement, compared to 2.0°C global warming.*

3.1 Introduction

The Arctic is one of the regions where the strongest warming is observed (IPCC, 2019). This warming is mainly driven by changes in external forcings and multiple feedbacks that result in 'Arctic Amplification' (AMAP, 2017a). As the Arctic climate is almost certain to continue to change, it is necessary to have some idea of the magnitude of the changes likely to take place in the coming decades since continued climate change in the Arctic will have major consequences for Arctic ecosystems (AMAP, 2017b). Coupled climate models are currently the best tool for investigating changes in the future climate system, which is controlled by the physical laws of fluid dynamics and thermodynamics. Global Climate Models (GCMs) and their projections form an important scientific base for the Intergovernmental Panel on Climate Change (IPCC) assessment reports. The models undergo continuous development, and every five to seven years a large set of coordinated climate model simulations are performed under the Coupled Model Intercomparison Project (CMIP), coordinated by the World Climate Research Programme (WCRP). This chapter reports on how the most up-to-date climate models simulate the present-day Arctic climate in the atmosphere, ocean, and sea ice. Projections of future climate change are dependent on scenarios of external forcing. To assess scenario uncertainty, several Shared Socioeconomic Pathways (SSPs) that describe possible future greenhouse gas emissions and which were used in CMIP Phase 6 are included in the discussion. This new set of emission scenarios has some overlap with the Representative Concentration Pathways (RCPs) used in CMIP Phase 5 (CMIP5), and the IPCC Fifth Assessment Report (AR5, IPCC, 2013), described in Section 3.3.1.

While GCMs provide credible quantitative estimates of future climate at continental scales and above, individual model performance varies for different regions, variables, and evaluation metrics (Overland et al., 2011). The explanation for their differing ability to represent different regions may be both because of the models' inherent skill, but also due to chance as a statistical spread would be expected when the regional scales are influenced by pronounced stochastic variability on decadal scales (Deser et al., 2012). Climate models have continued to be developed and improved since AR5, the range of climate variables and processes that have been evaluated has been expanded, and differences between models and observations are increasingly quantified using 'performance metrics' (IPCC, 2013). This chapter provides an evaluation of climate models in terms of both their simulated recent past climate in the Arctic and future projections. Projections are provided by time slices for a 20-year mean period in the mid-century (2041–2060, a period by which emission scenarios have not diverged greatly) so the choice of emission scenarios has less impact on the projected changes.

This illustration is augmented by time series of the areal mean of the Arctic for the entire simulation period up to year 2100.

Among the many changes that have been observed in the Arctic physical environment, the rapid increase in surface air temperature and the decline in sea-ice cover and thickness are the most pronounced and representative of the changes observed (AMAP, 2017a; Overland et al., 2019; Richter-Menge et al., 2019). As summarized in Chapter 2, the greatest change in near-surface air temperature over the past 49 years occurred over the Arctic Ocean during the cold season. Arctic sea-ice cover and thickness have shown major changes in recent decades, especially during the warm season (Maslanik et al., 2011; Olason and Notz, 2014; Kwok and Cunningham, 2015). The Arctic Ocean is a confluence of saline water from the Atlantic Ocean and relatively fresh water from the Pacific Ocean, river runoff, net precipitation (Carmack et al., 2016), and sea-ice melt. The key variables discussed here are surface air temperature, sea ice (extent and thickness), precipitation and snow cover, near-surface salinity and freshwater content in the ocean. The chapter also considers projections of change in the Arctic under the Paris Agreement, according to which nations have agreed to "Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels". The Paris Agreement was negotiated by representatives of 196 state parties at the 21st Conference of the Parties of the United Nations Framework Convention on Climate Change (UNFCCC) in Le Bourget, near Paris, France, and adopted by consensus on 12 December 2015.

3.2 Changes in the recent past from observation and hindcasting

The Arctic has warmed more than twice as fast as the global mean in recent decades. This amplified response in the Arctic to global warming is often seen as a leading indicator of global climate change, and termed Arctic Amplification (Manabe and Wetherald, 1975; Holland and Bitz, 2003). Other physical changes (such as a rapid decline in sea-ice cover and thickness, ocean freshening, melting of Greenland's ice sheet, permafrost warming and thawing, changing of circulation patterns and precipitation amount, in addition to those indicators listed in Chapter 2) have major implications for marine and terrestrial ecosystems, national security, transportation, and economic development in the Arctic and beyond. Climate models can simulate the general features of the recent change and climatology in relatively good agreement with observations. As shown in Figure 3.1, the 40-year (1975–2014) linear trend patterns in Arctic surface air temperature are captured well by CMIP6 models compared with observations. For sea-ice extent, ensemble means from CMIP6 show consistent results in the climatological mean (averaged over 1979–2005) seasonal cycle, as was also the case for CMIP5. Shu et al. (2020) found that the multi-model mean can adequately reproduce the seasonal cycles of Arctic sea-ice extent (Figure 3.2). The multi-model mean from CMIP5 is closer to observed values at the summer minimum compared to CMIP6. In both CMIP generations, the observed means are within the model spread (Figure 3.2). For the period 1979–2014, the mean over 44 CMIP6 models slightly underestimated the annual mean sea-ice extent trend at -0.70±0.06 million km^2/decade, compared with the observed linear trend of -0.82±0.18 million km^2/decade.

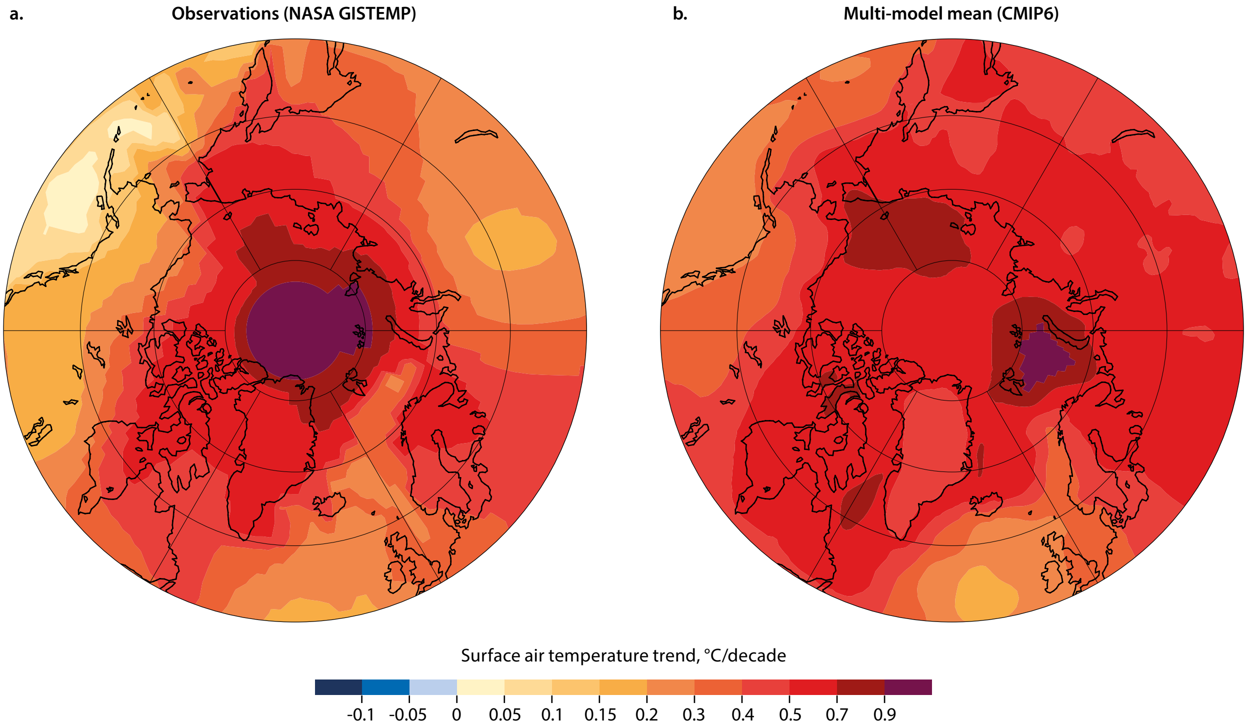

Figure 3.1 Annual mean surface air temperature for the period 1975–2014 based on observations (a) and the CMIP6 multi-model ensemble mean (b). The data source for observations is the NASA GISS Surface Temperature Analysis (GISTEMP) at data.giss.nasa.gov/gistemp/. Note that the Arctic Ocean is mostly a data void region, so the values are interpolated from surrounding stations. As a result, uncertainty is not uniform.

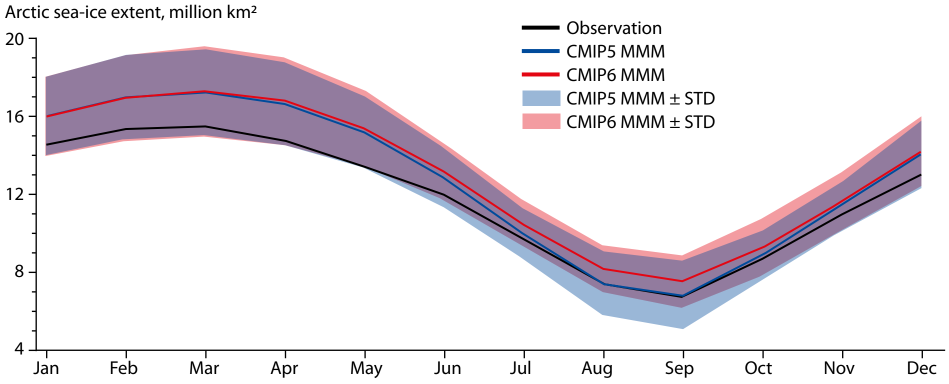

Figure 3.2 Climatology of Arctic sea-ice extent based on University of Bremen satellite retrieval and CMIP5 and CMIP6 multi-model means (MMMs) for the period 1979–2005. Only one member from each model is included in the analysis. Shading shows the range of one standard deviation for CMIP5 and CMIP6. Adapted from Shu et al. (2020).

3.3 Projections of future climate: CMIP6 update

3.3.1 Models and emission scenarios

Climate models are the main tools available for simulating past and future responses of the climate system to external forcing. The models used in climate research range from simple energy balance models to complex Earth System Models (ESMs) requiring high-performance computers (Holland et al., 2008). The choice of model depends on the scientific questions being addressed (Held, 2005; Collins et al., 2006). ESMs are the current state-of-the-art models, and expand on Atmosphere-Ocean General Circulation Models (AOGCMs) to include representation of various biogeochemical cycles such as those involved in the carbon cycle, the sulfur cycle, or ozone (Flato, 2011). Over the years, the modeling community has made tremendous improvements. Among others, these improvements include numerical schemes, physical processes, and model structure. The GCMs, such as those involved in the work of the IPCC, undergo continuous development, coordinated by the WCRP through the CMIP. There have been several generations of CMIP, involving increasingly advanced models, often referred to as CMIP1 (1995) to CMIP5 (2013). The number of models participating in the CMIPs has increased markedly: from 24 in CMIP3 (IPCC, 2007) to 39 in CMIP5 (IPCC, 2013). By summer 2020, more than 70 models had submitted simulation results to the Earth System Grid Federation (ESGF) portal, but not all of them submitted all required variables for all emission scenarios. A core group of 35 models is used in the present analysis whenever possible. Models with at least three future projections provided by the end of March 2020 were selected. Model names and the corresponding country and institutions are listed in Table 3.1.

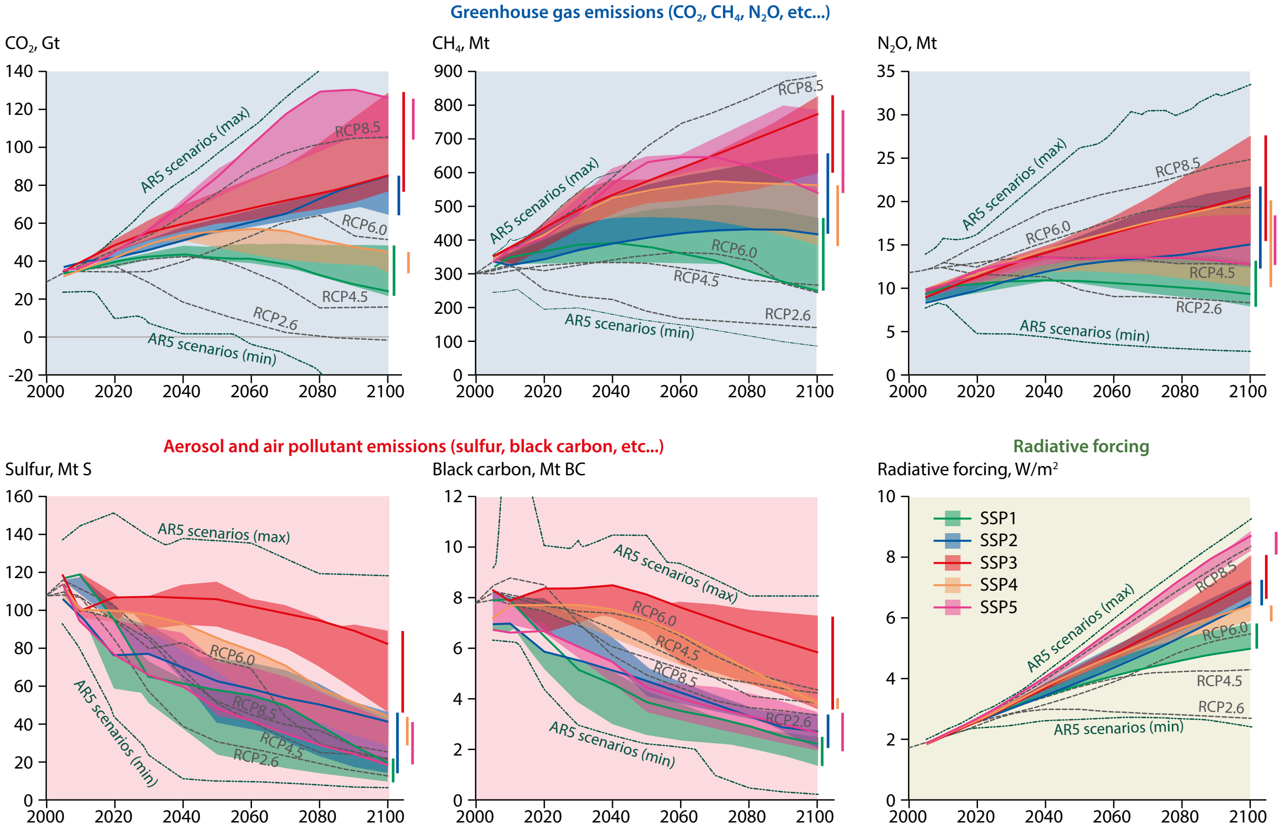

Figure 3.3 Global emissions and global average change in radiative forcing. SSP baseline marker scenarios (and ranges of SSP non-marker baseline scenarios) are compared to the RCPs (van Vuuren et al., 2011) and the full range of the IPCC AR5 scenarios (Clarke et al., 2014). Adapted from Riahi et al. (2017).

Table 3.1 Models generating simulation results used in the present analysis. See Appendix 3.1 for the fill name of each institution.

No	Model ID	Country	Institution ID	Atmosphere model	Sea-ice model	Ocean model
1	ACCESS-CM2	Australia	CSIRO-ARCCSS	MetUM-HadGEM3-GA7.1	CICE5.1.2	GFDL-MOM5
2	ACCESS-ESM1-5	Australia	CSIRO	HadGAM2	CICE4.1	ACCESS-OM2
3	AWI-CM-1-1-MR	Germany	AWI	ECHAM6.3.04p1	FESOM 1.4	FESOM 1.4
4	BCC-CSM2-MR	China	BCC	BCC_AGCM3_MR	SIS2	MOM4
5	CAMS-CSM1-0	China	CAMS	ECHAM5_CAMS	SIS 1.0	MOM4
6	CESM2-WACCM	USA	NCAR	CAM6	CICE5.1	POP2
7	CESM2	USA	NCAR	CAM6	CICE5.1	POP2
8	CNRM-CM6-1-HR	France	CNRM-CERFACS	Arpege 6.3	Gelato 6.1	NEMO3.6
9	CNRM-CM6-1	France	CNRM-CERFACS	Arpege 6.3	Gelato 6.1	NEMO3.6
10	CNRM-ESM2-1	France	CNRM-CERFACS	Arpege 6.3	Gelato 6.1	NEMO3.6
11	CanESM5-CanOE	Canada	CCCma	CanAM5	LIM2	NEMO3.4.1
12	CanESM5	Canada	CCCma	CanAM5	LIM2	NEMO3.4.1
13	EC-Earth3-Veg	Europe-wide	EC-Earth-Consortium	IFS cy36r4	LIM3	NEMO3.6
14	EC-Earth3	Europe-wide	EC-Earth-Consortium	IFS cy36r4	LIM3	NEMO3.6
15	FGOALS-f3-L	China	CAS	FAMIL2.2	CICE4.0	LICOM3.0
16	FGOALS-g3	China	CAS	GAMIL2	CICE4.0	LICOM3.0
17	FIO-ESM-2-0	China	FIO-QLNM	CAM4	CICE4.0	POP2-W
18	GFDL-CM4[a]	USA	NOAA-GFDL	GFDL-AM4.0.1	GFDL-SIM4p25	GFDL-OM4p25
19	GFDL-ESM4	USA	NOAA-GFDL	GFDL-AM4.1	GFDL-SIM4p5	GFDL-OM4p5
20	GISS-E2-1-G	USA	NASA-GISS	GISS-E2.1	GISS SI	GISS Ocean
21	HadGEM3-GC31-LL	UK	MOHC	MetUM-HadGEM3-GA7.1	CICE-HadGEM3-GSI8	NEMO-HadGEM3-GO6.0
22	INM-CM4-8	Russia	INM	INM-AM4-8	INM-ICE1	INM-OM5
23	INM-CM5-0	Russia	INM	INM-AM5-0	INM-ICE1	INM-OM5
24	IPSL-CM6A-LR	France	IPSL	LMDZ	NEMO-LIM3	NEMO-OPA
25	KACE-1-0-G	Korea	NIMS-KMA	MetUM-HadGEM3-GA7.1	CICE-HadGEM3-GSI8	
26	MCM-UA-1-0	USA	UA	R30L14	Thermodynamic ice model	
27	MIROC-ES2L	Japan	MIROC	CCSR AGCM	COCO4.9	COCO4.9
28	MIROC6	Japan	MIROC	CCSR AGCM	COCO4.9	COCO4.9
29	MPI-ESM1-2-HR	Germany	MPI-M	ECHAM6.3	Sea ice in MPIOM	MPIOM1.63
30	MPI-ESM1-2-LR	Germany	MPI-M	ECHAM6.3	Sea ice in MPIOM	MPIOM1.63
31	MRI-ESM2-0	Japan	MRI	MRI-AGCM3.5	MRI.COM4.4	MRI.COM4.4
32	NESM3	China	NUIST	ECHAM v6.3	CICE4.1	NEMO v3.4
33	NorESM2-LM	Norway	NCC	CAM-OSLO	CICE	MICOM
34	NorESM2-MM	Norway	NCC	CAM-OSLO	CICE	MICOM
35	UKESM1-0-LL	UK	MOHC	MetUM-HadGEM3-GA7.1	CICE-HadGEM3-GSI8	NEMO-HadGEM3-GO6.0

[a] GFDL-CM4 model is only used in the ocean analysis.

Future projections of climate models are driven by changes in external forcings. The projection results assessed in this chapter are mainly based on a new range of scenarios: the SSPs used in CMIP6. There are differences in the current SSPs compared to those used in CMIP5 emission scenarios, which were referred to as 'Representative Concentration Pathways' (RCPs). The new SSP scenarios are based on the forcing levels of the previous CMIP5 RCPs as well as spanning the same range, but differ by filling critical gaps for intermediate forcing levels in terms of short-lived species and land use (Eyring et al., 2016). The SSPs are part of a new scenario framework, established by the climate change research community to aid the integrated analysis of future climate impacts, vulnerabilities, adaptation, and mitigation (Riahi, et al., 2017). An important feature of the SSPs is that they cover a wider range of air pollutant emissions than the RCPs (Rao et al., 2017). In the SSP labels, the first number refers to the assumed shared socio-economic pathway, while the second refers to the approximate global effective radiative forcing by 2100. The assumed greenhouse gas emission levels and the radiative forcings applied to models under different SSPs are illustrated in Figure 3.3. The present study focuses on four scenarios: SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5. One of the reasons for this selection is so that the maximum number of models could be used.

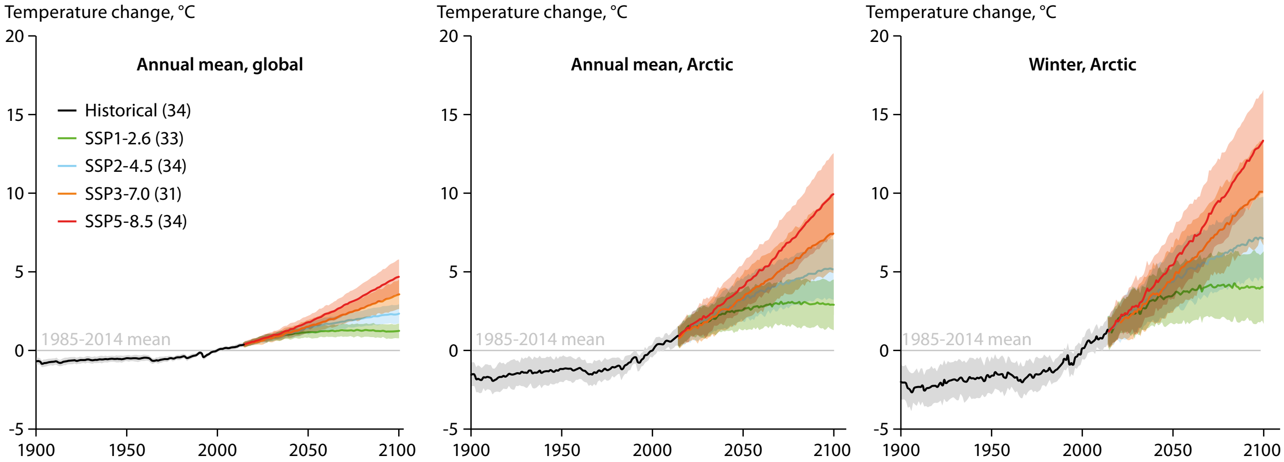

Figure 3.4 Annual mean surface air temperature anomalies averaged over the global and Arctic (60–90°N) domains, and Arctic winter season. The ensemble means (colored lines) and ensemble spread (shading) were based on inputs from several models as indicated for each scenario. The 30-year baseline period was 1985–2014.

3.3.2 Surface air temperature

The CMIP6 GCMs project that the amplified Arctic warming will be more than twice that of the global mean. Amplified warming will continue under all four emission scenarios, with even stronger warming in winter (Figure 3.4), and is consistent with findings based on CMIP5 models (Overland et al., 2014; Overland and Wang, 2018). Ongoing Arctic amplification, with the strongest warming taking place in winter, is likely to be a robust result since this has already been observed in recent decades (see Chapter 2). By the end of the 21st century, the magnitude of the multi-model mean warming under the highest scenario (SSP5-8.5) compared to the 1985–2014 mean is 4.7°C for the global annual mean, 10.0°C for the Arctic annual mean and 13.4°C for the Arctic winter mean. Under the lowest scenario (SSP1-2.6), the corresponding values are 1.4°C, 3.3°C, and 4.5°C, respectively.

The Arctic warming is not uniformly distributed (Figure 3.5). The strongest warming is projected to occur regardless of scenario in the center of the Arctic Ocean where the present-day conditions are influenced by the presence of sea ice. By mid-century (2041–2060), some regions can experience up to 11°C warming in the winter as projected by the CMIP6 models under scenario SSP5-8.5. The stronger warming over the ice-covered parts of the ocean is connected to the disappearance of the sea ice, because this changes the air-sea energy and humidity fluxes (AMAP, 2017b).

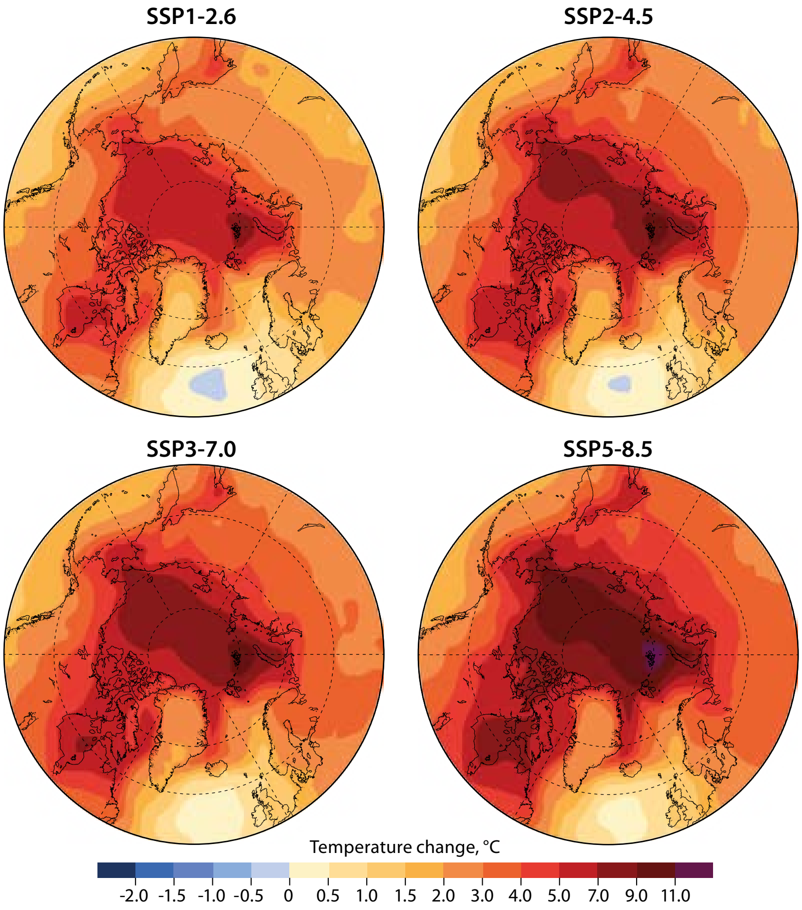

Figure 3.5 Projected temperature change based on the ensemble mean of 34 models for winter (DJF) averaged over 2041–2060. The baseline period is 1985–2014.

3.3.3 Sea ice

In recent decades, the Arctic sea-ice area has decreased rapidly, and a signal of forced sea-ice retreat has clearly emerged from the background noise of year-to-year variability (Stroeve and Notz, 2018). Because of this, the ability of climate models to plausibly simulate the observed changes in the Arctic sea-ice coverage has become a central measure of model performance in Arctic-focused climate model intercomparisons (e.g., Stroeve et al., 2007, 2012, 2014; Wang and Overland, 2009, 2012; Massonnet et al., 2012; Koenigk et al., 2014; Shu et al., 2015; Melia et al., 2016; Olonscheck and Notz, 2017). Two ice-associated variables are used here to characterize the changing sea-ice conditions: sea-ice extent and sea-ice thickness. Sea-ice extent is defined as the total area of all grid cells with at least 15% sea-ice concentration. A past study suggested that sea-ice extent is a strongly grid-dependent non-linear quantity, making it difficult to make a meaningful comparison between model output and satellite observations (Notz, 2014). The observational spread across different satellite products is also smaller for trends in sea-ice area than it is for trends in sea-ice extent (Comiso et al., 2017). Sea-ice extent is used in this study to be consistent with previous reports (Stroeve et al., 2012; Wang and Overland, 2012; IPCC, 2013; Shu et al., 2015).

Figure 3.6 shows the winter (March) and summer (September) sea-ice extent as projected by CMIP6 models (number of models used in the ensemble mean is noted in each plot). In terms of the multi-model ensemble mean, the models slightly overestimate the mean March sea-ice extent but capture the March and September decline since the 1980s well. Consistent with the projected radiative forcings, the March and September sea-ice extent is projected to stabilize under the SSP1-2.6 scenario by the end of the 21st century, while under the other scenarios, sea-ice extent continues to decline. For March, the change in projected sea-ice extent appears relatively sensitive to the forcing scenario. For September, with the exception of the SSP1-2.6 scenario (green curve), the multi-model mean shows the Arctic to become ice free between the 2060s and 2100 (when sea-ice extent is below 1 million km^2, as shown by the thin gray line in the right panel of Figure 3.6; Wang and Overland, 2009) under the SSP2-4.5, SSP3-7.0, and SSP5-8.5 scenarios. The Arctic Ocean is projected to be ice-free in the 2060s under the SSP5-8.5 scenario according to the CMIP6 multi-model ensemble mean. However, in terms of individual models, Notz et al. (2020) found that even under the SSP1-2.6 scenario, the vast majority of the CMIP6 models show an ice-free Arctic in September for the first time before the year 2050.

In addition to the temporal evolution of sea-ice area, Notz et al. (2020) also investigated the sensitivity of sea-ice loss to a given emission of anthropogenic carbon dioxide (CO_2) and to a given amount of global warming. They found that CMIP6 models generally perform better than earlier CMIP experiments.

The spatial pattern of changes in sea-ice concentration is explored in Figure 3.7. This shows that the projected reduction in summer sea-ice extent is mainly due to the reductions in sea-ice cover in the Chukchi Sea, Beaufort Sea, East Siberian Sea, and Kara Sea. At present, most of the central Arctic Ocean is covered by ice of nearly 100% concentration. By the mid-21st century (2041–2060), the southern part of the East Siberian Sea, Chukchi Sea, and Beaufort Sea will be open water in summer. The mean sea-ice concentration will also be less than 50% for most of the rest of the Arctic Ocean. By the end of the 21st century (2081–2100) not only will the area of ice cover be reduced but also its concentration. At the same time, the quality of the sea ice, which is characterized by its thickness, will also be reduced. Figure 3.8 shows the current (1985–2014) and projected ice thickness based on the multi-model means. At present, the central Arctic is covered mostly by ice more than 2 m thick. However, by mid-century (average of 2041–2060), this will be replaced by ice of around 1.5 m thickness over most of the Arctic domain, even under the scenario with the lowest emissions (SSP1-2.6). This is concerning, since thinner ice is prone to melt and rapid retreat. Models with an observational estimate are not compared here due to substantial uncertainties for reanalyzed and observed estimates of Arctic sea-ice thickness (e.g., Zygmuntowska et al., 2014; Chevallier et al., 2017; Bunzel et al., 2018).

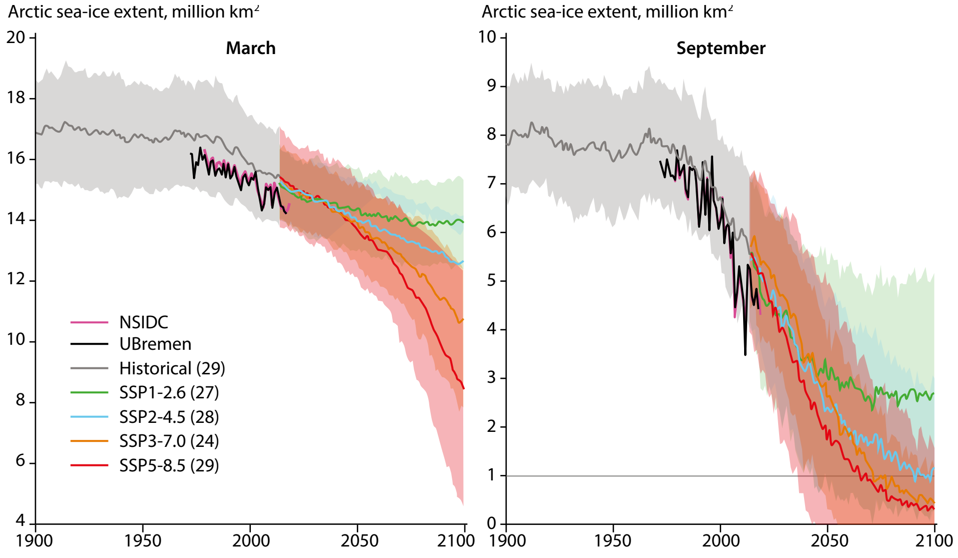

Figure 3.6 Time series of March and September sea-ice extent in terms of observations (black from the University of Bremen and pink from NSIDC), and ensemble mean and ensemble spread of CMIP6 models under different emission scenarios. The thin horizontal gray line marks the ice-free condition defined by Wang and Overland (2009).

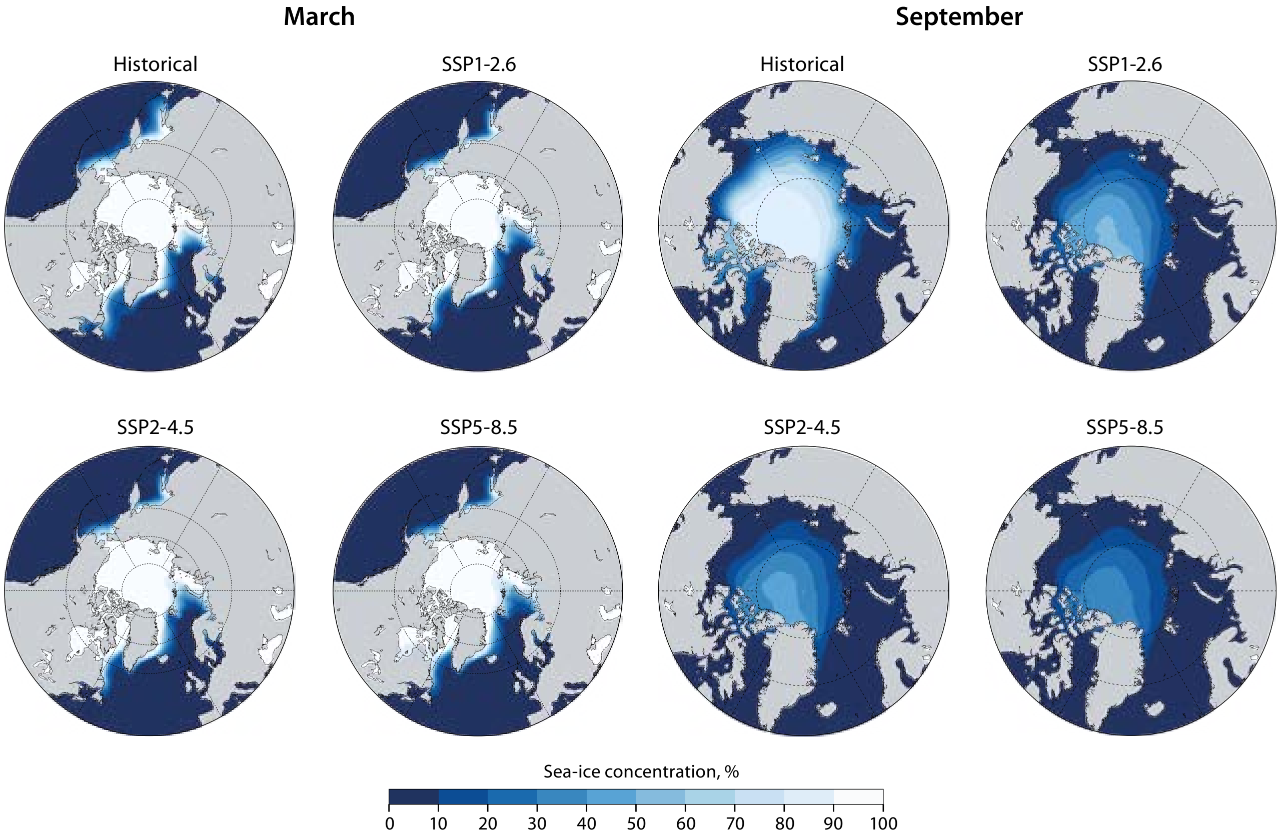

Figure 3.7 CMIP6 multi-model mean for March and September sea-ice concentration averaged over the 2041–2060 period under three (SSP1-2.6, SSP2-4.5, SSP5-8.5) scenarios, and historical simulations for the period 1985–2014.

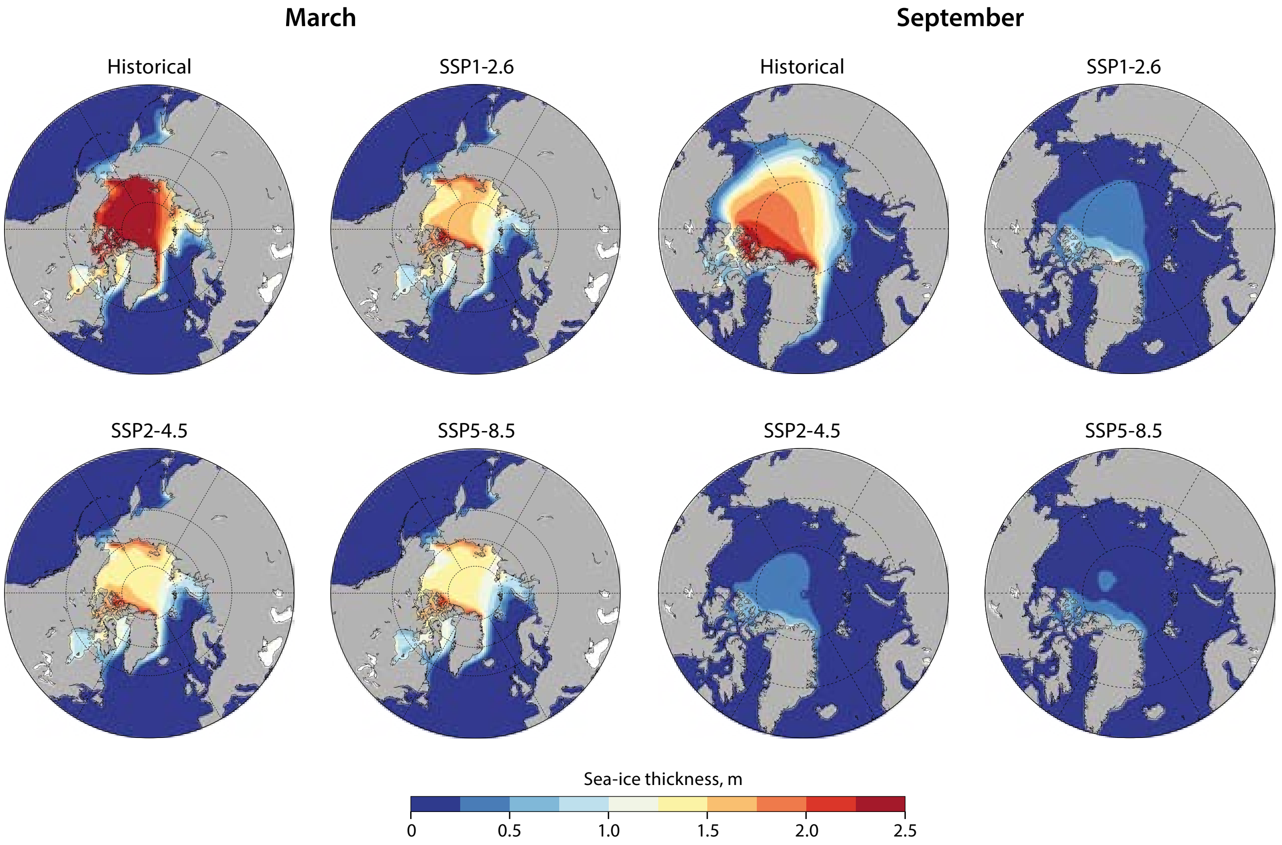

Figure 3.8 CMIP6 multi-model mean for March and September sea-ice thickness averaged over the 2041–2060 period under three (SSP1-2.6, SSP2-4.5, SSP5-8.5) scenarios, and historical simulations for the period 1985–2014.

3.3.4 Precipitation and snow cover

Increases in river discharge data provide indirect evidence for recent increased precipitation in the Arctic (AMAP, 2017b; see also Chapter 4). However, the sparse and uneven distribution of observing stations, together with problems in accurately measuring precipitation in cold windy environments, has made direct evidence of historical precipitation trends less compelling in the Arctic. By contrast, CMIP3- and CMIP5-based projections of Arctic precipitation point robustly to increased Arctic precipitation by the end of the 21st century (IPCC, 2013). Previous CMIP model evaluations also show increased intensities and/or shorter return periods for heavy precipitation events in the Arctic. When expressed as percentage changes, the heaviest precipitation amounts generally increase more than annual mean precipitation (Kharin et al., 2013). The CMIP5 models project increases of 20–30% for the maximum 5-day precipitation amounts within a year over most Arctic land areas by 2081–2100 under the RCP8.5 scenario (Collins et al., 2013).

An aggregation of results from eight CMIP5 models suggests that the 50-year return level of daily precipitation will increase in the high latitudes (Toreti et al., 2013). The regions with consistent results from the eight models include northern Eurasia in winter and the Arctic Ocean in summer. Based on the CMIP5 results, increases in the Arctic, particularly in winter, are also projected for the 20-year return level of daily precipitation (Kharin et al., 2013), very-wet-day precipitation, maximum 5-day precipitation, and the number of days with heavy precipitation (Sillmann et al., 2013). More recently, Kusunoki et al. (2015) examined changes in precipitation intensity projected for the Arctic (67.5–90°N) by a high-resolution (60 km) global atmospheric model. Monotonic increases in the late 21st century were found in the annual mean precipitation, a daily precipitation intensity index, and maximum 5-day precipitation totals averaged over the Arctic.

Landrum and Holland (2020) examined model-derived trends in Arctic precipitation. A key finding from that study, which was based largely on the CMIP5-generation CCSM4 model, was that the partitioning of snow and rain in the Arctic would undergo significant change over the coming decades. This transition from snow to rain has important implications for the winter snowpack and the seasonality of discharge from the major Arctic rivers.

The most comprehensive analysis to date of CMIP6 simulations of snow cover was reported by Mudryk et al. (2020). Their study synthesized information from 21 CMIP6 and 23 CMIP5 models, including their historical simulations and various SSP/RCP projections, together with several sources of observational data on snow extent and snow mass. In their historical simulations of snow extent, the CMIP6 multi-model mean shows a notable improvement over CMIP5 in its reduction of bias in the historical simulations of hemispheric snow cover (Figure 3.9). The bias reduction is especially apparent in the winter. However, the CMIP6 models simulate too much snow mass relative to historical reconstructions, and in some months this positive bias is even larger than in CMIP5. The CMIP6-simulated trends in snow extent and snow mass are negative in all months and slightly larger in magnitude than in CMIP5. The observed trends in snow extent in each calendar month are generally within the corresponding inter-model ranges of the CMIP6 models, but the simulated trends in total snow mass are at the lower end of the observed estimates for the winter months. The CMIP6 models and the observational reconstructions both show the largest negative trends in snow mass during April and May, when snow cover is found primarily in the higher northern latitudes.

An outstanding feature of the CMIP6 model simulations is that, consistent with the CMIP5 results, the spring (March-May) snow extent scales linearly with the global mean surface air temperature. This scaling applies across the historical simulations as well as the various projections: SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5 (Mudryk et al., 2020). For each 1°C increase in global mean surface air temperature, the spring snow extent decreases by approximately 8%. This sensitivity is slightly weaker than the corresponding observed sensitivity of 1.9×10^6 km^2/K with a 95% confidence range of $\pm0.9\times10^6$ km^2/K (Mudryk et al., 2017).

The projected changes in snow cover under the various forcing scenarios do not diverge noticeably until about 2040, or 25 years after the beginning of the projection period. The projections

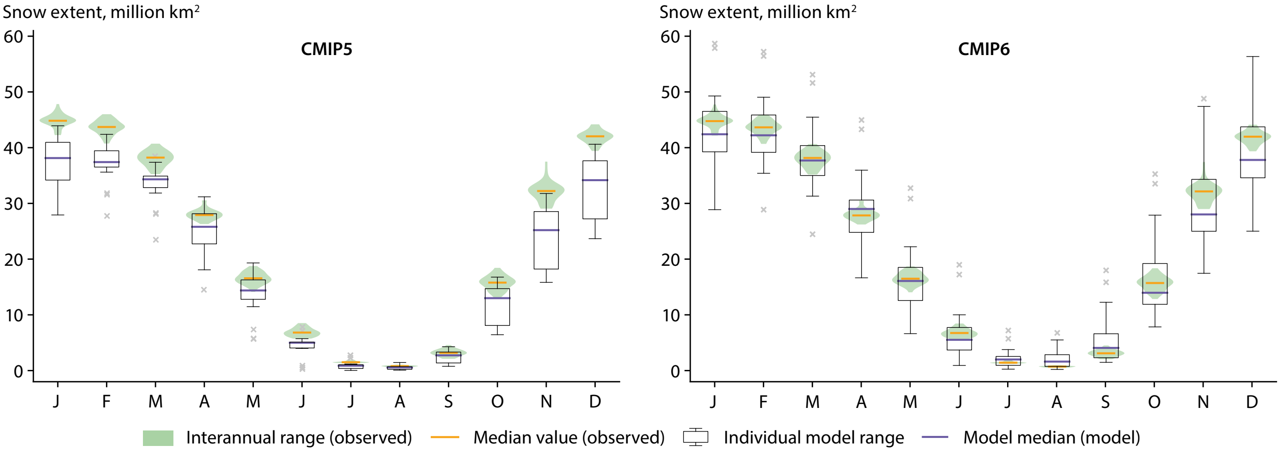

Figure 3.9 Monthly mean Northern Hemisphere snow extent for 1981–2014 as simulated by CMIP5 and CMIP6 models. The graphic shows the observed interannual ranges (and median values), with the box and whiskers representing individual model (first ensemble member) ranges for the 1981–2014 average (and model medians). The crosses each represent individual models that fall outside the 25% to 75% boxed region. Adapted from Mudryk et al. (2020).

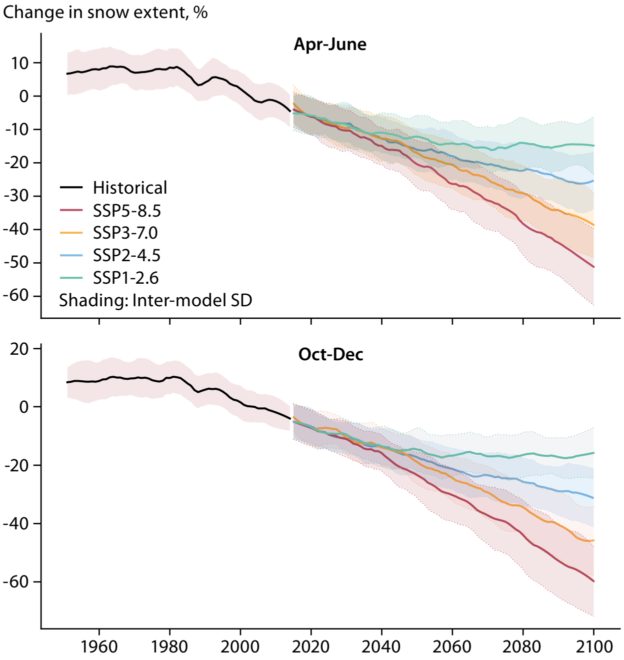

Figure 3.10 Changes in Northern Hemisphere snow extent relative to the 1995–2014 mean for April–June and October–December. The graphic shows multi-model means of first ensemble members of historical and scenario runs, and inter-model standard deviations (adapted from Mudryk et al., 2020).

have some commonality with the sea-ice projections in the sense that the snow extent stabilizes under the SSP1-2.6 scenario but continues to decrease through 2100 under the other scenarios (Figure 3.10). The stabilization under SSP1-2.6 occurs around 2060 at levels that are below the 1995–2014 averages by about 18% in spring and about 20% in autumn for the multi-model means. In contrast, the multi-model mean reduction of snow extent under the SSP5-8.5 scenario is about 55% in spring and 60% in autumn by 2100. At that time, the length of the snow-free season increases by about two months under global warming consistent with SSP5-8.5 (Mudryk et al., 2020, their Fig. 10), with major implications for the Arctic and its ecosystems. In all three seasons with substantial snow cover (autumn, winter, spring), the differences between the SSP1-2.6 and SSP5-8.5 multi-model means is greater than the across-model range of extents by 2100. This result points to the emission scenario as the greatest source of uncertainty in the late-century snow extent.

One of the snow characteristics yet to be fully explored in the CMIP6 simulations is the geographical dependence of the maximum snow mass (snow-water equivalent). In the 2017 SWIPA report, Brown et al.'s synthesis of CMIP5 output showed that the maximum (end-of-winter) snow-water equivalent decreased in most areas but increased in the coldest areas, such as the High Arctic where the effect of increased precipitation outweighs the effect of increased temperature (Brown et al., 2017). While the CMIP6 models are likely to show a similar pattern, the details of the changes in late-winter snow-water equivalent and corresponding changes in snow have not yet been published.

For snow extent, regional and sub-regional conditions show much greater annual variability, with a big impact on ecosystems. Significant decreases in snow extent have occurred in northern high latitudes in late spring and summer (Mudryk et al., 2020), as summarized above. Regional changes in snow extent are further investigated here. In North America (latitude band 60–70°N), snow has regularly disappeared during summer since 2009, a situation completely different to that of the early 2000s. North of 70°N, the decreasing trend in snow extent is more evident in Siberia than North America. The winter maximum snow cover shows no particular trend since the late 1960s. Climate models are now starting to operate at a spatial resolution sufficient to capture more local processes and provide a more realistic view of spatial variability in snow cover, thanks to the High Resolution Model Intercomparison Project (HighResMIP), a new development in the CMIP6 era. To better address these aspects and capabilities, outputs from models participating in the HighResMIP project (Haarsma et al., 2016) are compared here. This focuses on coupled experiments, considering those that are able to realistically capture the complexity of processes and interactions responsible for the snow-cover patterns occurring mainly during the transition from April to July. By May 2020, only four of the 18 models participating in HighResMIP had produced coupled runs for the period 1950–2014 (hist-1950), necessary to assess model performance with respect to observations, and for the period 2015–2050: EC-Earth3P (spatial resolution between 25 and 40 km), CNRM-CM6-1 (resolution about 35 km), CMCC-CM2-HR4 (resolution about 100 km), and CMCC-CM2-VHR4 (resolution about 25 km). Comparisons of model output with observations (NOAA, no date) clearly indicate some ability of these models to capture trends as well as spatial variability (Figure 3.11). It is promising to be able to obtain realistic projections at a resolution of a few tens of kilometers. As shown in Figure 3.11, model-simulated snow extent agrees well with observations in the four regions studied in deep winter (December to March). Agreement between models and observations is reasonably good for October and November, indicating that models are able to capture changes in phenomena delaying the arrival of snow and by producing the shift from solid to liquid precipitation (i.e., liquid rainfalls other than solid snow are simulated by these models). The situation starts to change in April when models begin to show more disagreement with respect to observations and to disagree with each other, showing a typical tendency to overestimate (EC-Earth3, CNRM-CM6-1) or underestimate (CMCC-HR, CMCC-VH) snow cover. Typical differences range between 30% and 50% in April and rise to 50% to 100% in May. The relevance of local mechanisms and of cumulative effects in determining the difficulties models have in reproducing observations is clearly demonstrated by the large increase in annual variability of the differences. In terms of CNRM-CM6-1, for example, the June snow extent exhibits differences that range from 20% in Greenland (Figure 3.11a) to more than 100% in North America (Figure 3.11b) and Siberia (Figure 3.11c). In this respect, EC-Earth3 is much more consistent among the four regions studied.

In northern Siberia (70°-82°N, Figure 3.11d), the difference between different models and between different ensemble members can be four times (from negative 150% to positive 200%).

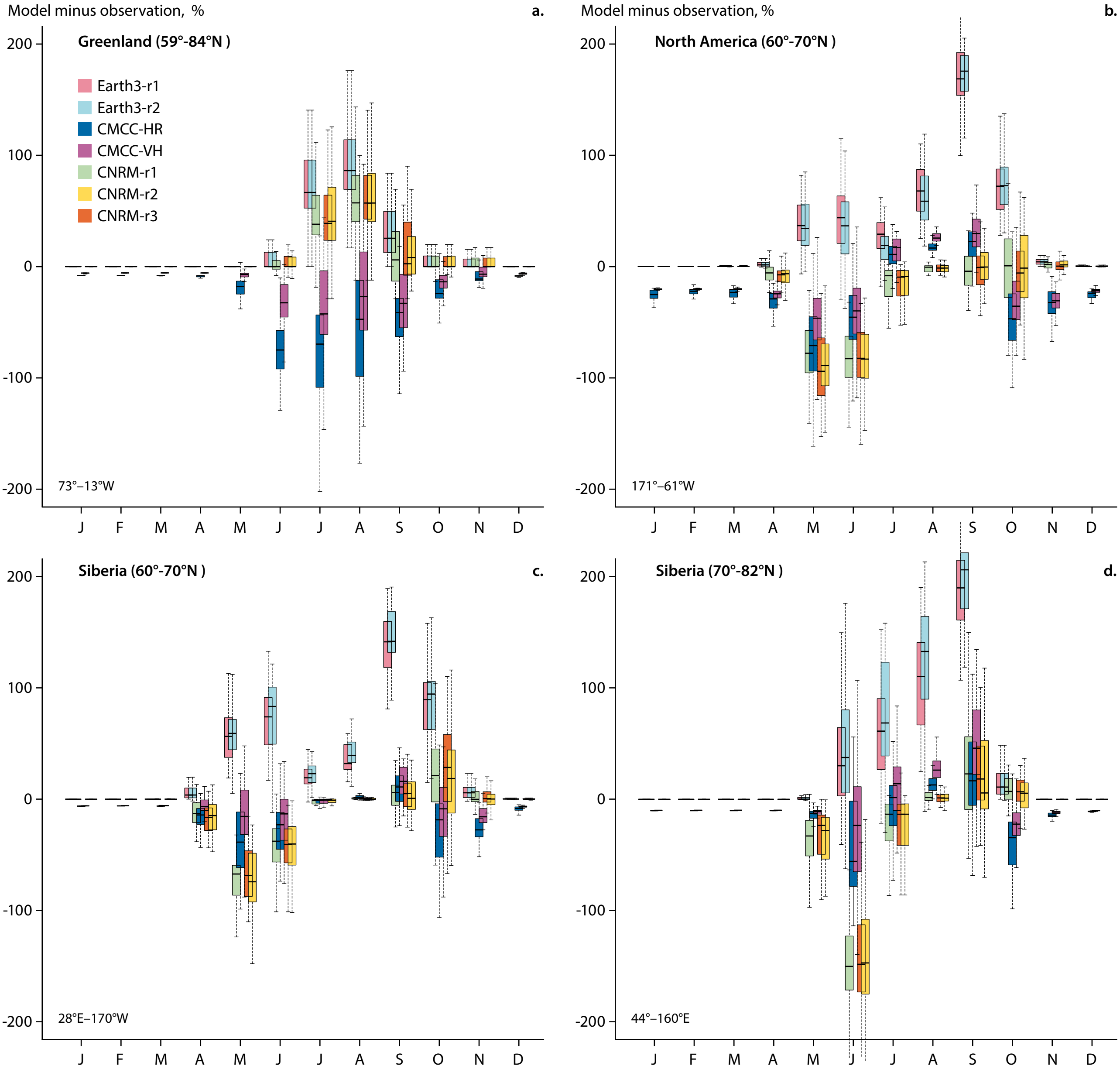

Figure 3.11 Normalized difference in monthly snow-cover extent between observations and CMIP6 models from the HighResMIP experiment in selected regions in the Arctic. Observations are from the NOAA Climate Data Record (www.ncei.noaa.gov/access/metadata/landing-page/bin/iso?id=gov.noaa.ncdc:C00756CDR). Differences are calculated for the 1967–2015 period and then normalized by the 1981–2010 observational mean. The horizontal line in each box shows the median value with the vertical lines showing the 75th and 25th percentile range.

3.3.5 Ocean condition: sea-surface salinity and freshwater content

The Arctic Ocean is a confluence of saline water from the Atlantic Ocean and relatively fresh water from the Pacific Ocean, river runoff, net precipitation and sea-ice melt (Carmack et al., 2016). In a warmer climate, all three freshwater sources might increase after the hydrological cycle is intensified; while sea-ice melting can mediate the spatial distribution of freshwater, it has little impact on overall freshwater storage (Wang et al., 2019). The Atlantic Water influx through Fram Strait and the Barents Sea Opening creates a saline tongue which stretches from the North Atlantic to the Eurasian Basin and reaches the northern Barents-Kara Boundary as shown by the PHC3.0 data (Figure 3.12a). The PHC3.0 data set (Steele et al., 2001) is the hydrological climatology of the Arctic Ocean. It is a merged product of the World Ocean Atlas and Arctic Ocean Atlas, both of which are interpolation data from in-situ observations. The river runoff discharge from Eurasia drains into and accumulates on the Siberian continental shelf, resulting in the low-salinity shelf region. The center of the Beaufort Gyre is also a region of low salinity due to the freshwater accumulation driven by Ekman convergence. The CMIP6 multi-model mean reproduces the dipole pattern (i.e., the saline Atlantic branch and low salinity of the Siberian Shelf), but does not capture the magnitude of the low sea-surface salinity in the Beaufort Gyre. Anomalously positive salinity biases, however, reside in the Beaufort Gyre and the East Siberian and the Kara seas, while the negative anomalous biases indicate that modelled sea-surface salinity in the Eurasian Basin and Barents Sea is too low (Figure 3.12c). An insufficient Atlantic Water invasion into the Arctic Ocean in the models could be a major cause of

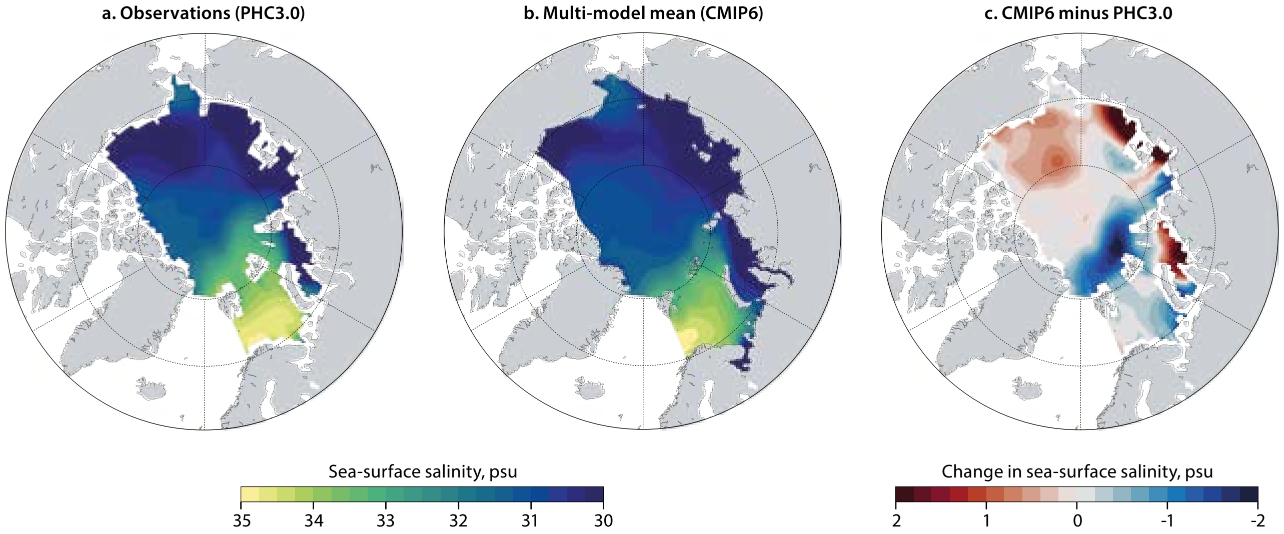

Figure 3.12 Sea-surface salinity of the Arctic Ocean from observations (PHC3.0), the CMIP6 multi-model mean for the period 1995–2014, and the difference between model simulation and PHC3.0 for the same period.

the negative biases on the Eurasian side. Similar salinity biases have been reported in CMIP5 models (Shu et al., 2018).

Impacted by the three-dimensional distribution of salinity, the freshwater content in the upper 250 m of the Arctic Ocean is not uniformly distributed but is inclined to accumulate in the Beaufort Gyre. In the Eurasian Basin where the Atlantic Water brings in saline water, the liquid freshwater content is relatively low (Figure 3.13a). The ensemble mean of the CMIP6 models reproduces the spatial pattern of this freshwater content reasonably well, while overestimating the spatial extent of the Beaufort Gyre (Figure 3.13b). CMIP6 models slightly underestimate the freshwater content of the Beaufort Gyre and East Siberian Sea, but overestimate the freshwater content in other parts of the Arctic Ocean, especially the Eurasian Basin (Figure 3.13c). In correspondence with the negative salinity bias (Figure 3.12c), the positive freshwater content bias can reach 6 m therein. As is documented by the results of the Coordinated Ocean-ice Reference Experiments phase II (CORE-II; Wang et al., 2016), the freshwater content overestimation in the Eurasian Basin seems to be a common problem of ocean climate models.

The strength of the dipole pattern in sea-surface salinity is projected to increase under all future scenarios (Figure 3.14). Compared with present-day conditions, CMIP6 models project that the water around the Canadian Archipelago region and off the eastern Siberian coast will become less saline, while water in the Eurasian Basin and Barents-Kara seas will become more saline by the mid-21st century. The pattern of salinification or freshening does not change much between different future scenarios. An increase in the Atlantic inflow through Fram Strait and across the Barents-Kara Boundary may be the reason for salinification in the Eurasian Basin. In the Amerasian Basin, CMIP6 models project a freshening trend. This salinity reduction can reach -2.0 PSU by the mid-21st century in the areas from the Canadian Arctic Archipelago to the northern coast of Greenland, where the oldest and thickest sea ice is now

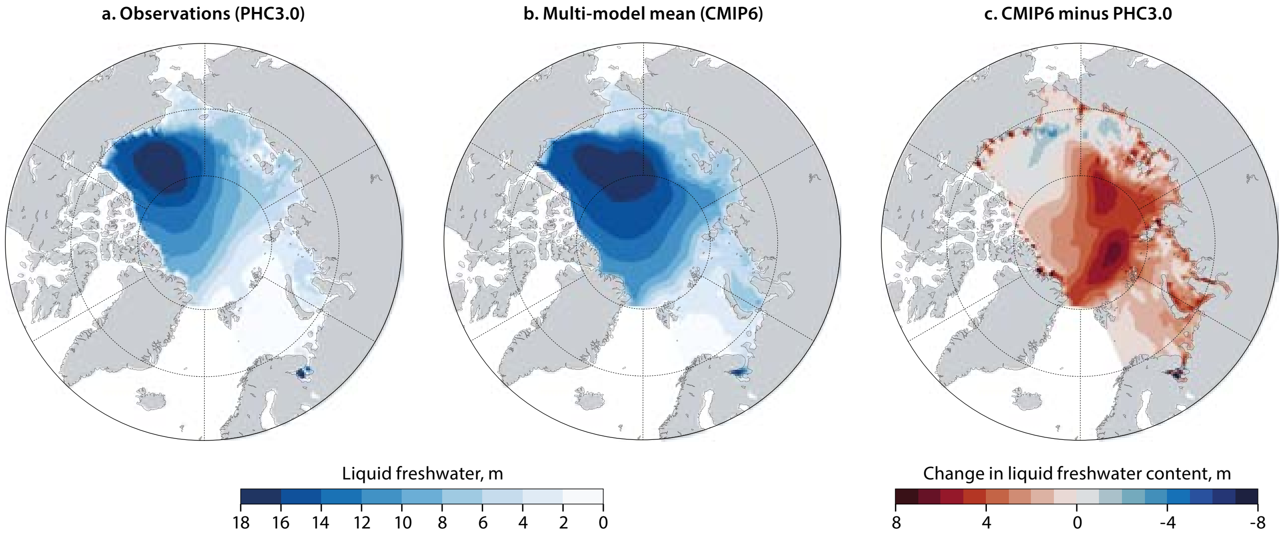

Figure 3.13 Liquid freshwater content in the upper 250 m of the Arctic Ocean from observations (PHC3.0), the CMIP6 multi-model mean for the period 1995–2014, and the difference between model simulation and PHC3.0 for the same period. The freshwater content is calculated by integrating the normalized salinity difference relative to 34.8 psu over depth, from the ocean surface to the depth of 34.8 isohaline or the depth of 250 m, whichever is reached first.

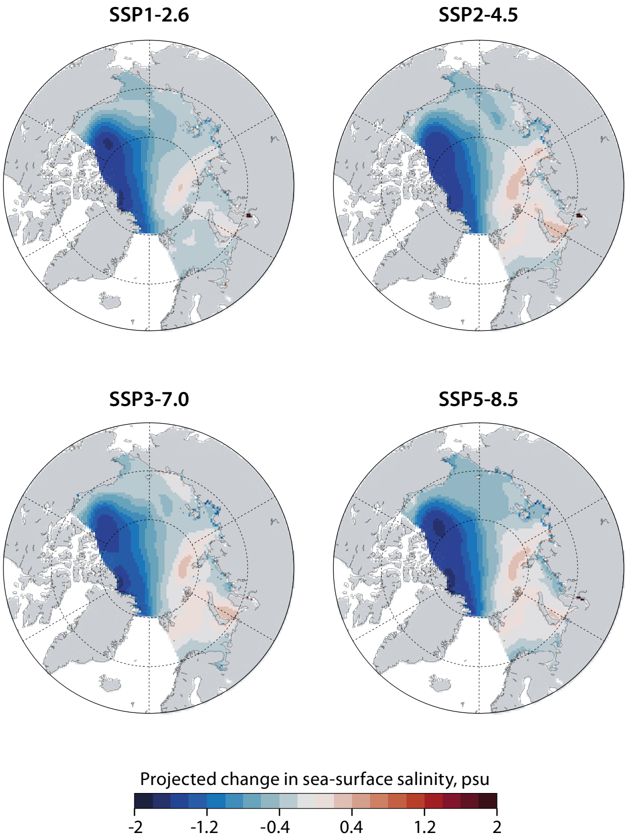

Figure 3.14 Projected sea-surface salinity change for the period 2041–2060 relative to present day (1985–2014) under four SSPs based on the multi-model ensemble mean.

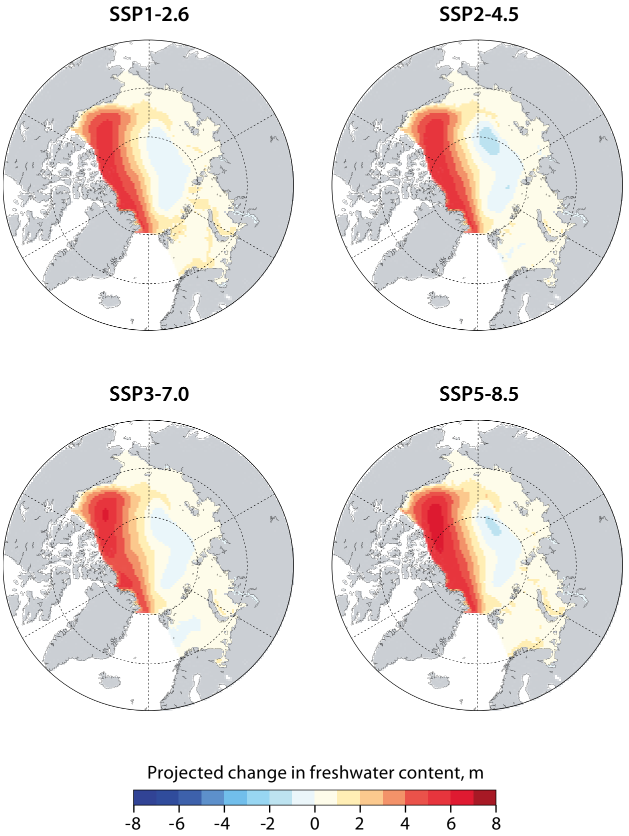

Figure 3.15 Projected change in the freshwater content of the upper 250 m for the period 2041–2060 relative to present day (1985–2014) under four SSPs based on the multi-model ensemble mean.

found. Nevertheless, sea ice in this region is currently losing ice mass at a rate twice that of the Arctic Ocean as a whole (Moore et al., 2019).

The dipole pattern of the change in sea-surface salinity is well reflected by the change in freshwater content (Figure 3.15). The freshwater content in the Amerasian Basin tends to increase while the Eurasian Basin freshwater content is projected to decrease slightly. The Beaufort Gyre will experience the greatest rise in freshwater content because sea-ice reduction in that region favors the momentum transfer from the wind to the ocean, thus accelerating the ocean circulation and increasing the Ekman convergence. The increase in the freshwater content can reach 6–8 m in the Beaufort Gyre. In the Canadian Arctic Archipelago, the rate of increase in freshwater content is also high and can be attributed to accelerated sea-ice melting from SSP1-2.6 to SSP5-8.5. Worth noting is the freshening in the Barents-Kara seas and around the Eurasian slope. In these shelf regions, the freshwater content is projected to rise more under higher emission scenarios than lower emission scenarios.

3.3.6 Arctic climate projected under the Paris Agreement

3.3.6.1 Introduction and methodology

Under the Paris Agreement, which was adopted by consensus by 196 state parties in 2015, nations agreed to “Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels” (United Nations, 2015). This section describes Arctic climate change as projected under a 1.5°C global warming (a level consistent with the Paris Agreement) and a 2.0°C global warming (a level that would exceed that agreed under the Paris Agreement). A third level of global mean warming often considered in the context of the Paris Agreement is 3.0°C, because that is the expected warming by 2100 under current emission reduction commitments to support the Agreement (Rogelj et al., 2016).

The issue of global mean temperature thresholds is complicated by uncertainties in the estimate of historical global warming, partly due to the uneven sampling of temperatures from the Earth’s surface (Benestad et al., 2019). Obtaining projections consistent with the Paris Agreement is also complicated by the typical climate model simulations, such as the CMIP6 simulations discussed in previous sections, not being explicitly designed to meet these temperature constraints, plus the uncertainties associated with emission scenarios. Instead, and as discussed in Section 3.3.2, they follow well-defined emission scenarios which yield varying global mean temperature responses, depending on the model’s climate sensitivity (Mitchell et al., 2016). One of the most common approaches for generating model projections consistent with the targets of the Paris Agreement is to sample climate projections in the transient warming simulations around the time that global mean temperatures reach 1.5°C or 2.0°C above pre-industrial levels (James et al., 2017; IPCC, 2018). A caveat of this approach is that this time-sampling methodology has limited value for providing projections under stabilized global mean temperatures, the target climate state under the Paris

Agreement. Systems with long memory, such as the ocean and cryosphere, may continue to change long after global mean temperatures have stabilized. To address this issue, this study also considers large initial-condition ensembles performed with a single CMIP5 model – the Canadian Earth System Model version 2 (CanESM2) – which were specifically designed to stabilize around 1.5°C and 2.0°C global warming under the RCP8.5 emission scenario (Sigmond et al., 2018).

3.3.6.2 Surface air temperature

Applying the time sampling methodology to CMIP6 transient warming simulations, Figure 3.16 shows the surface air temperature projections under global mean warming of 1.5°C and 2.0°C in CMIP6 models. The patterns of projected surface air temperature under global mean warming of 1.5°C and 2.0°C are similar to those of historical trends (Figure 3.1a), with stronger warming over the Arctic than the mid-latitudes, and stronger warming over the ocean than the land. The CanESM2 large ensemble stabilization simulations show that under stabilized warming, the amplitude of the Arctic mean warming does not undergo large changes, but instead remains fairly stable at roughly twice the global mean warming (Figure 3.16c). More regionally, on the other hand, these simulations indicate that after global warming stabilizes, the North Atlantic surface temperature will continue to rise for about 150 years, which is related to increased northward ocean heat transport due a strengthening Atlantic Meridional Overturning Circulation (Sigmond et al., 2020).

3.3.6.3 Sea ice

Based on transient warming simulations with CMIP5 models, Screen and Williamson (2017) found that the probability of experiencing at least one ice-free September prior to reaching 1.5°C global warming is extremely unlikely, whereas this probability increases to 1-in-3 prior to reaching 2.0°C global warming. As Screen and Williamson (2017) considered transient warming simulations that eventually exceeded the 1.5°C and 2.0°C thresholds, they were not

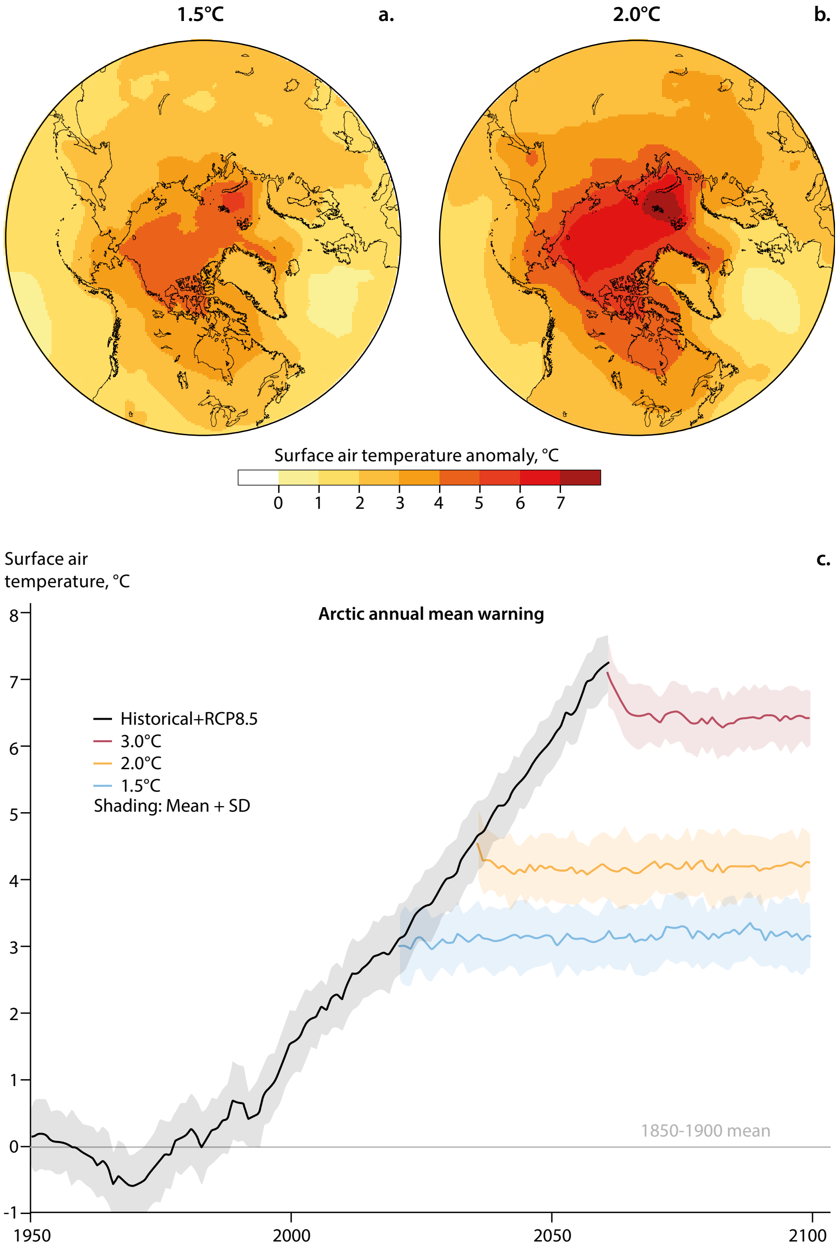

Figure 3.16 The multi-model mean of the annual mean surface air temperature anomaly relative to 1850–1900 in the first year that global warming reaches 1.5°C and 2.0°C in the CMIP6 SSP2-4.5 simulations. The graphic also shows time series of annual mean Arctic surface air temperature in a large initial condition ensemble of simulations that stabilize around 1.5°C, 2.0°C, and 3.0°C global warming, and the transient warming simulations (forced with historical + RCP8.5 scenario forcing) from which they branch off. Lines and shading represent the 50 ensembles mean and the mean ± one standard deviation, respectively.

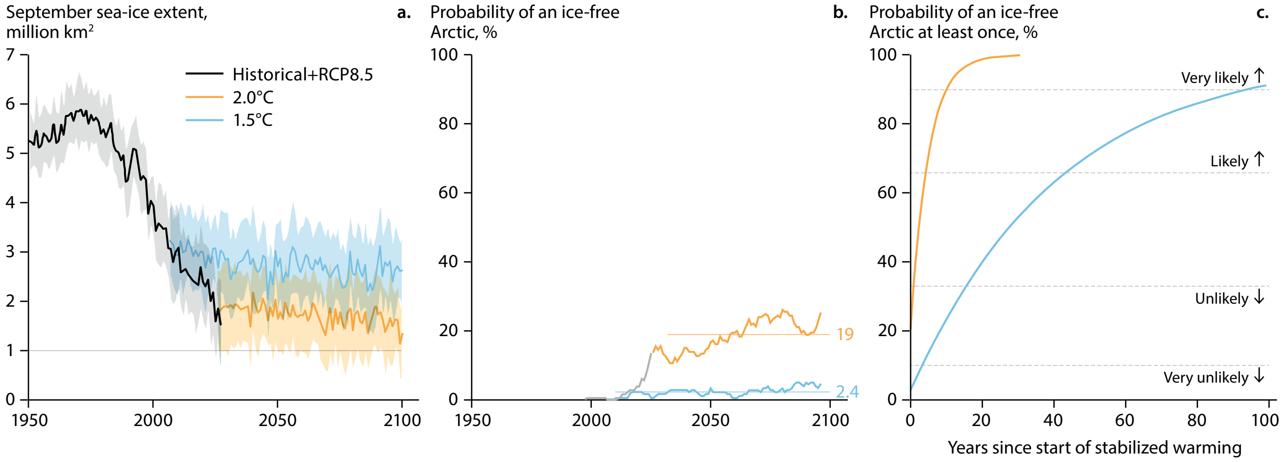

Figure 3.17 This graphic is as for the lower part of Figure 3.16 but shows September sea-ice extent, the probability of an ice-free Arctic in a given year with an 11-year running mean applied, and the probability of reaching an ice-free Arctic at least once as a function of years since global mean temperature stabilization. The thin horizontal gray line in the left panel shows the ice-free condition defined by Wang and Overland (2009). Adapted from Sigmond et al. (2018) and Screen (2018).

able to determine how this probability would evolve under an emission scenario consistent with the Paris Agreement that aims for a stabilized global mean temperature. Jahn (2018) and Sigmond et al. (2018) addressed this question with bias-corrected simulations that stabilized around 1.5°C or 2.0°C of global mean temperature warming. After global mean temperature warming stabilization, Sigmond et al. (2018) found that September sea-ice extent remains fairly constant (Figure 3.17a). Figure 3.17b shows the fraction of ensemble members with sea-ice extent dropping below 1 million km^2, which represents the probability of an ice-free summer in the Arctic in a given year (Wang and Overland, 2009). Sigmond et al. (2018) and Jahn (2018) found this ice-free probability to be an order of magnitude smaller for the 1.5°C scenario (~2% in both studies) compared to the 2.0°C scenario (19% for Sigmond et al., 2018 and Figure 3.17b, and 34% for Jahn, 2018). The chance of reaching an ice-free Arctic at least once increases with time. Based on the results of Sigmond et al. (2018) and Jahn (2018), the simple statistical model of Screen (2018) showed that even under 1.5°C warming, the Arctic is very likely (p>90%) to experience at least one ice-free summer after 100 years of stabilized warming. Under a 2.0°C stabilized warming, only 10 years of the new state are required for the probability of experiencing an ice-free summer in the Arctic to become very high (Figure 3.17c). Sigmond et al. (2018) found that under a 3.0°C global warming, every Arctic summer is expected to be ice-free.

3.3.7 What's new – two generations of climate simulations

Since CMIP5 (Taylor et al., 2012), further development has led to a new generation of GCMs and ESMs, known as CMIP6 (Eyring et al., 2016). There is also a difference between the more traditional GCMs and ESMs in that the latter also incorporate the carbon cycle, aiming to simulate the exchange of carbon between air, sea, and land. The term GCM is used here when referring to both, as no distinction is made between the coupled atmosphere-ocean circulation models and the ESMs. Both can also include additional aspects such as effects connected to chemistry, hydrology, the cryosphere and vegetation.

The different generations of GCMs have many aspects in common, such as the equations of the underlying physics and typically the same core design. This core design could be shared between different models from different modeling centers, which differ in terms of making different choices for representing different aspects. While some models contributed to CMIP from different institutions are indeed variants of the same model, many different dynamic cores are used that have a long history and independent development. This is also true for the components of models. One example, shown by Wang and Overland (2015), is that there were only five sea-ice models and their variations used in the 12 coupled models they selected that showed good fidelity to the observed mean and seasonal cycle of Arctic sea-ice extent. The GCMs also include several parameterization schemes that represent the effect of unresolved small-scale processes and conditions such as clouds and the boundary layer. Typically, subsequent generations of GCMs include more sophisticated parameterization schemes and attempt to capture more processes, and because of growing computational capacity, tend to have higher spatial resolution and more vertical layers.

CMIP6 also embraces a more federated structure with a range of CMIP-endorsed model intercomparison projects (MIPs) in addition to the core DECK (Diagnostic, Evaluation and Characterization of Klima) runs. An overview of CMIP5 GCMs indicates that the spatial resolution of the CMIP5 atmospheric models ranged from T42 (2.8°×2.8°) to T159 (0.75°×0.75°), and the more recent GCMs in CMIP6 available for this assessment show comparable and improved spatial resolutions, especially those in the HighResMIP, as discussed in Section 3.3.4.

One important aspect determining our capability to provide a representative outlook on potential projected outcomes concerning climate change is the ensemble size and number of models in CMIP5 and CMIP6. Spatial resolution is also an important consideration, and there is a trade-off between large ensembles with coarse models or a smaller number of models with higher spatial resolution, due to the high demand for computational resources (Benestad et al., 2017). While new simulations are emerging from the CMIP6 phase, CMIP5 has closed and comprises 37 different GCMs (including different resolutions) and more than 100 runs for the respective emission scenarios. Only the models available at summer 2020 are included in the following discussion.

There have been reports suggesting a change in climate sensitivity from CMIP5 to CMIP6, and Zelinka et al. (2020) reported a tendency of stronger positive cloud feedback in the more recent CMIP6 generation, which they attributed to decreased extratropical low cloud coverage and albedo. This decrease has led to substantially increased effective climate sensitivity (ECS, a hypothetical value of global warming at equilibrium for a doubling of CO_2). They examined 27 recent GCMs from CMIP6 and found a range of 1.8–5.6 K warming in the global mean due to a doubling of CO_2, of which ten exceeded 4.5 K. In the CMIP5 models, this range was 2.1–4.7 K. In other words, a more advanced representation of clouds in the CMIP6 GCMs has introduced a weaker response than before of extratropical low cloud cover and water content to unforced variations in surface temperature. This effect was mainly found in the Southern Hemisphere mid-latitudes, and the effect on climate sensitivity is an estimate on the global scale. One question is how these differences translate to the Arctic. Meehl et al. (2020) also reported that the range of ECS in the CMIP6 generation of models is the largest of any generation of models dating back to the 1990s. Meanwhile, the range in transient climate response (TCR, the surface temperature warming around the time of CO_2 doubling in a 1% per year CO_2 increase simulation) for the CMIP6 models of 1.7°C (1.3°C to 3.0°C) is only slightly larger than for the CMIP3 and CMIP5 models. Flynn and Mauritsen (2020) found that in the CMIP6 models, 5 out of 25 models have ECS values exceeding 5 K. Precise definition and estimation of ECS continues to challenge model intercomparison (Dunne et al., 2020).

Seneviratne and Hauser (2020) found that the regional climate sensitivity of climate extremes (extreme temperatures and heavy precipitation) was very similar in CMIP5 and CMIP6, unlike global climate sensitivity. Regional climate sensitivity in the ESMs is defined as the regional responses as a function of global warming (Seneviratne et al., 2016, 2018; Wartenburger et al., 2017). Seneviratne and Hauser (2020) reported that the model spread in regional climate sensitivity in CMIP6 contributes more to the uncertainty of projected extremes than global climate sensitivity, and argued for the need to consider regional climate sensitivity as a distinct feature of ESMs and a key determinant of projected regional impacts, which is largely independent of the models' response in global climate sensitivity.

The tool GCMeval (Parding et al., 2020; https://gcmeval.met.no) enables a comparison between the projected changes in temperature and precipitation over the Arctic (60–90°N) for the period 2071–2100 (Figure 3.18) and an evaluation of the models involved. Although the emission scenarios differ, there is some correspondence between respective RCP and SSP. Figure 3.18 shows a comparison between projected annual temperature and precipitation for the Arctic region from the RCP8.5 CMIP5 ensemble and the SSP5-8.5 CMIP6 ensemble. As with global climate sensitivity, the CMIP6 models exhibit a wider scatter than CMIP5 that extends to higher values for both temperature and precipitation. A comparison between Arctic temperature projections for different emission scenarios shows that the SSP2-4.5 scenario gives a range that matches the lower limit of RCP4.5 that was most commonly produced in the past but also extends to greater values in the upper bound (data not shown).

Compared with the ensemble mean of 49 CMIP5 models, the newer group of CMIP6 models presents very similar results in simulating sea-ice cover, especially in the winter sea-ice extent. In summer, the ensemble mean of sea-ice extent climatology is slightly higher in CMIP6 models than CMIP5 models relative to the satellite retrievals (Figure 3.2, and Shu et al., 2020). Notz et al. (2020) found that over the period 1979–2014, the CMIP6 multi-model ensemble mean provides a more realistic estimate of the sensitivity of September Arctic sea-ice area to a given amount of anthropogenic CO_2 emissions and to a given amount of global warming, compared with earlier CMIP experiments.

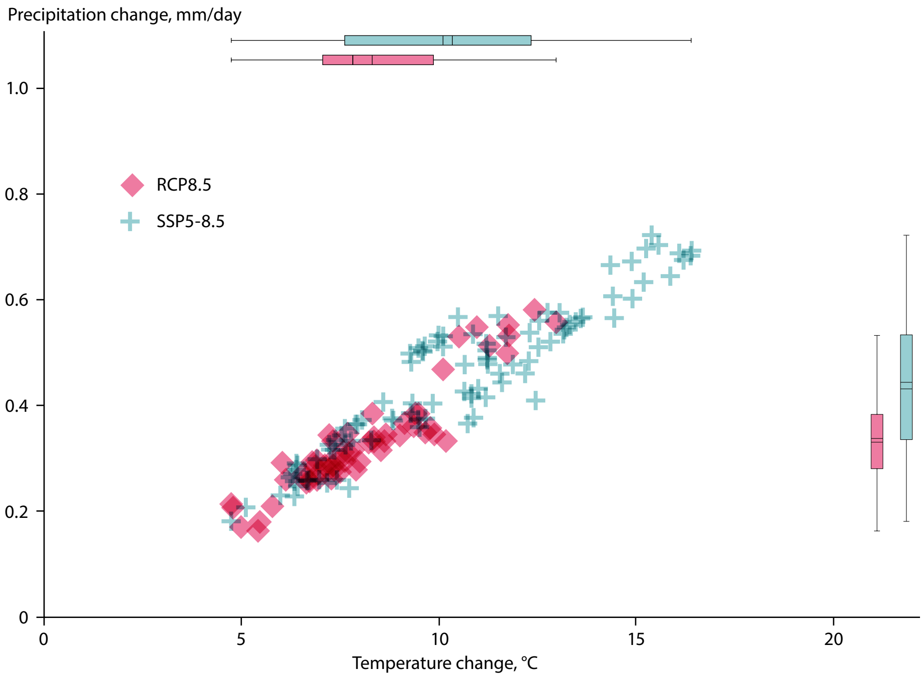

Figure 3.18 Scatter plot of projected change in annual mean temperature and precipitation in the Arctic. Change is illustrated as the difference between present-day conditions (1981-2010) and projected future conditions (2071-2100). The box and whisker plots show the spread of model results under SSP5-8.5 and RCP8.5: boxes show the range between the first quartile (Q1, 25%) and third quartile (Q3, 75%); whiskers show the minimum and maximum values; and the two lines inside the boxes show the mean and median values (Parding et al., 2020).

3.4 Summary

Amplified warming in the Arctic is projected to continue as the global climate continues to warm, with an even stronger warming signal in winter. The CMIP6 simulations show similar conclusions to CMIP5 in terms of Arctic warming, and a reduction in sea-ice cover and snow cover. The CMIP6 model simulations of Arctic sea-ice extent are close to the observational record in the multi-model ensemble spread. The sensitivity of September Arctic sea-ice area to a given amount of anthropogenic CO_2 emissions and a given amount of global warming of the Arctic sea ice to changes in the forcing is better captured by CMIP6 models than by the previous generation of CMIP models. The majority of available CMIP6 simulations lose most September sea ice (an ice-free summer Arctic) before the end of the 21st century under three out of four emission scenarios (SSP2-4.5, SSP3-7.0, SSP5-8.5), and the earliest ice-free summer in the Arctic could be reached for the first time before 2050 under the SSP5-8.5 scenarios. The probability of experiencing at least one ice-free September prior to reaching 1.5°C global warming is extremely unlikely, whereas the probability increases to 1-in-3 prior to reaching a 2.0°C global warming based on transient warming simulations with CMIP5 models and applying a technique that uses observations to constrain the projections. Accompanying the reduction in sea-ice cover and thickness, Arctic surface water is projected to be less saline in the Amerasian Basin and central Arctic. In these shelf regions, the freshwater content (upper 250 m of the water column) is projected to rise more under a stronger emission scenario (e.g., SSP5-8.5). The models also project that the Arctic Ocean will become fresher in the Pacific sector, and more saline in the Atlantic sector. A similar dipole pattern of freshwater content in the top 250 m matches what is projected for the change in surface salinity. Significant decreases in snow extent have been observed in recent decades in northern high latitudes during spring (April to June), but the trends are much weaker during winter months. Both CMIP5 and CMIP6 projections point to a shortening of the snow season over the entire Arctic, with both a later snow onset date in autumn and an earlier snow-off date in spring. As for precipitation, increased intensities and/or shorter return periods for heavy precipitation events in the Arctic are projected by previous models and the more recent CMIP6 models. As with global climate sensitivity, the CMIP6 models exhibit a wider scatter than the CMIP5 models that extends to higher values for both temperature and precipitation. The CanESM2 large ensemble stabilization simulations show that under a stabilized global warming of below 1.5°C and 2.0°C, the amplitude of the Arctic mean warming does not show large changes, but instead remains fairly stable at roughly twice the global mean warming, and the September sea-ice extent remains fairly constant. The probability of an ice-free Arctic summer is an order of magnitude smaller under 1.5°C global warming than 2.0°C global warming, a scenario consistent with the Paris Agreement.

The climate-induced changes in seasonal sea-ice extent and thickness and ocean stratification are altering marine primary production, with impacts on ecosystems. The projected physical changes reported here will have further impacts on Arctic ecosystems, shipping activity, habitat and biome shifts, Arctic hydrology, wildfire, land vegetation, and water and food security. The Arctic will be profoundly different in the future compared with today, and the degree and nature of that difference will depend strongly on the rate and magnitude of global climate change (Meredith et al., 2019).

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References

AMAP, 2017a. Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2017. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway.

AMAP, 2017b. Adaptation Actions for a Changing Arctic (AACA) – Perspectives from the Barents Area. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway.

Benestad, R., J. Sillmann, T.L. Thorarinsdottir, P. Guttorp, M.D.S. Mesquita, M.R. Tye, P. Uotila, C.F. Maule, P. Thejll, M. Drews and K.M. Parding, 2017. New vigour involving statisticians required to overcome ensemble fatigue. Nature Climate Change, 7:697-703.

Benestad, R.E., H.B. Erlandsen, A. Mezghani and K.M. Parding, 2019. Geographical distribution of thermometers gives the appearance of lower historical global warming. Geophysical Research Letters, 46:7654-7662.

Brown, R., D. Vikhamar Schuler, O. Bulygina, C. Derksen, R. Luojus, L. Mudryk, L. Wang and D. Yang, 2017. Arctic terrestrial snow cover. In: Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2017, pp. 25-64, Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway.

Bunzel, F., D. Notz and L.T. Pedersen, 2018. Retrievals of Arctic sea-ice volume and its trend significantly affected by interannual snow variability. Geophysical Research Letters, 45:11,751–11,759.

Carmack, E.C., M. Yamamoto-Kawai, T.W.N. Haines, S. Bacon, B.A. Bluhm, C. Lique, H. Melling, I.V. Polyakov, F. Straneo, M.-L. Timmermans and W.J. Williams, 2016. Freshwater and its role in the Arctic marine system: sources, disposition, storage, export, and physical and biogeochemical consequences in the Arctic and global oceans. Journal of Geophysical Research: Biogeosciences, 121:675-717.

Chevallier, M., G. Smith, F. Dupont, F.-F. Lemieux and 23 others, 2017. Intercomparison of the Arctic sea ice cover in global ocean–sea ice reanalyses from the ORA-IP project. Climate Dynamics, 49:1107-1136.

Clarke, L., K. Jiang, K. Akimoto, M. Babiker, G. Blanford, K. Fisher-Vanden, J.-C. Hourcade, V. Krey, E. Kriegler, A. Löschel, D. McCollum, S. Paltsev, S. Rose, P.R. Shukla, M. Tavoni, B.C.C. van der Zwaan, and D.P. van Vuuren, 2014. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Collins, W.D., C.M. Bitz, M.L. Blackmon, G.B. Bonan, C.S. Bretherton, J.A. Carton, P. Chang, S.C. Doney, J.J. Hack, T.B. Henderson, J.T. Kiehl, W.G. Large, D.S. McKenna, B.D. Santer and R.D. Smith, 2006. The Community Climate System Model version 3 (CCSM3). Journal of Climate, 19:2122-2143.

Collins, M., R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W.J. Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A.J. Weaver and M. Wehner, 2013. Long-term climate change: projections, commitments and irreversibility. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press. pp. 1083-1086.

Comiso, J.C., W.N. Meier and R. Gersten, 2017. Variability and trends in the Arctic sea ice cover: Results from different techniques. Journal of Geophysical Research: Oceans, 122:6883-6900.

Deser, C., R. Knutti, S. Solomon and A.S. Phillips, 2012. Communication of the role of natural variability in future North American climate. Nature Climate Change, 2:775-779.

Dunne, J.P., M. Winton, J. Bacmeister, G. Danabasoglu, A. Gettelman, J.-C. Golaz, C. Hannay, G.A. Schmidt, J.P. Krasting, L.R. Leung, L. Nazarenko, L.T. Sentman, R.J. Stouffer and J.D. Wolfe, 2020. Comparison of equilibrium climate sensitivity estimates from slab ocean, 150-year, and longer simulations. Geophysical Research Letters, 47:e2020GL088852.

Eyring, V., S. Bony, G.A. Meehl, C.A. Senior, B. Stevens, R.J. Stouffer and K.E. Taylor, 2016. Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. Geoscientific Model Development, 9:1937-1958.

Flato, G., 2011. Earth system models: an overview. WIREs Climate Change, 2:783-800.

Flynn, C.M. and T. Mauritsen, 2020. On the climate sensitivity and historical warming evolution in recent coupled model ensembles. Atmospheric Chemistry and Physics, 20:7829-7842.

Haarsma, R.J., M.J. Roberts, P.L. Vidale, C.A. Senior, A. Bellucci, Q. Bao, P. Chang, S. Corti, N.S. Fučkar, V. Guemas, J. von Hardenberg, W. Hazeleger, C. Kodama, T. Koenigk, L.R. Leung, J. Lu, J.-J. Luo, J. Mao, M.S. Mizielinski, R. Mizuta, P. Nobre, M. Satoh, E. Scoccimarro, T. Semmler, J. Small, and J.-S. von Storch, 2016. High Resolution Model Intercomparison Project (HighResMIP v1.0) for CMIP6. Geoscientific Model Development, 9:4185-4208.

Held, I.M., 2005. The gap between simulation and understanding in climate modeling. Bulletin of the American Meteorological Society, 86:1609-1614.

Holland, M.M. and C.M. Bitz, 2003. Polar amplification of climate change in the coupled model intercomparison project. Climate Dynamics, 21:221-232.

Holland, M.M., C.M Bitz, L.-B. Tremblay and D.A. Bailey, 2008. The role of natural versus forced change in future rapid summer Arctic sea ice loss. In: DeWeaver, E.T., C.M. Bitz and L.-B. Tremblay (eds.), Arctic Sea Ice Decline: Observations, Projections, Mechanisms, and Implications. pp. 133-150.

IPCC, 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

IPCC, 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

IPCC, 2018. Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Intergovernmental Panel on Climate Change (IPCC).

IPCC, 2019. IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Intergovernmental Panel on Climate Change (IPCC).

Jahn, A., 2018. Reduced probability of ice-free summers for 1.5°C compared to 2°C warming. Nature Climate Change, 8:409-413.

James, R., R. Washington, C.F. Schleussner, J. Rogelj and D. Conway, 2017. Characterizing half-a-degree difference: a review of methods for identifying regional climate responses to global warming targets. WIREs Climate Change, 8:3457.

Kharin, V.V., F.W. Zwiers, X. Zhang and M. Wehner, 2013. Changes in temperature and precipitation extremes in the CMIP5 ensemble. Climatic Change, 119:345-357.

Koenigk, T., A. Devasthale and K.G. Karlsson, 2014. Summer Arctic sea ice albedo in CMIP5 models. Atmospheric Chemistry and Physics, 14:1987-1998.

Kusunoki, S., R. Mizuta and M. Hosaka, 2015. Future changes in precipitation intensity over the Arctic projected by a global atmospheric model with a 60-km grid size. Polar Science, 9:277-292.

Kwok, R. and G.F. Cunningham, 2015. Variability of Arctic sea ice thickness and volume from CryoSat-2. Philosophical Transactions of the Royal Society A, 373:20140157.

Landrum, L. and M.M. Holland, 2020. Extremes become routine in an emerging new Arctic. Nature Climate Change, 10:1108-1115.

Manabe, S. and R.T. Wetherald, 1975. The effects of doubling the CO2 concentration on the climate of a general circulation model. Journal of the Atmospheric Sciences, 32:3-15.

Maslanik, J., J. Stroeve, C. Fowler and W. Emery, 2011. Distribution and trends in Arctic sea ice age through spring 2011. Geophysical Research Letters, 38(13).

Massonnet, F., T. Fichefet, H. Goosse, C.M. Bitz, G. Philippon-Berthier, M.M. Holland and P.Y. Barriat, 2012. Constraining projections of summer Arctic sea ice. The Cryosphere, 6:1383-1394.

Meehl, G.A., C.A. Senior, V. Eyring, G. Flato, J.-F. Lamarque, R.J. Stouffer, K.E. Taylor and M. Schlund, 2020. Context for interpreting equilibrium climate sensitivity and transient climate response from the CMIP6 Earth system models. Science Advances, 6:eaba1981.

Melia, N., K. Haines and E. Hawkins, 2016. Sea ice decline and 21st century trans-Arctic shipping routes. Geophysical Research Letters, 43:9720-9728.

Meredith, M., M. Sommerkorn, S. Cassotta, C. Derksen, A. Ekaykin, A. Hollowed, G. Kofinas, A. Mackintosh, J. Melbourne-Thomas, M.M.C. Muelbert, G. Ottersen, H. Pritchard and E.A.G. Schuur, 2019. Polar Regions. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate.

Mitchell, D., R. James, P.M. Forster, R.A. Betts, H. Shiogama and M. Allen, 2016. Realizing the impacts of a 1.5°C warmer world. Nature Climate Change, 6:735-737.

Moore, G. W. K., A. Schweiger, J. Zhang and M. Steele, 2019. Spatiotemporal variability of sea ice in the Arctic's last ice area. Geophysical Research Letters, 46:11237-11243.

Mudryk, L., P. Kushner, C. Derksen and C. Thackeray, 2017. Snow cover response to temperature in observational and climate model ensembles. Geophysical Research Letters, 44:919-926.

Mudryk, L., M. Santolaria-Otín, G. Krinner, M. Ménégoz, C. Derksen, C. Brutel-Vuilmet, M. Brady and R. Essery, 2020. Historical Northern Hemisphere snow cover trends and projected changes in the CMIP-6 multi-model ensemble. The Cryosphere Discussions, 1-35, doi.org/10.5194/tc-2019-320

NOAA, no date. NOAA snow chart Climate Data Record. www.ncei.noaa.gov/access/metadata/landing-page/bin/iso?id=gov.noaa.ncdc:C00756

Notz, D., 2014. Sea-ice extent and its trend provide limited metrics of model performance. The Cryosphere, 8:229-243.

Notz, D. and SIMIP Community, 2020. Arctic sea ice in CMIP6. Geophysical Research Letters, 47:e2019GL086749.

Olason, E. and D. Notz, 2014. Drivers of variability in Arctic sea-ice drift speed. Journal of Geophysical Research: Oceans, 119:5755-5775.

Olonscheck, D. and D. Notz, 2017. Consistently estimating internal climate variability from climate model simulations. Journal of Climate, 30:9555-9573.

Overland, J.E. and M. Wang, 2018. Arctic-midlatitude weather linkages in North America. Polar Science, 16:1-9.

Overland, J.E., M. Wang, N.A. Bond, J.E. Walsh, V.M. Kattsov and W.L. Chapman, 2011. Considerations in the selection of global climate models for regional climate projections: the Arctic as a case study. Journal of Climate, 24:1583-1597.

Overland, J.E., M. Wang, J.E. Walsh and J.C. Stroeve, 2014. Future Arctic climate changes: Adaptation and mitigation time scales. Earth's Future, 2:68-74.

Overland, J.E., E. Hanna, I. Hanssen-bauer, S.-J. Kim, J.E. Walsh, M. Wang and U.S. Bhatt, 2019. Surface air temperature. Bulletin of the American Meteorological Society, 100:S144-S146.

Parding, K.M., A. Dobler, C.F. McSweeney, O.A. Landgren, R. Benestad, H.B. Erlandsen, A. Mezghani, H. Gregow, O. Räty, E. Viktor, J. El Zohbi, O.B.Christensen and H. Loukos, 2020. GCMeval–An interactive tool for evaluation and selection of climate model ensembles. Climate Services, 18:100167.

Rao, S., Z. Klimont, S.J. Smith, R. Van Dingenen, F. Dentener, L. Bouwman, K. Riahia, M.Amann, B.L. Bodirskyi, D.P. van Vuuren, L.A. Reis, K. Calvin, L. Drouet, O. Fricko, S. Fujimori, D. Gernaat, P. Havlik, M. Harmsen, T. Hasegawa, C. Heyes, J. Hilaire, G. Luderer, T. Masui, E. Stehfest, J. Strefler, S. van der Sluis and M. Tavoni, 2017. Future air pollution in the Shared Socio-economic Pathways. Global Environmental Change, 42:346-358.

Riahi, K., D.P. van Vuuren, E. Kriegler, J. Edmonds and 42 others, 2017. The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview. Global Environmental Change, 42:153-168.

Richter-Menge, J., M.L. Druckenmiller and M. Jeffries (eds.), 2019. Arctic Report Card 2019. www.arctic.noaa.gov/Report-Card

Rogelj, J., M. den Elzen, N. Höhne, T. Fransen, H. Fekete, H. Winkler, R. Schaeffer, F. Sha, K. Riahi and M. Meinshausen, 2016. Perspective: Paris Agreement climate proposals need boost to keep warming well below 2°C. Nature Climate Change, 534:631-639.

Screen, J.A., 2018. Arctic sea ice at 1.5°C and 2.0°C. Nature Climate Change, 8:362-363.

Screen, J.A. and D. Williamson, 2017. Ice-free Arctic at 1.5°C? Nature Climate Change, 7:230-231.

Seneviratne, S.I. and M. Hauser, 2020. Regional Climate Sensitivity of Climate Extremes in CMIP6 Versus CMIP5 Multimodel Ensembles. Earth's Future, 8:e2019EF001474.

Seneviratne, S.I., M.G. Donat, A.J. Pitman, R. Knutti and R.L. Wilby, 2016. Allowable CO_2 emissions based on regional and impact-related climate targets. Nature, 529:477-483.

Seneviratne, S.I., R. Wartenburger, B.P. Guillod, A.L. Hirsch, M.M. Vogel, V. Brovkin, D.P. van Vuuren, N. Schaller, L. Boysen, K.V. Calvin, J. Doelman, P. Greve, P. Havlik, F. Humpenöder, T. Krisztin, D. Mitchell, A. Popp, K. Riahi, J. Rogelj, C.-F. Schleussner, J. Sillmann and E. Stehfest, 2018. Climate extremes, land–climate feedbacks and land-use forcing at 1.5°C. Philosophical Transactions of the Royal Society A, 376:20160450.

Shu, Q., Z. Song and F. Qiao, 2015. Assessment of sea ice simulations in the CMIP5 models. The Cryosphere, 9:399-409.

Shu, Q., F. Qiao, Z. Song, J. Zhao and X. Li, 2018. Projected freshening of the Arctic Ocean in the 21st century. Journal of Geophysical Research: Oceans 123:9232-9244.

Shu, Q., Q. Wang, Z. Song, F. Quiao, J. Zhao, M. Chu and X. Li, 2020. Assessment of sea ice extent in CMIP6 with comparison to observations and CMIP5. Geophysical Research Letters, 47:e2020GL087965.

Sigmond, M., J.C. Fyfe and N.C. Swart, 2018. Ice-free Arctic projections under the Paris Agreement. Nature Climate Change, 8:404-408.

Sigmond, M., J.C. Fyfe, O.A. Saenko and N.C. Swart, 2020. Ongoing AMOC and related sea level and temperature changes after achieving the Paris targets. Nature Climate Change, 10:672-677.

Sillmann, J., V.V. Kharin, X. Zhang, F.W. Zwiers and D. Bronaugh, 2013. Climate extremes indices in the CMIP5 multimodel ensemble: Part 1. Model evaluation in the present climate. Journal of Geophysical Research: Atmospheres, 118:1716-1733.

Steele, M., R. Morley and W. Ermold, 2001. PHC: A global ocean hydrography with a high-quality Arctic Ocean. Journal of Climate, 14:2079-2087.

Stroeve, J. and D. Notz, 2018. Changing state of Arctic sea ice across all seasons. Environmental Research letters, 13:103001.

Stroeve, J., M.M. Holland, W. Meier, T. Scambos and M. Serreze, 2007. Arctic sea ice decline: Faster than forecast. Geophysical Research Letters, 34:L09501.

Stroeve, J., V. Kattsov, A. Barrett, M. Serreze, T. Pavlova, M. Holland and W.N. Meier, 2012. Trends in Arctic sea ice extent from CMIP5, CMIP3 and observations. Geophysical Research Letters, 39:L16502.

Stroeve, J., A. Barrett, M. Serreze and A. Schweiger, 2014. Using records from submarine, aircraft and satellites to evaluate climate model simulations of Arctic sea ice thickness. The Cryosphere, 8:1839-1854.

Taylor, K.E., R.J. Stouffer and G.A. Meehl, 2012. An overview of CMIP5 and the experiment design. Bulletin of the American Meteorological Society, 93:485-498.

Toreti, A., P. Naveau, M. Zampieri, A. Schindler, E. Scoccimarro, E. X., H.A. Dijkstra, S. Gualdi and J. Luterbacher, 2013. Projections of global changes in precipitation extremes from Coupled Model Intercomparison Project Phase 5 models. Geophysical Research Letters, 40:4887-4892.

United Nations, 2015. Paris Agreement. https://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf

Van Vuuren, D.P., J. Edmonds, M. Kainuma, K. Riahi, A. Thomson, K. Hibbard, G.C. Hurtt, T. Kram, V. Krey, J.-F. Lamarque, T. Masui, M. Meinshausen, N. Nakicenovic, S.J. Smith and S.K. Rose, 2011. The representative concentration pathways: an overview. Climatic Change, 109:5.

Wang, M. and J.E. Overland, 2009. A sea ice free summer Arctic within 30 years? Geophysical Research Letters, 36:L07502

Wang, M. and J.E. Overland, 2012. A sea ice free summer Arctic within 30 years: an update from CMIP5 models. Geophysical Research Letters, 39:L18501.

Wang, M. and J.E. Overland, 2015. Projected future duration of the sea-ice-free season in the Alaskan Arctic. Progress in Oceanography, 136:50-59.

Wang, Q., M. Ilicak, R. Gerdes, H. Drange, Y. Aksenov, D.A. Bailey, M. Bentsen, A. Biastoch, A. Bozec, C. Böning and C. Cassou, 2016. An assessment of the Arctic Ocean in a suite of interannual CORE-II simulations. Part II: Liquid freshwater. Ocean Modelling, 99:86-109.

Wang, Q., C. Wekerle, S. Danilov, D. Sidorenko, N. Koldunov, D. Sein, B. Rabe and T. Jung, 2019. Recent sea ice decline did not significantly increase the total liquid freshwater content of the Arctic Ocean. Journal of Climate, 32:15-32.

Wartenburger, R., M. Hirschi, M.G. Donat, P. Greve, A.J. Pitman and S.I. Seneviratne, 2017. Changes in regional climate extremes as a function of global mean temperature: An interactive plotting framework. Geoscientific Model Development, 10:3609-3634.

Zelinka, M.D., T.A. Myers, D.T. McCoy, S. Po-Chedley, P.M. Caldwell, P. Ceppi, A. Klein and K.E. Taylor, 2020. Causes of higher climate sensitivity in CMIP6 models. Geophysical Research Letters, 47:e2019GL085782.

Zygmuntowska, M., P. Rampal, N. Ivanova and L.H. Smedsrud, 2014. Uncertainties in Arctic sea ice thickness and volume: new estimates and implications for trends. The Cryosphere, 8:705-720.

Appendix 3.1 Institution full name

AWI	Alfred Wegener Institute
BCC	Beijing Climate Center
CAMS	Chinese Academy of Meteorological Sciences
CAS	Chinese Academy of Sciences
CCCma	Canadian Centre for Climate Modelling and Analysis
CNRM-CERFACS	Centre National de Recherches Météorologiques and Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSIRO-ARCCSS	Commonwealth Scientific and Industrial Research Organisation - Australian Research Council Centre of Excellence for Climate System Science
EC-Earth-Consortium	AEMET, Spain; BSC, Spain; CNR-ISAC, Italy; DMI, Denmark; ENEA, Italy; FMI, Finland; Geomar, Germany; ICHEC, Ireland; ICTP, Italy; IDL, Portugal; IMAU, The Netherlands; IPMA, Portugal; KIT, Karlsruhe, Germany; KNMI, The Netherlands; Lund University, Sweden; Met Eireann, Ireland; NLeSC, The Netherlands; NTNU, Norway; Oxford University, UK; surfSARA, The Netherlands; SMHI, Sweden; Stockholm University, Sweden; Unite ASTR, Belgium; University College Dublin, Ireland; University of Bergen, Norway; University of Copenhagen, Denmark; University of Helsinki, Finland; University of Santiago de Compostela, Spain; Uppsala University, Sweden; Utrecht University, The Netherlands; Vrije Universiteit Amsterdam, The Netherlands; Wageningen University, The Netherlands.
FIO-QLNM	First Institute of Oceanography and Qingdao National Laboratory for Marine Science and Technology
INM	Institute of Numerical Mathematics
IPSL	Institut Pierre-Simon Laplace
MIROC	Center for Climate Systems Research (CCSR), the University of Tokyo, the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), and the National Institute for Environmental Studies (NIES)
MOHC	Met Office Hadley Centre
MPI-M	Max Planck Institute for Meteorology
MRI	Meteorological Research Institute
NASA-GISS	National Aeronautics and Space Administration - Goddard Institute for Space Studies
NCAR	National Center for Atmospheric Research
NCC	Norwegian Climate Centre
NIMS-KMA	National Institute of Meteorological Sciences - Korea Meteorological Administration
NOAA-GFDL	National Oceanic and Atmospheric Administration - Geophysical Fluid Dynamics Laboratory
NUIST	Nanjing University of Information Science and Technology
UA	University of Arizona, Department of Geosciences

4. Extreme events and thresholds in the Arctic

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Key findings

- *There is strong evidence for recent increases in the frequency and/or intensity of several types of extreme events in the Arctic: extreme high temperatures, rapid sea-ice loss events, and widespread melt events on the Greenland Ice Sheet.*
- *There is strong evidence for decreases in the frequency of extreme cold events in the Arctic.*
- *The types of extreme events for which there is little or no evidence of recent Arctic-wide changes include drought, freezing rain and inland flooding.*
- *There are generally high levels of confidence in future changes in high-impact events, including wildfires, coastal flooding and erosion.*
- *Largely because of the pervasiveness of the cryosphere, the Arctic offers more possibilities for abrupt changes and thresholds than other parts of the Earth system.*
- *Thresholds or tipping points have received more attention in the biological and ecological components than in the physical components of the Arctic system. Likelihoods of threshold exceedances are priorities for evaluation in the Arctic.*

Abstract

The greatest impacts of climate change on ecosystems, wildlife and humans often arise from extreme events rather than changes in climatic means. The Arctic experiences a variety of climate-related extreme events, yet there has been little attempt to synthesize information on extreme events in the Arctic. This chapter reviews work on thirteen types of Arctic extreme events, addressing (i) the evidence for variations and changes based on analyses of recent historical data and (ii) projected changes based primarily on studies utilizing global climate models. The chapter also points out associated thresholds to the extent they are known. The survey of extreme weather and climate events includes temperature, precipitation, snow, freezing rain, atmospheric blocking, cyclones, and wind. The survey also includes cryospheric and biophysical impacts: rapid sea-ice loss events, Greenland Ice Sheet melt, floods, drought, coastal erosion and wildfire. Temperature, sea-ice loss events, and Greenland melt events rank at the high end of the spectra of evidence for change and confidence in future change, while event types such as drought, inland flooding and cyclones rank at the lower end. Research priorities identified on the basis of this review include further work on attribution, impacts on ecosystems and humans, and thresholds. The thresholds can pertain either to tipping points in one or more components of the Arctic system or to thresholds for particular impacts on humans, infrastructure or ecosystems. In either case, extreme events can be responsible for threshold exceedances or tipping points.

4.1 Introduction

Extreme climate and weather events, especially changes in extremes, often have greater impacts on ecosystems (Ummenhofer and Meehl, 2017), infrastructure (Pregnolato et al., 2016) and humans (Curtis et al., 2017) than changes in climate averages. Moreover, extreme events can trigger exceedances of thresholds for impacts and for abrupt changes in parts of the Arctic system. As the climate changes and new weather patterns emerge, events previously considered extreme become increasingly routine (Landrum and Holland, 2020). While a general lack of studies of extreme events in the Arctic has been noted in previous Arctic assessment reports (e.g., AMAP, 2011, 2017), such events have begun to receive attention by the research community as well as the media. Examples of recent record-setting events include the lack of Bering Sea ice in the winters of 2018 and 2019, Siberian wildfires in spring and summer 2020, record North American snowfall in October 2020, and record high pressure in Siberia in December 2020 with associated eastern Asia cold events. However, the studies to date of Arctic extreme events are largely uncoordinated. This chapter represents a survey of recent work on extreme events in the Arctic as a step towards a synthesis and an identification of gaps and priorities. It also includes information on thresholds, abrupt changes and tipping points in the Arctic system to the extent they may be triggered by extreme events.

As noted by the Intergovernmental Panel on Climate Change (IPCC), the identification and definition of weather and climate events that are relevant from an impacts perspective are complex and depend on the stakeholders involved (IPCC, 2012). The weather and climate literature has tended to define an extreme weather or climate event in terms of the occurrence of a value of a weather or climate variable above or below a threshold within the range of observed values of the variable (IPCC, 2012:116). The choices of thresholds vary, but can include exceedances of ±2 standard deviations or values with a less than 10%, 5%, or 1% chance of occurrence. Absolute thresholds (rather than these relative thresholds based on the range of observed values of a variable) can also be used to identify extreme events. Even for a given approach to extreme event definition, the criteria will vary from place to place in an absolute sense (e.g., the threshold temperature for a hot day in the Arctic will be different from in the tropics).

Complicating the definition of extreme events is the fact that high-impact events such as floods and droughts may be the result of an accumulation of non-extreme weather or climate events, while it is the accumulation of the events that is extreme. Compound events (two or more events occurring sequentially or even two types of events occurring simultaneously) can produce some of the greatest impacts even when the individual events are not extreme. Conversely, not all weather and climate events meeting criteria for 'extreme' may have notable impacts.

Extreme events can be defined quantitatively in terms of either their probability of occurrence or in terms of a magnitude (or, in an aggregate sense, in terms of the probability that a particular magnitude or threshold will be reached). Moreover, in addition to the actual magnitude of extremes (and its associated probability of occurrence or its return period), the criteria for an extreme event may be impact-based, in which case they can be derived from the event's duration, the spatial area affected, timing, frequency, onset date, continuity (i.e., whether or not 'breaks' occur), and preconditioning (IPCC, 2012:117).

In view of the absence of a universal definition for extreme events, it is not surprising that the literature reviewed here includes a variety of criteria for extreme events and their changes. Changes in extreme events can be addressed in terms of event frequency, intensity and location. Changes in frequency can arise from changes in the mean as well as from changes in the shape of a distribution. While relatively little work has been done on changes in frequency distributions of Arctic variables, recent changes in the means of many Arctic variables are unequivocal (Chapter 2). Various studies surveyed in this chapter point to changes in intensity of extreme events in the Arctic, particularly in the occurrence of extremes of unprecedented intensity. These changes vary by location, although internal variability confounds the attribution of geographical shifts in extreme events.

From chaos theory, increases in extremes of both positive and negative values could be a precursor for change, especially if thresholds are inherent in a system. Rather than projecting a smooth trajectory for the state of climate change of the Arctic over the next 50 years as often simulated in climate models (Bathiany et al., 2016; Cai et al., 2018), current conditions do not rule out a more rapid transition within the next decades (Screen and Deser, 2019; Landrum and Holland, 2020). The timing of abrupt transitions, by their non-linear nature, can be impossible to predict. Current multiple environmental signs imply that an Arctic abrupt change may be more approachable compared to 30 years ago when thick sea ice provided a multi-year climate buffer to vigorous ocean-atmosphere interactions and large excursions from the mean.

There are linkages between the Arctic and the rest of the global system, and these linkages may involve extreme events in mid-latitudes and the Arctic. The subject of Arctic/mid-latitude linkages is an active topic of research that has its own evolving literature (e.g., Cohen et al., 2020) and is the focus of Chapter 5. In view of the increasing evidence for Arctic-global linkages, recent global assessments of changes in extreme events (IPCC, 2012, 2013, 2019) are used here to provide context for variations and trends in some of the types of extreme events addressed in this chapter.

In the following sections, recent work is surveyed on extremes of Arctic temperature, precipitation, inland flooding, snow, freezing rain, atmospheric blocking, cyclones, wind, sea ice (rapid ice-loss events), the Greenland Ice Sheet (extreme melt events), drought, wildfire, and coastal erosion. For each of these topics, past work on historical trends and future projections is reviewed. The historical reviews are based primarily on observational studies (including those based on reanalysis products), while the survey of projected changes draws primarily on model-based studies. The timescales of the extreme events generally range from daily to annual. While daily-timescale events can be characterized as 'weather' rather than climate, changes in climate can alter the characteristics (frequency, intensity, duration) of high-impact extreme weather events. Changes in climate can also result in new threshold exceedances relevant to impacts and to abrupt changes in the Arctic system.

A variable notably absent from this review is permafrost. While associated with a clearly defined threshold (0°C), changes in permafrost are often slow-onset responses to accumulated forcing over periods of years and longer. In this case, the key drivers are air temperature and winter snow cover. Abrupt changes on a local scale can occur in association with thermokarst formation or the erosion of coastal or riverine permafrost. However, in the case of erosion the key to the extreme event is the atmospheric or marine/hydrological event. With regard to the latter, this chapter includes a section on coastal erosion (Section 4.2.13), although it is apparent in that section that changes in sea ice and storm events are leading causes of changes in coastal erosion, whether of permafrost or unfrozen ground. Similarly, permafrost thaw can be accelerated by other extreme events such as unusually warm summers, wildfire and high-snowfall winters (Lewkowicz and Way, 2019). The focus in Section 4.2 is on these drivers rather than on the spatially and temporally more heterogeneous response of permafrost *per se*. Permafrost responses to atmospheric drivers are addressed in more detail in the recent volume edited by Yang and Kane (2020).

As the Arctic does not have a universally accepted spatial extent, the spatial domain of this review is broadly defined as northern high latitudes. This domain includes the Arctic, for which there is no universal definition. Definitions of the Arctic range from the area north of the Arctic Circle (66.5°N) to the region poleward of the boreal forest, to broader definitions that encompass the entirety of the watersheds of the major rivers draining into the Arctic Ocean. These watersheds extend equatorward of 45°N in some cases. The choice here of 'northern high latitudes' is intended to include the Arctic and adjacent regions that are affected by the same weather systems, climate variations, and ocean anomalies. A key feature of the domain is the prominence of the cryosphere: sea ice, seasonal snow cover, perennially or seasonally frozen ground, and land ice. The latter includes the Greenland Ice Sheet.

In this review, the major impacts of the various types of extreme events are briefly mentioned as motivation for the inclusion of each topic. However, this does not emphasize impacts or their changes over time. An assessment of impacts of climate and weather in the Arctic is an activity under development within the Arctic Monitoring and Assessment Programme (AMAP) and its Climate Expert Group. Nevertheless, impact-relevant thresholds that may be exceeded by extreme events are noted here, to the extent that such thresholds are known. The most obvious such threshold is the freezing temperature (0°C), exceedance of which in the annual mean has major consequences for cryospheric variables such as sea ice and permafrost. On shorter timescales of extreme events, exceedance of this threshold during winter precipitation events can result in freezing rain or rain-on-snow events.

Section 4.2 is structured by the various types of extreme event listed above. In each case, there are separate subsections for the recent (historical) trends and for future projections of change. Each event type then has a final 'Summary' subsection in which the preceding literature review is distilled into an assessment of the strength of evidence for the recent changes and the level of confidence in the future changes. The three-tiered ratings of the evidence/confidence (low, medium, high) are based on the comprehensiveness and consistency of the reviewed literature on each variable. The ratings are presented in a synthesis across all event types in Section 4.4. The Summary subsection for each variable also addresses thresholds relevant to the various types of extreme event, although it will be apparent that the information on thresholds is rather uneven across the different event types.

4.2 Recent and projected changes of extremes in the Arctic

4.2.1 Temperature

Temperature is the climate variable for which the most extensive weather and climate data exist for northern land areas. Because global temperature changes are amplified in the Arctic, temperature gives the Arctic a central role in discussions of global warming. While Arctic amplification is generally addressed in terms of mean temperatures, it also has major implications for changes in extreme temperatures, which in turn impact other temperature-sensitive variables at high latitudes.

4.2.1.1 Recent trends

Several timescales of temperature extremes in the Arctic can be distinguished, ranging from daily to monthly, seasonal and yearly. There is evidence that warm extremes are increasing on all of these timescales. At the longer end of the time range, the occurrence of extreme yearly temperatures is a striking indication of the impact of the background warming. As shown in Figure 4.1, the seven warmest years since 1900 have been the most recent seven years (2014–2020). The three warmest years were 2016, 2019, and 2020. The spread between the Arctic and global annual mean temperature departures from their 1981–2010 means was also greatest in recent years, as 2016, 2019 and 2020 all showed Arctic Amplification in the upper decile based on Arctic-global temperature differences. According to the IPCC (2019) report, the record warmth of the Arctic in 2016 would not have been possible without anthropogenic forcing (see also Kam et al., 2018).

Monthly and seasonal temperatures have also set new records in the past several years. Finland, Norway and Svalbard all recorded their warmest spring months on record in May 2018; in all cases, periods of record extend back to approximately 1900 (Overland et al., 2018). The record heat continued into summer 2018, with many parts of Fennoscandia setting records for summer heat. Finland, for example, broke its record for the hottest July (and any calendar month) in 2018. Major heatwaves over Europe in summer 2019 contributed to the advection of anomalously warm air over Greenland, which experienced extreme summer melt discussed later in Section 4.2.10. The following winter of 2019–2020 was the warmest on record for Europe and Asia (NOAA, no date a), with unprecedented heat continuing into the spring and summer over northern Asia (Overland and Wang, 2020). Alaska experienced its warmest spring of the post-1925 period of record in 2016, only to exceed that record in 2019 (NOAA no date b). Alaska's four warmest winters and two warmest autumns have occurred since 2000. Notably absent from the monthly and seasonal anomalies of the past several years are records for extreme cold.

While observational syntheses of monthly and seasonal temperature records in the Arctic are generally lacking, there have been several evaluations of statistics of daily temperature extremes. In some cases, these evaluations have made use of the indices developed by the World Climate Research Program's Expert Team on Climate Change Detection and Indices (ETCCDI), often referred to as the CLIMDEX (Climate Data Extremes) with processing enabled by the CLIMDEX analysis software (e.g., Sillmann et al., 2013a). Indices include exceedances of the 10th percentile and 90th percentile values of the daily high and low temperatures in a month. Exceedances of these thresholds are termed 'cold days' and 'cold nights' (for the 10th-percentiles), and 'warm days' and 'warm nights' (for the 90th percentiles). Such metrics were mapped for land

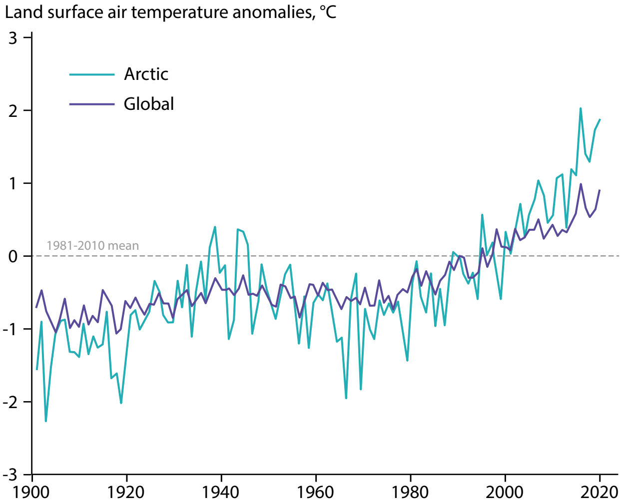

Figure 4.1 Global and Arctic (north of 60°N) annual land-surface air temperature anomalies for the period 1900–2020 relative to the 1981–2010 mean value. Adapted from Ballinger et al. (2020), based on the CRUTEM4 dataset - Climatic Research Unit (University of East Anglia) and Met Office (no date).

areas globally by the IPCC (2013: fig. 2.32), showing that there have been statistically significant changes since 1950 in all four metrics of extreme temperature over all land areas of the Arctic: occurrences of cold days and cold nights have decreased significantly, while occurrences of warm days and warm nights have increased significantly throughout the Arctic. The actual magnitudes of the changes (days per decade) are larger for the night-time metrics, consistent with greater night-time warming than daytime warming.

In a study focused on the Arctic, Graham et al. (2017) provided statistics of winter warming events over the central Arctic Ocean, where these events were associated with cyclone systems originating from the Atlantic and Pacific Oceans. The loss of winter sea ice reduces the over-ice trajectory of warmer maritime air during these events, favoring extreme winter warming such as the December 2015 event that raised temperatures above 0°C at the North Pole (Moore, 2016). The frequencies of winter air temperatures above -5°C have been found to be increasing by 4.25 days per decade in the North Pole region and by 1.16 days per decade in the Pacific sector of the Arctic Ocean. These trends are consistent with Moore's (2016) finding that the highest mid-winter temperatures at the North Pole have been increasing at twice the rate of warming of the mean midwinter temperatures near the Pole. A complementary synthesis of recent trends in daily temperature extremes over Arctic land areas was performed by Matthes et al. (2015), who evaluated trends in extreme cold spells and extreme warm spells during winter and summer. The results showed widespread decreases in extreme cold spells over the Arctic during 1979–2013, although there were small areas of statistically significant increases in cold spells in Siberia. Long cold spells (cold events lasting more than 15 days) have almost completely disappeared since 2000. Similarly, the Northern Hemisphere's coldest airmasses, which are generally found over the Arctic, have shown a significant moderation over the past six decades (Kanno et al., 2019). This warming of the coldest airmasses is consistent with Screen et al.'s (2015a) model-derived conclusion that warming of Arctic airmasses will ultimately outweigh the effects of changes in the frequency of cold air outbreaks, thereby reducing the risks of cold extremes in middle latitudes of North America beyond the next few decades.

A more recent study of the CLIMDEX metrics over the 1979–2015 period partitioned the changes for the winter months into four Arctic subregions: Northwest Eurasia, Northeast Eurasia, Alaska, and Canada (Siu et al., 2017). While the trends were not statistically significant for all metrics in all subregions, the Canadian sector showed especially large and statistically significant decreases in cold nights and cold days, while Northwest Eurasia showed especially large and statistically significant increases in warm nights and warm days. An analysis of data for Svalbard over the 1975–2014 period found that all four extreme temperature metrics (cold days, cold nights, warm days, warm nights) show trends consistent with the background warming in both winter and summer (Wei et al., 2016). For the Alaska region, several studies show that new high temperature records are occurring far more frequently than new low temperature records on both daily and monthly timescales (Bieniek and Walsh, 2017; Thoman and Walsh, 2019).

Observations suggest that the polar front jet stream has become more meandering during recent decades (Overland et al., 2012; Cattiaux et al., 2016; Vavrus et al., 2017). This favors the occurrence of meridional circulation patterns with strong poleward transport of heat and moisture, resulting in warm extremes in the Arctic (Vihma, 2017; Messori et al., 2018). Among others, Overland et al. (2014) concluded that a high-amplitude jet stream was responsible for the warm extremes of the 2014 winter in Alaska. Also, the extremely high air temperatures at the North Pole in December 2015 were associated with a strongly meandering jet stream (Moore, 2016). These events are often associated with atmospheric blocking, which is discussed in Section 4.2.6.

4.2.1.2 Future projections

Consistent with the ongoing and projected Arctic warming, climate models project changes in extreme temperature occurrences over Arctic land areas. By 2081–2100 under the RCP8.5 scenario, the coldest daily minimum temperature of the year is projected to be 10–12°C warmer than during the 1981–2000 reference period, while the highest daily maximum temperature of the year is projected to be 5–7°C warmer during 2081–2100 than during 1981–2000 (Collins et al., 2013: fig. 12.13). This seasonality conforms to the broader global pattern in which extreme minimum temperatures are projected to increase more than extreme maximum temperatures (Sillmann et al., 2013b). According to Screen et al. (2015b), the increase in new extremes of maximum temperature and the decrease in new extremes of minimum temperature are driven by the background global warming but amplified by the loss of sea ice in the Arctic. The sea-ice-driven changes in projected temperature extremes are especially large in the North American Arctic (Screen et al., 2015b: fig. 3).

4.2.1.3 Summary

The studies reviewed here provide consistent and compelling evidence that warm extremes are increasing and cold extremes are decreasing in the Arctic. The evidence spans the daily, seasonal and yearly timescales, and pertains to extremes both as new records and as increased frequencies-of-occurrence of temperatures in the high-end tails of historical distributions. All the studies of future changes point to continuations of these changes in temperature extremes. Therefore, in the synthesis at the end of this chapter, high-latitude temperature extremes merit a rating of 'high' for evidence of change and for confidence in future changes.

Aside from the 0°C freezing temperature, absolute thresholds of temperature have received relatively little attention in studies of high-latitude trends. This situation contrasts with assessments for middle latitudes, where many studies have evaluated historical and projected changes in 'hot days' defined by 30°C, 90°F, etc. While the preceding survey points to an extensive literature on changes in occurrences of extreme Arctic temperatures, especially daily maximum and minimum temperatures, there is a notable absence of studies of exceedances of impact-relevant thresholds. For example, vegetation, insects and even some terrestrial and marine species have known temperature tolerances, yet there has been little attempt to quantify changes in corresponding temperature threshold exceedances. One reason for the absence of published work on impact-relevant threshold exceedances is that impacts of extreme temperatures on species survival are often intertwined with effects of wind, snow conditions, and other environmental factors.

4.2.2 Precipitation

Assessing historical trends in extremes of precipitation in the Arctic presents challenges because (i) precipitation amounts often vary substantially over small scales, especially in the warm season, (ii) the precipitation gauge network in the Arctic is sparse and biased towards low elevations, and (iii) gauge undercatch is known to be a problem in cold windy environments (Yang et al., 2005). Gauge undercatch is especially problematic in northern regions, where Pan et al. (2020) have recently documented striking patterns in under-measurement of long-term mean daily maximum precipitation. Partly for these reasons, model-based studies, including atmospheric reanalyses, have played a greater role in evaluations of trends of Arctic precipitation and their extremes. However, studies based on atmospheric reanalyses include major uncertainties, as estimates of Arctic precipitation may differ by more than 50% between various reanalyses (Boisvert et al., 2018). Assessments of trends in extreme precipitation in the Arctic are further complicated by the use of several different metrics to quantify precipitation extremes (Vihma et al., 2016). The following summary pertains to total precipitation (liquid and solid). Section 4.2.4 focuses specifically on extreme snow events.

4.2.2.1 Recent trends

In an early evaluation of changes in intense precipitation, Groisman et al. (2005) showed that the Arctic and subarctic land areas were among the regions in which there had been disproportionate changes in heavy precipitation relative to changes in annual and seasonal mean precipitation. The 2013 IPCC report (AR5) presented global land surface maps of trends in heavy precipitation. The number of days when precipitation exceeded the 95th percentile (R95p) showed significant increases over Finland and northwestern Russia, but inadequacies in the station data precluded assessments in most other Arctic regions (Hartmann et al., 2013). Increases in daily precipitation intensity were statistically significant over a much larger area of the subarctic, including northeastern Canada and much of northern Russia as well as Finland and northern Sweden.

On a regional basis, trends in heavy precipitation events are sensitive to the time period and to the choice of region and season. For example, the number of days with heavy precipitation has shown significant increasing trends in large parts of the terrestrial Arctic (Alexander et al., 2006; Vincent and Mekis, 2006; Borzenkova and Shmakin, 2012; Donat et al., 2013) but decreasing trends in western Canada (Alexander et al., 2006). Daily precipitation intensity has increased in northern Canada (Vincent and Mekis, 2006; Peterson et al., 2008; Donat et al., 2013) and Eurasia (Donat et al., 2013) but decreased in southern Canada (Vincent and Mekis, 2006; Peterson et al., 2008; Donat et al., 2013) and coastal northern Russia (Donat et al., 2013). Extreme precipitation events were found to show no systematic temporal trend at Svalbard from 1979 through the early 2000s (Serreze et al., 2015), and there is similarly no trend in heavy precipitation events in Alaskan station data over 1949–2012 (Bieniek and Walsh, 2017). Lader et al. (2017) evaluated the frequency of extreme precipitation days in Alaska using both station data and five different atmospheric reanalyses; no notable trends were found over the 1979–2009 period (Lader et al., 2017: fig. 10). On the other hand, the most recent U.S. National Climate Assessment shows that the percentage of precipitation falling in the heaviest percentile of precipitation events over Alaska increased by 11% during the 1958–2012 period, although the trend is not statistically significant (USGCRP, 2014: fig. 2.17). The regional trends reported above are very sensitive to the study period, especially for a variable such as precipitation for which internal variability is large. The combination of internal variability and relatively short (several decades) study periods is likely to be the reason for the decreases noted above in parts of Canada.

4.2.2.2 Future projections

In contrast to the general lack of observational evidence for consistent trends in extreme precipitation over the circumpolar Arctic, projections of Arctic precipitation point to increased intensities and/or shorter return periods for heavy precipitation events. When expressed as percentage changes, the heaviest precipitation amounts generally increase more than the annual mean precipitation (Kharin et al., 2013). The Coupled Model Intercomparison Project phase 5 (CMIP5) models project increases of 20–30% for the maximum 5-day precipitation amounts within a year over most Arctic land areas by 2081–2100 under the RCP8.5 scenario (Collins et al., 2013:1083-1086). These increases are consistent with projections for much of the Northern Hemisphere and with the 7% increase of saturation vapor pressure per °C of warming (Clausius-Clapeyron equation).

An aggregation of results from eight selected CMIP5 models suggests that the 50-year return amounts of daily precipitation will increase in high latitudes (Toreti et al., 2013). The regions with consistent results from the eight models include northern Eurasia in winter and the Arctic Ocean in summer. Based on the CMIP5 results, increases in the Arctic, particularly in winter, are also projected for the 20-year return level of daily precipitation (Kharin et al., 2013), very-wet-day precipitation, maximum 5-day precipitation, and the number of days with heavy precipitation (Sillmann et al., 2013b). More recently, Kusunoki et al. (2015) examined changes in precipitation intensity projected for the Arctic by a high-resolution (60 km) global climate model. Monotonic increases in the late 21st century were found in the Arctic's (67.5–90°N) annual mean precipitation, a daily precipitation intensity index, and maximum 5-day precipitation totals (R5d) averaged over the Arctic.

In addition to changes in the return periods and intensities of precipitation events of various thresholds, changes in the phase of precipitation present challenges in the Arctic. Freezing rain is a high-impact weather phenomenon in the Arctic, and its trends and changes are discussed in Section 4.2.5. More generally, changes associated with the transition from snow to rain in a warming climate can shorten the snow season to the extent that snow season lengths previously considered extremely short may become the norm in the future. Landrum and Holland (2020) showed that, while a statistically significant signal of this change from snow to rain has not yet emerged in the Arctic, it is likely to emerge in the mid- to late 21st century and impact the hydrological regime of the Arctic.

4.2.2.3 Summary

The preceding review points to a consistent expectation that heavy precipitation events will increase in northern high latitudes. However, the evidence for an observed increase over recent decades is mixed, at best. The evidence to date is also less compelling than for corresponding mid-latitude regions (IPCC, 2013; USGCRP, 2014). Measurement challenges, regional variability, sensitivity to record length, and the variability of precipitation are factors contributing to the weaker signal in the extremes of high-latitude precipitation. Nevertheless, heavy precipitation events have major impacts, so the emergence of the signal indicated by climate models should be a high priority for climate monitoring in high latitudes.

As is the case with extreme temperatures, there is little published literature on changes in the exceedances of precipitation thresholds for particular impacts. This situation is not surprising because the precipitation thresholds for particular impacts vary with region and season, with the duration of the precipitation event, and usually with preconditions (soil moisture, freeze/thaw state of the ground, presence of snow or ice). Nevertheless, the evaluation of frequencies of threshold exceedances targeted to particular impacts represents an opportunity to bridge climate science with the needs of communities and other stakeholders. Flooding, which is the topic of the following section, is perhaps the most obvious example of the need for user-relevant applications of research on extreme precipitation.

4.2.3 Inland flooding

Extreme flooding events in the Arctic fall into two categories: coastal floods and river floods. Coastal floods generally result from wind-driven waves, often associated with coastal storms, and are often exacerbated by elevated sea level resulting from low atmospheric pressure (inverse barometer effect), high tides, the slow background rise of sea level driven by climate change, and destabilization of the coastline because of thawing permafrost. As discussed later (Section 4.2.13), the loss of sea ice has resulted in increased vulnerability to coastal flooding and erosion in many Arctic coastal regions. The focus of this section is on interior regions where heavy rainfall events are key drivers of river floods, although compounding factors in high latitudes include the springtime snowmelt and ice jams on rivers. The presence of permafrost in Arctic catchments may further promote flooding of wetland areas due to reduced infiltration. Examples of recent high-latitude floods in which springtime snowmelt and ice jams played key roles include the major flood disasters in Edeytsy on the Lena River and Galena on the Yukon River in spring 2013 (Kontar et al., 2018). Figure 4.2 shows the Galena flood. More recently a flood event caused by heavy rains occurred in the Irkutsk Oblast region, southeastern Siberia, in June 2019. Over 6000 homes were inundated and the floods affected more than 30,000 people (Floodlist, 2019a). The area was hit by a second flood at the end of July, which led to another 2600 people being affected (Floodlist, 2019b). Summer floods attributable to heavy rain have also been documented in unpopulated areas such as Alaska's North Slope, where a 50-hour duration heavy rain event in July 1999 led to flooding of the Kuparuk River (Kane et al., 2003).


E. Plumb, NOAA/ National Weather Service

Figure 4.2 Ice-jam flooding in Galena, Alaska during May, 2013. The ice-covered Yukon River is in the upper left part of the photo.

4.2.3.1 Recent trends

Arheimer and Lindström (2015) used data from 69 gauging sites in Sweden to conclude that there has been no significant trend in the annual maximum daily river discharge over the past 100 years. Their results were qualitatively in agreement with those of Shiklomanov et al. (2007), who analyzed data on floods in Russia, where flooding causes more damage than any other type of natural disaster. While the authors found a significant shift to earlier spring discharge, there was no evidence of widespread trends of maximum-discharge events over the Russian Arctic, leading Shiklomanov et al. (2007) to question the validity of hypotheses that the risks of extreme floods are increasing. In the North American sector of the Arctic, a trend towards an earlier spring discharge peak in the Mackenzie River was reported by Yang et al. (2014) for the period 1973–2011, together with a decrease in the maximum spring flow. More recently, Burn et al. (2016) studied flood regimes for four periods spanning 50 to 80 years in 132 Canadian watersheds using a peak-over-threshold (POT) approach. Their results indicate that there are smaller magnitude snowmelt events, but an increased number of POT events over the study period. Burn et al. (2016) also noticed a shift in flood regimes, with decreased importance of snowmelt events and increased importance of rain-on-snow and rainfall events. For the Yukon Basin in Alaska, Ge et al. (2012) found a small increase in the springtime peak flow over the 1977–2006 period, together with a slight shift to an earlier date, consistent with springtime warming. The magnitude of the yearly maximum flood peak in the Yukon Basin is positively correlated with yearly maximum snow-water equivalent (Yang et al., 2009).

Glacial melt during the warm season can trigger floods in some areas of the Arctic. Dahlke et al. (2012) examined trends in flooding in northern Sweden, focusing on two subarctic catchments with contrasting glacier coverage. While both catchments experienced warming but little change in precipitation over the study period (1985–2009), the glaciated catchment showed a statistically significant increase in flood magnitudes, while the non-glacierized catchment showed a significant decrease. Drainage of ice-dammed lakes, or glacial outburst floods, occur when an ice-dam fails or a moraine is breached (e.g., Emmer, 2017) in various Arctic and subarctic regions, including Alaska, Canada and the Himalayas. However, there has been little work on temporal trends in glacial outburst floods.

4.2.3.2 Future projections

Several studies have addressed future changes in high-latitude flooding. Hirabayashi et al. (2013) found that, during the 21st century, the projected return period of the 100-year flood decreases in most of the river basins included in their global analyses. Considering the largest rivers in the Arctic, the return period is expected to decrease for the Yukon, Mackenzie, Yenisey, and Lena basins, but increase for the Ob basin where the peak of spring snowmelt will decrease, as is the case for smaller rivers in northern Europe. This finding is consistent with the results of Arheimer and Lindström (2015) for Sweden and Olsson et al. (2015) for Finland. According to Arheimer and Lindström (2015), high-resolution climate model projections suggest a future decrease of the annual maximum daily river discharge by approximately 1% per decade, driven mostly by a decrease of spring snowmelt. On the other hand, the autumnal maximum daily river discharge may increase by 3% per decade, driven by more intense precipitation. Further, the boundary zone between snow- and rain-driven floods in Sweden is projected to move northwards. According to Olsson et al. (2015), spring floods in Finland will occur earlier and become weaker towards the end of the century, also yielding mostly negative trends in annual high flows. Lehner et al. (2006) showed that, even if spring floods become weaker in Fennoscandia, the overall frequency of extreme floods (during the entire year) may increase. Finally, Shevnina et al. (2017) compared the periods 2010–2039 and 1930–1980, and identified large regions in the Russian Arctic where the spring runoff flood depth is projected to increase by more than 30%. Their study was based on a probabilistic hydrological model, which used climate model projections as input.

While most of the studies surveyed above pertain to inland flooding, Arctic coastal regions are increasingly vulnerable to floods as the loss of sea ice increases the likelihood of large waves in conjunction with storm surges. A prime example in northern Alaska is Utqiagvik (Lynch et al., 2004), where recent floods have threatened the community's freshwater reservoir. Future projections point to increasing frequencies of wave-driven flooding. For example, along the Beaufort Sea coastline, a once-in-20 year event under historical (1979–2005) climate is projected to occur, on average, once every 2 to 5 years by the late 21st century (Casas-Prat and Wang, 2020).

4.2.3.3 Summary

Inland flooding differs in its causes from coastal flooding, for which there is evidence that impacts are increasing because of the loss of sea ice. An overall assessment of trends in inland flooding is challenging because the climate literature does not provide evidence of widespread (pan-Arctic) trends. Inland flooding is nevertheless a high-impact and high-visibility feature of high-latitude climate. The absence of widespread trends in inland flooding is consistent with the absence of spatially homogeneous trends in heavy precipitation (Section 4.2.2.1). Rather, the spatially heterogeneous changes in heavy precipitation and inland flooding point to the more local nature of reports of increased flooding (Chapter 7). As noted in Section 4.2.2.2, however, the projected increases in heavy precipitation and hence the potential for increased flooding are a robust feature of climate model projections for northern land areas.

Of the various extreme events discussed thus far, floods have arguably the most clearly defined thresholds if using water levels as metrics. Burn et al.'s (2016) peak-over-threshold approach serves as an example, although the incorporation of atmospheric drivers into this approach is confounded by the roles of snowmelt and river ice in ice-jam flooding. Nevertheless, hydrological modeling offers the potential to incorporate information on climate change into quantitative assessments of changes in flood threshold exceedances.

4.2.4 Snow

Metrics of snow include both snowfall and snow-on-ground (extent, depth, location). The vast majority of climatological studies have been based on the latter category of metrics, in part because direct measurements of snowfall in the Arctic are sparse, subject to substantial error, and often spatially unrepresentative.

4.2.4.1 Recent trends

Recent studies that have documented variations in the extent and duration of snow cover in the Arctic include those of Brown et al. (2017) and Mudryk et al. (2019). The variations and trends identified in these studies provide a backdrop for evaluations of extreme snow event occurrences. Consistent with the recent climate warming, there is a general trend towards a shorter snow season and reduced snow extent, especially in the spring months of April–June. For both May and June, recent years have seen record low monthly snow extents in both Eurasia and North America (Mudryk et al., 2019: fig. 5.19; see also Chapter 2). An important caveat is that interannual variability is large. For example, the April snow-water equivalent over Eurasia was actually a new extreme maximum in 2018 (Mudryk et al., 2019).

Few studies have addressed extremes of individual snowfalls or related snow metrics in the Arctic or other regions (NAS, 2016). Among the exceptions are several studies documenting the impacts of aggregate snowfall events that have impacted wildlife populations (Klein et al., 2009; Schmidt et al., 2019). While these two studies demonstrate negative impacts of heavy snow events on wildlife, other environmental factors (e.g., icing, temperature, vegetative disturbance by fire and insects) as well as population density can also be major determinants of the impacts. Nevertheless, these types of study indicate that wildlife populations are vulnerable to threshold exceedances, even though the thresholds may be multivariate and/or dependent on multiple events that contribute to environmental conditions of exceptional severity.

4.2.4.2 Future projections

The general decreases of snow extent and duration are projected to continue through the remainder of the 21st century (Brown et al., 2017; Landrum and Holland, 2020). However, the annual maximum snow-water equivalent is projected to increase over much of northeastern Asia and northern Canada (Brown et al., 2017: fig. 3.18), even under the RCP8.5 scenario, pointing to a likely increase of heavy snow events during the shortened cold season. The increase in heavy snowfalls near the Arctic Ocean should be enhanced by the increased fluxes of latent and sensible heat resulting from the reduction of the sea-ice cover (Liu et al., 2012). The combination of a shorter snow season but greater water equivalents is consistent with O'Gorman's (2014) conclusion that, for the coldest climates, the occurrence of extreme snowfalls should increase with warming due to increasing atmospheric water vapor, while for warmer climates it should decrease because sub-freezing temperatures will be less frequent.

4.2.4.3 Summary

While there have been evaluations of model projections of changes in mean snow cover, maximum snow depth, and snow-season length (e.g., Brown et al., 2017; Mudryk et al., 2020; see also Chapter 3), the authors of this review are not aware of any systematic evaluations of future changes in heavy snow or other snow-related extreme events in the Arctic. It is expected that future changes in heavy snowfall in northern high latitudes will be spatially divergent and sensitive to air temperature. In the warmer climate zones, given the evidence for decreasing snow extent, especially in the spring season, it may reasonably be inferred that heavy snowfall events have also been decreasing and will continue to decrease as mean snowfall and snow extent decrease in the future. In the colder zones, an increase of heavy snowfall events is expected. Therefore, trends in heavy snow events are assigned medium levels of confidence in the summary assessment in Section 4.3. The use of thresholds is notably absent from evaluations of trends in extreme snow events.

4.2.5 Freezing rain

A type of extreme event with major impacts in the Arctic is freezing rain, often referred to as a rain-on-snow event. Because ice layers can persist for weeks or even months in the Arctic, freezing rain is a major hazard to surface transportation and to foraging wildlife (Hansen et al., 2011) and it may increase the risk of avalanches (Conway and Raymond, 1993). Forbes et al. (2016) described major rain-on-snow events during November 2006 and 2013 that resulted in massive reindeer mortality on Russia's Yamal Peninsula. However, applying stochastic models of population dynamics, Hansen et al. (2019) concluded that more frequent rain-on-snow events may stabilize the population of wild reindeer in Svalbard.

4.2.5.1 Recent trends

In one of the few systematic evaluations of freezing rain occurrences, Groisman et al. (2016) showed that freezing rain frequencies in the North American Arctic increased by about one day per year in the 2005–2014 decade relative to the three previous decades. Substantial increases were detected over northern Norway, while somewhat less coherent patterns of increase were found over Siberia and European Russia. A similar hemispheric-scale analysis for a longer period (1979–2014) by Cohen et al. (2015) was based on two atmospheric reanalysis products (MERRA and ERA-Interim). Cohen et al.'s (2015) results showed little coherence in winter trends of rain-on-snow events on the continental scale, although there were decreases in the frequency of the MERRA-derived events during autumn and winter over western Scandinavia and southwestern Alaska. Cohen et al.'s (2015) noted decrease over Norway contrasts with Groisman et al.'s (2016) results, pointing to the sensitivity to the timeframe as well as to the potentially important distinction between freezing rain events documented by Groisman et al. (2016) and rain-on-snow events documented by Cohen et al. (2015). Focusing on Svalbard, Peeters et al. (2019) found that at Ny Ålesund (data since 1969) and Svalbard Airport (data since 1957), every third to fourth winter during the earlier decades elapsed with practically no rain, but in 1998 the climatic regime shifted so that some rain occurred in virtually every winter.

4.2.5.2 Future projections

With regard to future changes, Hansen et al. (2014) examined the temperature dependence of historical freezing rain events in Svalbard and concluded that the frequency of rain-on-snow events is likely to increase in the Arctic. On the basis of output from 37 CMIP5 climate models, Bintanja and Andry (2017) calculated that during this century in the Arctic (70–90°N), the average annual snowfall will decrease but rain will increase. The increase of rain will be strongest in summer and autumn but will also occur in winter, which will result in increasing occurrence of rain-on-snow events. On the basis of regional climate model simulations, Bieniek et al. (2018) showed that rain-on-snow events are projected to increase in frequency over much of Alaska but are expected to decline over southwestern/southern Alaska. The increases in frequency are the result of more frequent winter rainfall, while the decrease of freezing rain in southwestern Alaska is attributable to the rise of temperatures above the freezing threshold. Based on associations derived from remote sensing products over a shorter period (2003–2016), Pan et al. (2018) also concluded that rain-on-snow events will increase in frequency and extent over much of Alaska in the future. This increase is consistent with a broader projected increase of 40% in the total hemispheric rain-on-snow area by 2080–2089 (Rennert et al., 2008). Excursions of temperature above the 0°C threshold in the lower troposphere are clearly at the core of any changes from snow events to rain-on-snow or freezing rain. There have been few diagnoses of changes in freezing rain events in terms of lower tropospheric temperature profiles, presumably because of the challenges in resolving the vertical structure of temperature profiles conducive to freezing rain. An exception is Jeong et al.'s (2019) evaluation of annual maximum freezing rain amounts and ice accretion design loads over North America based on an ensemble of Canadian regional climate model simulations. As shown in Figure 4.3, the annual freezing precipitation amounts and corresponding ice loads were found to increase with global mean temperatures poleward of about 60°N but to decrease substantially in middle latitudes of North America.

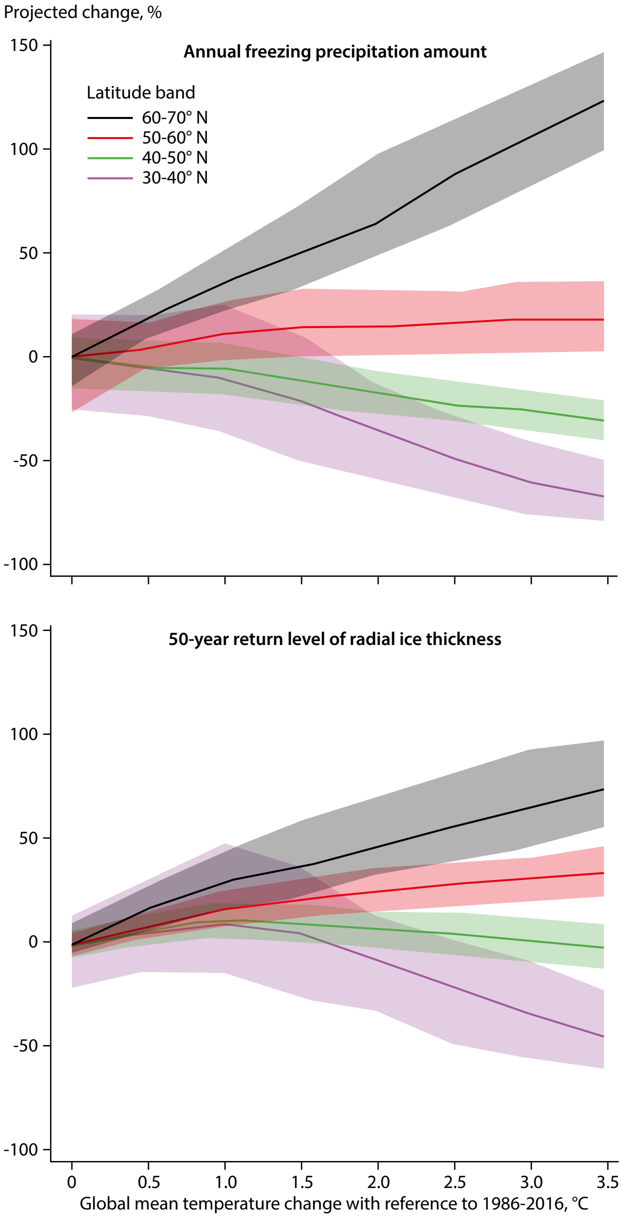

Figure 4.3 North American latitudinal averages of annual freezing precipitation amount and the 50-year return level of radial ice thickness as a function of the global mean temperature change. Results are based on an ensemble of 50 Canadian regional climate model (CanRCM4) simulations and are shown for four latitude bands. Shading denotes range between 5th and 95th percentiles. Source: Jeong et al. (2019).

4.2.5.3 Summary

It is apparent from Section 4.2.5.1 that evidence for systematic changes of freezing rain occurrences in northern regions is not strong and is limited to specific areas for which appropriate data exist. However, the absence of widespread changes may be due largely to the inadequate data on freezing rain, which is not readily derivable from models or reanalysis products and which is often not captured by the sparse reporting network of high latitudes. There is good consistency in model projections of a change in the rain-snow partitioning and the potential for freezing rain in high latitudes. To the extent that the surface remains below freezing in these regions, a general increase of freezing rain is a reasonable expectation. The relevant threshold is clearly 0°C for both the surface and the lower atmospheric temperature profile.

4.2.6 Atmospheric blocking

High-latitude blocking often represents persistent, quasi-stationary anticyclonic conditions that divert the zonal path of the polar jet stream and tend to yield more meridional transport of storms into and out of the Arctic (Woollings et al., 2018). High-latitude blocking has received increased interest in recent years, especially in the context of Arctic/mid-latitude linkages in weather and climate (e.g., Vihma, 2017; Cohen et al., 2020).

4.2.6.1 Recent trends

As with analyses of Arctic storminess (see Section 4.2.7), there are varied findings related to trends in blocking. Such changes tend to be sensitive to the selection of the blocking index and associated measurement characteristics (i.e., frequency, intensity, and event duration thresholds) (Woollings et al., 2018), not to mention the time period of analysis (Barnes et al., 2014). Using three distinct blocking indices, Barnes et al. (2014) did not find increases in Northern Hemispheric blocking frequency at the seasonal scale over the 1980–2012 period. However, the authors noted substantial spatio-temporal variability and an increasing summer (JJA) regional trend over 1980–2012 in North Atlantic sector blocking based on an index identifying persistent 500 hPa geopotential height reversals. Davini et al. (2012) found a decreasing trend in winter (DJF) blocking events of at least five days during 1951–2010, including over the Canadian Archipelago and northern Siberia, while Luo et al. (2019) found increases in winter high-latitude European and Ural blocking events of three or more days during 1979–2015 under low (versus high) sea-ice conditions.

Regional metrics and assessments have been developed for blocking hotspots using domain-averaged geopotential height fields, including for Arctic sectors centered on Greenland (e.g., Hanna et al., 2016; McLeod and Mote, 2016), and Alaska (McLeod et al., 2018). McLeod et al. (2018) identified statistically significant increases in Alaskan Blocking Index (ABI) values over annual and summer periods during 1981–2010. For the Atlantic sector, Hanna et al. (2016) constructed a long-term (1851–2015) Greenland Blocking Index (GBI) and found a statistically significant increasing linear trend in the index across all seasons, most notably a trend during summer from 1981–2010 that exceeded changes in previous epochs. In complementary daily analyses, Hanna et al. (2018a) noted that the number of GBI days exceeding 1 and 2 standard deviations from the mean had increased since 1990 during summer, winter, and on the annual timescale. Remarkably, over the aforementioned period, the authors detected a statistically significant increase of about 43 days in the annual number of days with GBI values >1; this trend reflects a clear change toward increasing frequency of northwest Atlantic extreme high-pressure patterns with consequences for the region's cryosphere (see Section 4.2.10). Assessing 7-year periods since 1958, McLeod and Mote (2016) found a consistent increase in the annual number of Greenland extreme blocking events (i.e., ≥5d of GBI ≥97th percentile of daily values) from 1986–1992 to 2007–2013, which suggests an increase in blocking duration as well as frequency over the recent period of accelerating Arctic change.

Despite historical changes in high-latitude blocking characteristics, atmosphere-only (e.g., AMIP) and coupled (e.g., CMIP) climate model simulations have generally failed to capture such changes. Relative to previous generations of coupled models, Davini and D'Andrea (2016) noted improvement for the winter season in the CMIP5 ensemble mean in depicting retrospective Pacific blocking frequency, but little advancement for the Greenland region. Hanna et al. (2018b) and Delhasse et al. (2021) similarly found that all CMIP5 and CMIP6 models, under RCP4.5 and RCP8.5/SSP5-8.5 scenarios, greatly underestimated the observed magnitude of Greenland summer blocking increases over the 1996–2015 period. Analyses using CMIP6 suggest that the current generation of global models continues to underestimate the frequency of Greenland blocking during summer (Davini and D'Andrea, 2020).

4.2.6.2 Future projections

In view of the major shortcomings of global climate models in capturing recently observed high-latitude blocking frequency and intensity changes, especially over Greenland, it is not surprising that robust conclusions about future changes in blocking events in high latitudes have yet to emerge. It follows that, at the present stage of the science, future projections of high-latitude blocking should be interpreted with caution.

4.2.6.3 Summary

While there are indications of recent changes in atmospheric blocking in some regions and seasons, the evidence is not sufficient to permit definitive conclusions about hemispheric or even pan-Arctic trends. Moreover, climate models do not simulate blocking sufficiently well to permit conclusions about future changes based on model projections. One of the challenges in such assessments is the use of different metrics for blocking activity. A generally accepted and consistently applied metric of blocking is a prerequisite for definitive evaluations of trends in blocking over northern regions.

4.2.7 Cyclones

Arctic cyclones occur in all seasons and range in scale from mesocyclones ('polar lows') to frontal cyclones with scales that can exceed a thousand kilometers (Tilinina et al., 2014). Arctic cyclones affect coastal infrastructure and erosion rates (Section 2.13), as well as sea ice and subsequent Arctic temperatures through their effects on sea ice. These effects on sea ice include reduced sea ice growth during winter due to the influxes of atmospheric and ocean heat, insulation of the sea ice by the deeper snow pack, and the formation of high-salinity 'snow ice' when the weight of the snow pack results in a negative freeboard (Graham et al., 2019). The deepened snow pack caused by storms has recently been shown to have a greater impact on sea-ice thickness than the direct effect of the transient warming driven by the same storms (Merkouriadi et al., 2020).

4.2.7.1 Recent trends

Analyses of observational data have produced mixed results on trends of high-latitude cyclones and storminess. In two of the more recent studies, increases in Arctic cyclone activity were detected by Rudeva and Simmonds (2015) for the period 1979–2013 and by Zahn et al. (2018) for the period 1981–2010. Rinke et al. (2017) found that the frequency of extreme cyclone events in the subarctic North Atlantic has increased at a rate of six events per decade over 1979–2015. This trend is dominated by large increases in November and December, consistent with a diminished sea-ice cover (Moore, 2016) and changes in atmospheric blocking patterns in the North Atlantic sector (see Section 4.2.6). For the period 1979–2016, Wickström et al. (2020) detected an increase in the occurrence of winter (DJF) cyclones around Svalbard and the northwestern Barents Sea, while Koyama et al. (2017) reported an increase in the occurrence of extreme cyclones in the Svalbard region.

In most of the above-mentioned studies, the increase in Arctic cyclone activity has been associated with a northward shift of storm tracks. McCabe et al. (2001) reported such a shift over the Northern Hemisphere during the last decades of the 20th century. Wang et al. (2006) detected a northward shift of cyclone activity, primarily during winter, over Canada during 1953–2002, and this meridional shift was confirmed more generally in a more recent study by the same group (Wang et al., 2013). The Third U.S. National Climate Assessment (Melillo et al., 2014) pointed to a poleward shift of storm tracks over North America during recent decades. Further, Tamarin-Brodsky and Kaspi (2017) suggested that cyclones propagate further north under externally forced (anthropogenic) climate change.

In contrast to the findings summarized above, other studies suggest little or no increase in cyclone activity. Mesquita et al. (2010) found that temporal trends of cyclones in the North Pacific Ocean have generally been weak over the 60-year period ending 2008. Walsh et al. (2011a,b) concluded that storminess had increased in parts of the North American Arctic since the 1960s, but not in the circumpolar Arctic as an average. Koyama et al. (2017) detected an increase in baroclinicity in the Arctic but not in the occurrence of cyclones except for extreme cyclones in the Svalbard region (see above). In contrast to their results for the Svalbard region, Wickström et al. (2020) detected a decrease in cyclone occurrence in the southeastern Barents Sea during 1979–2016, associated with an increased occurrence of a Scandinavian blocking pattern.

Some of the most intense Arctic cyclones are mesoscale low-pressure systems, often referred to as 'polar lows' (Rasmussen and Turner, 2009; Kolstad, 2011; Stoll et al., 2018). While they can occur in all subpolar seas when cold air flows over open water in the subarctic region, polar lows are most common in the high latitudes of the North Atlantic, especially the Nordic Seas (Noer et al., 2011; Rojo et al., 2019). Global reanalyses and climate models generally lack the spatial resolution to capture these mesoscale systems. Condron et al. (2006) and Condron and Renfrew (2013) have shown that in the subarctic North Atlantic this under-representation is especially problematic. Because of the difficulties in resolving polar lows and documenting their occurrences, there is little available pan-Arctic information on historical trends or projections of future changes in polar low activity. In regional studies, Zahn and von Storch (2008) found little evidence of historical trends in North Atlantic polar lows.

4.2.7.2 **Future projections**

With regard to future changes in Arctic cyclones, the published literature does not reveal a consistent pan-Arctic signal. Based on CMIP5 simulations forced by the RCP4.5 scenario, Zappa et al. (2013) found a general decrease in future cyclone activity over the North Atlantic Ocean, except for a projected increase in the cyclone track density near the southern tip of Greenland in summer. On the broader hemispheric scale, projected changes in the frequency of extratropical cyclones are generally small in the aggregate of the CMIP5 models. There are some hints of a northward shift in the storm tracks, but overall the Northern Hemisphere shows a weaker and much less spatially coherent poleward shift of storm tracks than is apparent in the projections for the Southern Hemisphere (Collins et al., 2013: fig. 12.20).

Zahn and von Storch (2010) found that the frequency of occurrence of polar lows in the North Atlantic is projected to decrease because of a projected increase of the static stability of the air over the North Atlantic. Further, using marine cold-air outbreaks as a proxy for the occurrence of polar lows, Kolstad and Bracegirdle (2008) projected a northward migration of polar lows, following the retreating sea-ice margin. Landgren et al. (2019) also found a northward migration in their dynamically downscaled projections of future changes of polar lows in the Nordic and Barents Seas.

4.2.7.3 **Summary**

As was the case with atmospheric blocking, the evidence for changes in cyclones in northern regions is mixed. The discrepancies among the findings in Section 4.2.7.1 may arise in part from differences in the cyclone tracking algorithms applied, especially with respect to the threshold for cyclone identification. Rudeva et al. (2014), for example, showed that even the basic climatological characteristics of cyclones are sensitive to the algorithms used in identifying and tracking cyclones. The trends may also be affected by changes in the availability of *in situ* and remote sensing data. While model projections of future changes are also inconclusive on the hemispheric scale, the suggested northward shift of storm tracks, together with increased availability of heat and moisture from the ice-diminished Arctic Ocean, makes plausible the hypothesis that storm activity may increase in the Arctic.

The impacts of changes in Arctic storm activity are compounded by changes in sea ice, which can serve as a buffer protecting a coastline from wave-driven flooding and erosion. In this context, the U.S. Global Change Research Program (Karl et al., 2009) has used the northern Alaskan coast to illustrate the risks of flooding and coastal erosion. Since the open water season offshore of northern Alaska has lengthened by one to three months in recent decades (Stroeve and Notz, 2018; Thoman and Walsh, 2019), this region highlights the fact that storms in coastal areas of the Arctic pose increasing risks regardless of whether storm activity is changing.

4.2.8 **Wind**

Extreme wind events are generally associated with strong near-surface pressure gradients or orographic effects. The strong pressure gradients often, but not always, occur in association with cyclones. Because high-wind events are impactful whether or not a cyclone is the key atmospheric feature, this section provides a more general assessment of high-wind events.

4.2.8.1 **Recent trends**

While extreme temperature and precipitation events have been the subject of various studies, there are relatively few analyses of high-wind events in the Arctic, especially in the context of climate change. However, extreme winds are common in the Arctic. According to ERA-Interim based global climatology (Kumar et al., 2015), the mean of the annual maximum wind speed is largest in Antarctica, Greenland and other Arctic islands, as well as coastal regions of Siberia, with increasing trends in eastern Greenland. The studies to date of high-wind events have drawn upon a variety of sources of wind information. For example, Lynch et al. (2004) made use of wind observations from Utqiakvik (Barrow) in northern Alaska to assess the impacts of extreme wind events at a single location. Hughes and Cassano (2015) used winds obtained from several reanalysis products and a regional climate model to map the median and 99th percentile wind speeds across the Arctic, with an emphasis on the comparison between the regional model simulations and the reanalyses. Redilla et al. (2019) have recently shown that high-wind events in the Alaska region are associated with synoptic-scale cyclones, with strong anticyclones often in close proximity to enhance the pressure gradient (Figure 4.4).

Orographic effects also play a role in the occurrence and strength of extreme winds (Jonassen et al., 2020). These effects include downslope wind storms (Oltmanns et al., 2014), tip jets (Renfrew et al., 2009), and barrier winds (Harden et al., 2011; DuVivier et al., 2017). Climatologies of the occurrence of orographically-forced strong winds have been calculated for the Greenland region (Harden et al., 2011), for the tip jet south of Spitsbergen (Reeve and Kolstad, 2011), for winds over Novaya Zemlya (Moore, 2013), and for Arctic low-level jets (Tuononen et al., 2015). Downscaling methods have been developed to estimate the high-resolution spatial distribution of strong winds, for example to evaluate the damage they cause to forests in northern Finland (Venäläinen et al., 2017). However, there have been few attempts to assess climatological trends in extreme winds, either historically or in the future. One example is Mölders et al.'s (2016) downscaling of winds for a near-future (2016–2032) time slice in a case study targeting wind energy at a site near Juneau, Alaska.

4.2.8.2 **Future projections**

Several regional studies have pointed to future increases of wind speeds on the northern flanks of present-day storm tracks. Ruosteenoja et al. (2019) analyzed the output of 21 CMIP5 models in the European and North Atlantic sector covering latitudes from 30° to 85°N. Comparing the periods

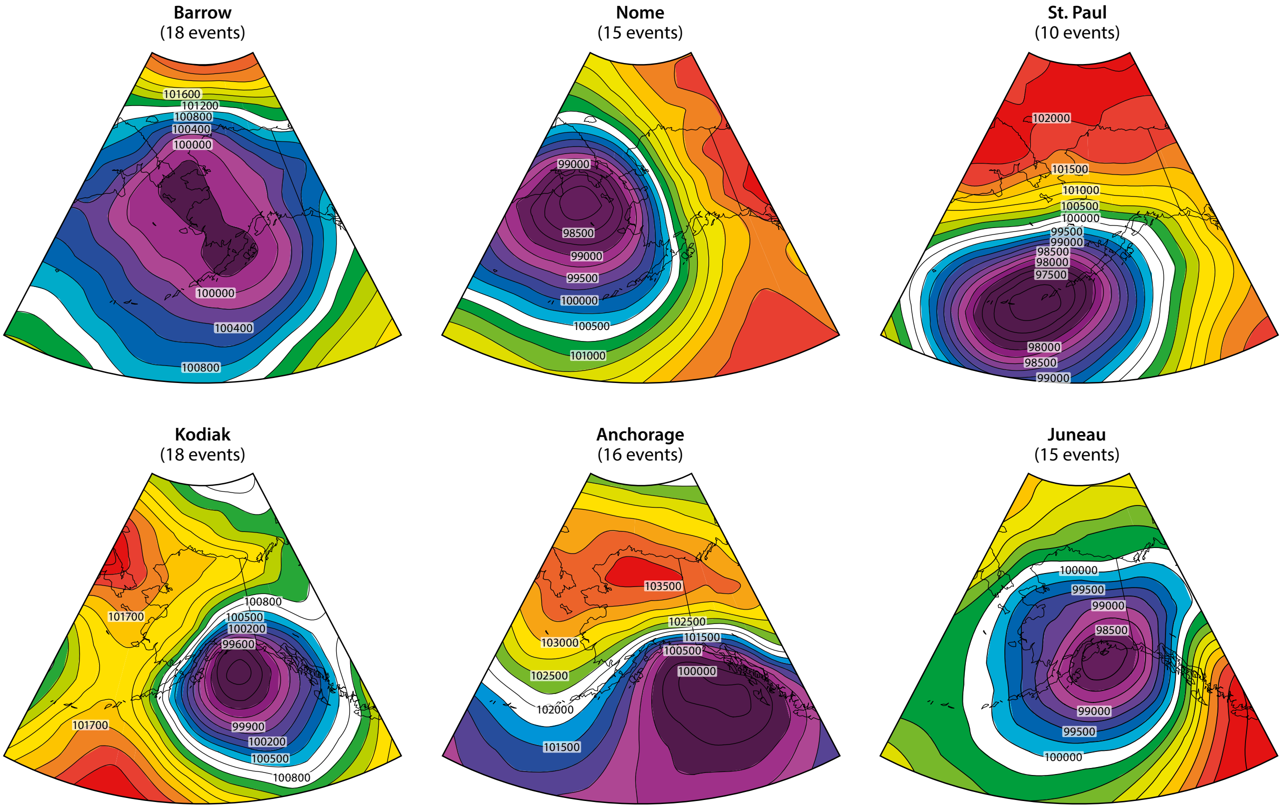

Figure 4.4 Composite sea-level pressure fields for extreme wind events during 1980–2014 at six coastal Alaska locations: Utqiagvik (Barrow), Nome, St. Paul, Kodiak, Anchorage, and Juneau. The number of extreme wind events at each location during this period is as shown. Blue and purple shades denote low pressure, orange and red shades denote high pressure. Units of pressure on the isobar contours are Pascals (Pa); 100 Pa = 1 millibar. Threshold and duration for high-wind events at each location are given by Redilla et al. (2019). Data and mapping software from NOAA Earth System Research Laboratory, www.esrl.noaa.gov/psd/data/composites/hour

1971–2000 and 2070–2099 under the RCP8.5 emission scenario, they found that in all seasons the 99th percentile of the near-surface wind speed will increase most in the northernmost part of the study region. The largest increases were found over the Arctic Ocean north of Greenland and Ellesmere Island in autumn (>10% relative increase) and over the Barents and Kara Seas in winter (5–10%). Over Greenland the 99th percentile near-surface wind speeds were projected to mostly decrease, especially in winter.

In a recent study for the Pacific subarctic, Redilla et al. (2019) synthesized observational data and bias-corrected model output to evaluate the frequencies of occurrence of historical and projected (future) changes of winds at coastal locations around Alaska. High-wind events over the 1980–2014 historical period were found to be most common during autumn and winter, with increasing frequencies in northern and western Alaska and decreases in the southeast. For the future, a regional climate model forced by output from two global climate models projected an increase of high-wind events in the northern and western Alaska coastal regions, which are precisely the regions in which the protective sea-ice cover has decreased (and is projected to decrease further), pointing to increased risks of coastal flooding and erosion.

4.2.8.3 Summary

As is the case with cyclones, the evidence for changes in high-wind events in northern regions is limited, both in the historical data and in climate model projections for the future. The lack of evidence may be partly attributable to the general absence of studies of high-wind events in the Arctic, especially in comparison with evaluations of extreme temperatures and precipitation occurrences. Similarly, there are no consistently utilized thresholds for defining high-wind events in the Arctic. The use of impact-relevant thresholds of wind speed offers an avenue to incorporating thresholds into more systematic assessments of high-wind events in the Arctic. Both marine (e.g., wave-generation) and terrestrial (infrastructure damage) impacts offer possibilities for threshold determination.

4.2.9 Sea ice: rapid ice loss events

The trajectory of Arctic sea ice towards record minima in recent years has received widespread attention in the context of global change. The IPCC (2019: table 6-2), for example, concluded that the record minima of winter/spring 2016 would not have been possible without anthropogenic forcing, but that the relative roles of preconditioning, interannually varying atmosphere/ocean forcing, and storm activity in determining the evolution of Arctic sea ice are still highly uncertain (Petty et al., 2018).

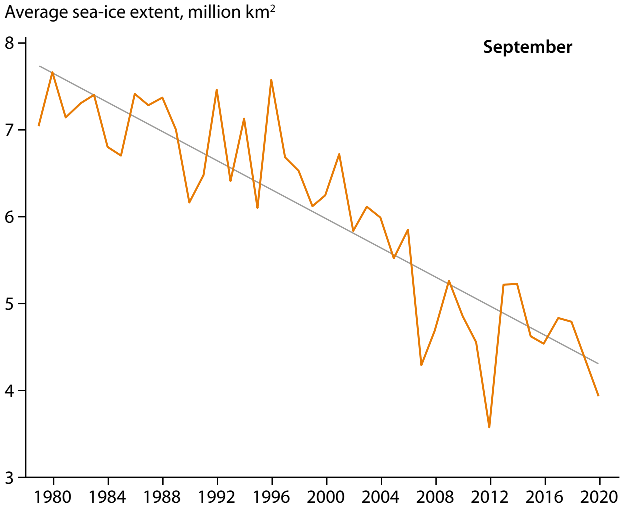

Figure 4.5 September sea-ice extent in the Arctic for the period 1979–2020. Source: National Snow and Ice Data Center.

4.2.9.1 Recent trends

On the interannual to decadal timescales, the decrease of Arctic sea ice has been characterized by years of exceptionally large ice loss, often followed by a year or two in which sea-ice extent increases but not to its prior level (Figure 4.5). In the post-2000 period, 2007 and 2012 stand out as such years, as do 1985, 1990, and 1995 in earlier decades. Holland et al. (2006, 2008) examined rapid ice loss events (RILEs), which were defined as periods when the loss of September sea-ice extent over a five-year period exceeded 0.5 million km^2. These events, defined by various similar criteria, have been addressed further in the context of interannual-to-decadal changes by Döscher and Koenigk (2013) and Rogers et al. (2015), among others. RILEs have accounted for most of the reduction of Arctic sea-ice extent over the past several decades (Holland et al., 2006).

Much less attention has been paid to extreme losses over shorter timescales, i.e., several days. The work that has been done on these timescales has generally focused on storm events. The thinning and reduction of extent of Arctic sea ice can make the ice cover more vulnerable to the wind-forcing and associated ocean mixing. Indeed, the record minimum of sea-ice extent in September 2012 (lower by 0.67 million km^2 than any other year on record through 2019) has been attributed partially to the occurrence of a strong cyclone in August 2012 (Parkinson and Comiso, 2013). However, while the 2012 Arctic cyclone was indeed extreme (Simmonds and Rudeva, 2012), another study (Zhang et al., 2013) concluded that the storm accounted for only 0.15 million km^2 of sea-ice loss. Regardless of the role of the strong cyclone, the extreme minimum of sea-ice extent in 2012 has been shown by Kirchmeier-Young et al. (2017) to be consistent with a scenario including anthropogenic forcing and extremely unlikely in a scenario excluding anthropogenic forcing.

Wang et al. (2020) identified large daily loss events (LDLEs) both regionally and on a pan-Arctic basis. LDLEs in most regions show significant associations with poleward moisture transport into the region and with column water vapor in the immediate vicinity. Central Arctic LDLEs are associated with warm air inflow from the North Atlantic but not the North Pacific. Signatures of atmospheric rivers are apparent in regional LDLEs from the Greenland Sea through the Russian subarctic to the Beaufort/Chukchi/East Siberian Seas. Pan-Arctic LDLEs show no such signature. The number of LDLEs is significantly correlated with September ice extent on the pan-Arctic scale and in several subregions, including the central Arctic.

4.2.9.2 Future projections

While there is a growing literature on projected future changes in mean sea-ice extent and thickness (see Chapter 3), little work has been done on future RILEs. A few model-based studies suggest that RILEs will continue to account for most of the reduction of Arctic sea-ice extent in the future (Holland et al., 2006; Paquin et al., 2013). Holland et al. (2008) used the CCSM3 model to evaluate the future trajectory of the Arctic's summer sea ice, which is driven by a combination of anthropogenic forcing and natural variability. The natural variability was found to increase as the ice thins, but there was no strong evidence of a threshold beyond which rapid year-to-year ice loss increases. Future changes in the LDLEs, during which sea ice is lost rapidly over synoptic timescales (days), have yet to be addressed.

4.2.9.3 Summary

There is strong evidence that Arctic sea-ice coverage has decreased in recent decades and that it will continue to decrease in the future if anthropogenic forcing continues to increase. There is also evidence that much of the loss of sea ice occurs during 'rapid' year-to-year loss events, and that this will continue to be the case in the future. It follows that the increased sea-ice loss of the past few decades occurred during a period of more frequent rapid ice-loss events compared to earlier decades. While this trend can be expected to continue, the more aggressive scenarios of ice loss result in an ice-free Arctic during summers by mid-century, in which case there will be little or no ice to lose in RILEs. The same reasoning applies to short-term (days) ice loss events in response to cyclones or other high-wind events, as a thinner ice cover will be increasingly vulnerable to storms in coming decades but the frequency of large loss events will decrease when there is little ice to lose. For both the synoptic (daily) and interannual timescales, there is no strong evidence of specific thresholds pertaining to large ice loss events.

4.2.10 Greenland Ice Sheet: extreme melt events

The Greenland Ice Sheet (GrIS) has been losing mass at accelerated rates in recent decades (King et al., 2020). While much of the mass loss occurs through discharge of outlet glaciers, summer melt also contributes substantially to the loss of mass. Because summer melt events are more directly linked to extreme atmospheric forcing events (e.g., anomalous summer warmth), the focus is on Greenland's extreme melt events in this review. Calving and discharge from outlet glaciers are not included here because ice sheet and glacier dynamics are driven in more complex ways by forcing over a broader spectrum of timescales.

4.2.10.1 Recent trends

The GrIS has experienced record melt in recent years, including 2012 and 2019 (Figure 4.6). These extreme summer melt years are part of an ongoing trend towards increased melt, runoff and mass loss from the GrIS (IPCC, 2019: section 3.3; Hanna et al., 2020a), and reflect significant Greenland warming that, as part of Arctic Amplification, averaged around 1.7°C in summer for the period 1991–2019 (Hanna et al., 2020a). The increase in melt is non-linear, and recent melt levels in central-west Greenland have not been seen for at least 7000 years (Trusel et al., 2018). While oceanic drivers including the Atlantic Multidecadal Oscillation (AMO) are increasingly recognized as playing a role in recent mass losses, atmospheric factors contributing to this trend include a background warming and a general decrease in the magnitude of the North Atlantic Oscillation (NAO) since 1990 with more frequent and higher intensity blocking weather patterns over Greenland (Tedesco et al., 2013; Hanna et al., 2015, 2016, 2018b), decreased summer cloud cover/increased shortwave insolation (Hofer et al., 2017), and surface albedo feedbacks (Box et al., 2012; Cook et al., 2019). These factors combine to produce extreme melt events such as those of 2012 and 2019 (Hanna et al. 2014, 2020a).

Although the summers of 2012 and 2019 both had extreme blocking over Greenland (see Section 4.2.6), their synoptic characteristics were somewhat different. The mid-July 2012 melt peak involved advection of relatively warm air from the southwest up over the western flank of the ice sheet, which is the more conventional direction of airflow seen in most other recent warm summers. By contrast, the 2019 extreme melt in late July / early August was driven by a plume of warm air originating from record-breaking heat over Europe, from where this airmass was transported westwards over Greenland and warmed adiabatically as it descended over the west side of the ice sheet (NSIDC, 2019; Hanna et al., 2020a). As a result, Summit at the top/center of the GrIS (3200-m elevation) experienced its highest temperature on record (1.2°C) on 31 July 2019, while Danmarkshavn (northeast Greenland coast) recorded a new record maximum August temperature of 19.7°C. The 2019 warmth/melt was most extreme in far northern Greenland, somewhat following the pattern of 2015, which was another Greenland high melt year (Tedesco et al., 2016). This may reflect northward recession of sea ice earlier in the melt season, as well as a systematic shift in the North Atlantic atmospheric circulation towards a more negative summer NAO and increased (decreased) cloud coverage over northern (southern) Greenland since the 1990s (Noël et al., 2019). Because the GrIS is already relatively warm around its margins in summer, more frequent and extreme melt events occur with only modest (~1°C) additional temperature rises; this is also a function of the gently-sloping surface topography at and above elevations of ~1500–2000 m (around the level of the current equilibrium line altitude), which exposes much greater areas of the GrIS to surface melt as it gets warmer (Hanna et al., 2020b).

Quantification of GrIS melt extremes also depends on the metrics used. Välisuo et al. (2018) found that interannual variations in the maximum melt extent differed from those in the number of melt days, cumulative melt extent, and modeled melt amount. During years 2000 to 2014, total column water was the forcing factor most strongly correlated with interannual variations in the number of melt days ($r^2 = 0.83$), cumulative melt extent (0.84), and modeled melt amount (0.82). According to Välisuo et al. (2018), the maximum melt extent was most strongly (negatively) correlated with the occurrence of airmasses of northeasterly origin on the high plateau.

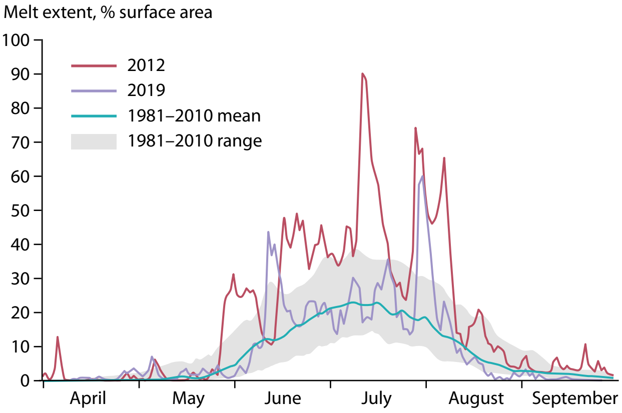

Figure 4.6 Seasonal evolution of the melt area of the Greenland Ice Sheet during 2012 and 2019. Climatology (1981–2010) and range are also shown. Source: Thomas L. Mote, University of Georgia.

4.2.10.2 Future projections

Projected rates of GrIS mass loss by 2100 under all emissions scenarios exceed maximum rates in the last 12,000 years (Briner et al., 2020). Greenland melt projections from a regional climate model driven by several initially-available CMIP6 simulations suggest a range of 4.0–6.6°C of additional summer warming over Greenland if following the SSP5-8.5 (high emissions) emissions scenario: the resulting surface melt could contribute at least 10–13 cm to global sea-level rise (Hanna et al., 2020a). Under that scenario, surface melt events covering nearly the entire GrIS, as occurred in 2012, could become commonplace well before 2050. Also, such events contribute significantly to yearly GrIS mass loss values (NSIDC, 2019). It is therefore crucial to improve climate model projections, which generally fail to capture the recent increase in summer blocking over Greenland that is evident from the atmospheric reanalysis record (Hanna et al., 2018b).

Mass losses from GrIS outlet glaciers are also important, and are particularly affected by changes in ocean circulation, but are likely to be overtaken by melt and surface mass losses from the main ice sheet in an increasingly warm climate (Hanna et al., 2020b). However, estimates of the relative mass loss contributions from GrIS surface mass balance and dynamics vary and – due to limitations of ice-sheet models and verification data – there remains a significant lack of understanding of the interaction between these processes (Hanna et al., 2020b).

4.2.10.3 Summary

The GrIS's rate of mass loss has increased in recent decades, at least in part because of melt events (with additional loss by calving). In the case of the ice sheet melt events, there is a clearly defined threshold, which is the temperature of 0°C. The near-certainty that Arctic warming will continue into future decades implies more frequent excursions above 0°C for all or most of the GrIS, so there is high confidence that the GrIS's mass loss will continue and probably accelerate in the coming decades. In the longer term, there is the possibility of a threshold of warming for the stability of the GrIS. According to Lenton (2012) and AMAP (2017), that threshold is a global warming of about 3°C, although a significant difference in GrIS stability could arise from limiting global warming to 1.5°C rather than 2°C (Pattyn et al., 2018). However, due to reduced ice-sheet area dominating over reduced surface altitude under sustained warming, Gregory et al. (2020) found no evidence for such a threshold warming unless the sea-level equivalent declines from the current 7 m to about 4 m.

4.2.11 Drought

Droughts are largely the result of precipitation deficits, often exacerbated by high temperatures and low humidities that favor enhanced evapotranspiration. For this reason, extreme drought events are closely related to persistent negative anomalies of precipitation. However, drought in northern land areas presents special challenges associated with surface hydrology. First, the timing of snowmelt has a major impact on the surface moisture and energy budgets of high-latitude land areas. Early snowmelt adds to the moisture demand on the land surface, increasing the likelihood that a period of dry weather will induce moisture stress and result in drought at some point during the longer snow-free season. As shown in Section 4.2.3, there are indeed indications that northern land areas are losing their snow cover earlier in the year, and this trend is projected to continue. Second, because permafrost acts as a barrier to infiltration, permafrost thaw in a warming climate can add to surface moisture deficits. Bring et al. (2016) and Yang and Kane (2020) provide more comprehensive discussions of the hydrological implications of permafrost.

4.2.11.1 Recent trends

As reported in the *Annual State of the Climate* (BAMS, 2016 and subsequent annual reports), droughts have occurred in northern countries in recent years (e.g., Fennoscandia in 2018, western Canada in 2015, southeastern Alaska in 2018–2019). Another example is the 2010 drought in Russia, which was intense and covered a large area, resulting in environmental degradation, large economic losses and impacts on human health (Kogan and Guo, 2016). The drought together with an intensive heatwave also triggered numerous wildfires which resulted in up to 2 million hectares burned in northeastern Siberia (García-Lázaro et al., 2018).

A recent study of paleoclimatic data has suggested links between Arctic warming and drought in middle latitudes (Routson et al., 2019). Cvijanovic et al. (2017) arrived at a similar conclusion based on climate model sensitivities to sea-ice loss. However, droughts in the Arctic *per se* have received little attention by the climate research community. The increasing frequency of severe wildfire seasons (see Section 4.2.12) suggests that the effect of longer and warmer summers may favor summer drying in the Arctic even if precipitation increases, although wildfire season severity is also complicated by the important role of lightning as an ignition source (Veraverbeke et al., 2017). One of the few systematic evaluations of changing aridity in a high-latitude land region is Ryazanova and Voropay's (2017) calculation of a reanalysis-based aridity index for southern Siberia (50°–65° N, 60°–120° E), where the mountain areas in the eastern part of the domain were found to have become increasingly arid in recent decades.

4.2.11.2 Future projections

In view of the general increase of Arctic precipitation in recent decades (Min et al., 2008) and projections of continued increases in the future (Bintanja and Selton, 2014; Flato and Ananicheva, 2017), drought occurrences in the Arctic could be expected to decrease. Indeed, a synthesis of global climate model output shows a projected reduction by 5–10 days in the yearly maximum number of consecutive dry days over Arctic land areas (Collins, 2013: fig. 12.26d).

Similarly, in the most recent IPCC assessment, the number of consecutive dry days is projected to decrease in the Arctic (IPCC, 2018: fig. 3.13). In addition, the IPCC (2018: fig. 3.12) shows that the Arctic land surface is projected by climate models to gain moisture through an increase of P-E (precipitation minus evapotranspiration). For both metrics (consecutive dry days and P-E), the future changes become larger as global warming increases above the 1.5°C target of the Paris Agreement. Nevertheless, in the context of broader climate change, drought in the Arctic appears to be an under-researched type of extreme event.

4.2.11.3 Summary

Drought in northern regions is an under-researched topic, so it is not surprising that there is little evidence of systematic changes in high-latitude droughts over recent decades. The absence of comprehensive assessments of drought in the Arctic is in part because (i) many parts of the Arctic receive little precipitation in comparison with middle latitudes and (ii) much of the Arctic land surface is underlain by permafrost. For the future, increased temperatures (and hence evapotranspiration) and increased precipitation will have opposing influences on changes in drought occurrence. The preponderance of the results from the few studies to have addressed future droughts in the Arctic (Section 4.2.11.2) suggests that the balance will tilt towards increased moisture availability and a decrease in the occurrence of drought in high latitudes. However, the dearth of research on high-latitude drought implies that this trend can be assigned only low confidence. Finally, there is a general lack of thresholds pertaining to drought in the Arctic, and it is unclear whether criteria and thresholds used for droughts in lower latitudes will be appropriate for the Arctic.

4.2.12 Wildfire

Wildfire in Arctic and subarctic regions has major impacts on terrestrial ecosystems, carbon release, and air quality. Recent severe fire years in Russia (2019, 2020, 2021), Fennoscandia (2018) and Alaska (2015, 2019) have highlighted these impacts. Although wildfires in the middle latitudes generally receive the greatest media coverage, the area burned in northern forests is greater than in middle latitudes during most years.

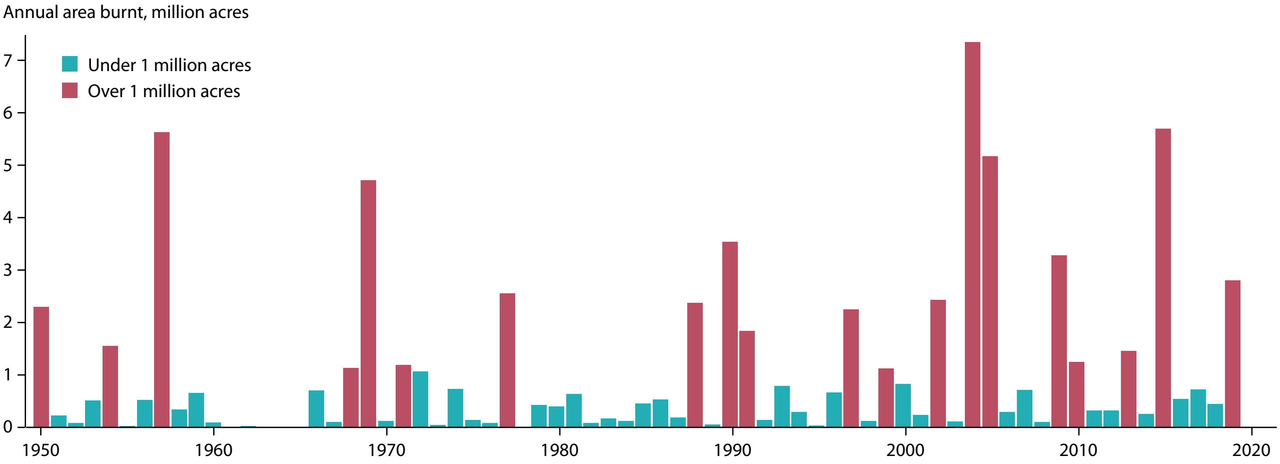

Figure 4.7 Annual number of acres burned by wildfires in Alaska over the period 1950–2019. Source: Thoman and Walsh (2019).

4.2.12.1 **Recent trends**

Data for monitoring wildfire activity on a year-to-year basis and for detecting trends over time exist mainly for Alaska and Canada, while comparable data for Siberia are less available. As shown in Figure 4.7, the frequency of extreme wildfire years in Alaska has increased. Of the 20 years with more than a million acres burned since 1950, seven occurred in the first half of the record and thirteen in the latter half. The impact of a million-acre fire year on air quality is apparent in the satellite images for July 2019 (Figure 4.8). For Canada, any analogous trend is threshold-dependent (Natural Resources Canada, no date), precluding definitive statements about trends in extreme fire years in Canada. Wildfire frequency and burned area increased in Siberian forests between 1996 and 2015, where frequency is correlated with air temperature anomalies and the drought index SPEI (Standardized Precipitation Evapotranspiration Index) (Ponomarev et al., 2016; Kharuk and Ponomarev, 2017). On the century timescale, however, wildfires have strongly decreased since 1900 in Fennoscandian forests, as they are actively monitored and fought due to the economic importance of forestry (Aakala, 2018). Recent research has shown that lightning is a major driver of recent fire years in North American boreal forests. Veraverbeke et al. (2017) found that lightning ignitions have increased since 1975 and that the extreme fire years of 2014 (Canada) and 2015 (Alaska) coincided with record numbers of lightning ignitions.

4.2.12.2 **Future projections**

Using convective precipitation as a proxy for lightning, Veraverbeke et al. (2017) obtained projected increases of lightning-driven burn areas of 29–35% for Canada's Northwest Territories and 46–55% for Interior Alaska by the late 21st century (Veraverbeke et al., 2017: table 2). Bieniek et al. (2020) estimated an even larger increase, approximately a doubling, of summer lightning activity over Alaska by 2100 based on convection metrics applied to downscaled climate model output. Finally, while wildfires are much less common in tundra areas than in the boreal forest, there are indications that tundra wildfires may be increasing. An unusually large wildfire in the tundra of western Greenland in August 2017 was part of Greenland's most extensive wildfire season since the beginning of the satellite record in 2000 (Di Libetro, 2017). Alaska has also seen large tundra fires in recent years, including the massive Anaktuvuk River fire of 2007 (Hu et al., 2010). On the circumpolar scale during 2001–2015, Masrur et al. (2018) showed that warm and dry weather in late spring to mid-summer has favored tundra wildfire occurrence and fire intensity. Negative anomalies in precipitation and soil moisture in winter and spring were also found to favor increased fire intensity.

4.2.12.3 **Summary**

Recent trends of wildfire activity are generally positive, with increases in Alaska and Siberia but not in Canada, where the trends are sensitive to the record length and thresholds used in the analysis. There is also a general expectation of increased wildfire severity in the future as summers become longer and warmer. Projected increases in lightning activity over northern land areas add to this expectation. However, offsetting factors include the projected increase in moisture availability (via precipitation) and the associated low confidence in the future trajectory of high-latitude drought (Section 4.2.11). The aggregate of the available information points to low-to-medium confidence in future increases of wildfire activity in northern land areas, in contrast to mid-latitude areas for which stronger signals of future drying lead to higher levels of confidence in future increases of wildfire.

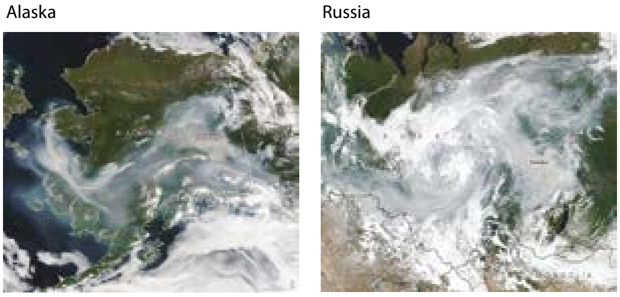

Figure 4.8 Images from NASA's Aqua satellite showing wildfire smoke over Alaska and Russia during July 2019. Source: NASA Earth Observatory (no date).

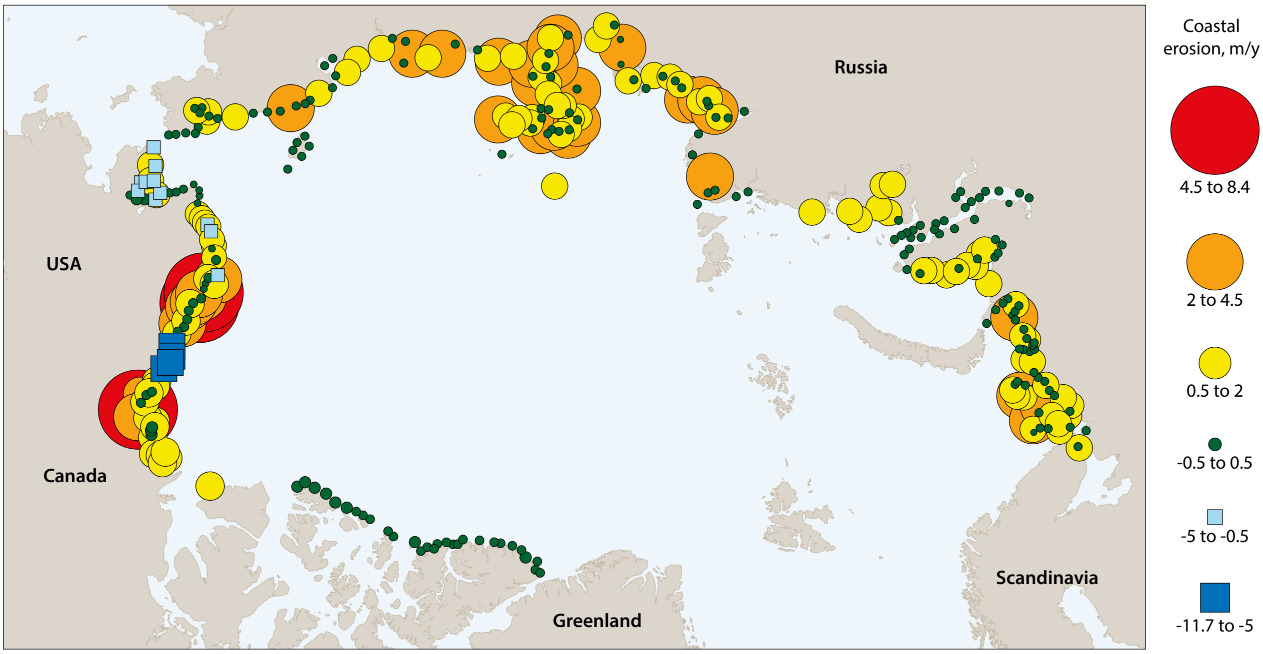

Figure 4.9 Coastal erosion rates in the Arctic. The highest erosion rates are seen along the U.S. and Canadian Beaufort Sea coast. Source: Frederick et al. (2016), adapted from Lantuit et al. (2012) and Barnhart et al. (2014).

4.2.13 Coastal erosion

Coastal erosion is one of the more visible manifestations of extreme weather and climate events in northern regions. Coastal erosion rates in the Arctic are among the largest globally, with average rates of retreat of several metres per year along much of the Russian and Alaskan coasts (Figure 4.9). Rates exceeding 5 m/y are found along parts of Alaska's Beaufort Sea coast (Gibbs and Richmond, 2015). Because much of the Arctic coastline is permafrost (Lantuit et al., 2012), thermal as well as dynamical processes play a role in the retreat of far northern coasts.

4.2.13.1 Recent trends

Various studies have pointed to a doubling (and even more) of coastal erosion rates in the Arctic in recent decades (Jones et al., 2009; Arp et al., 2010; Overeem et al., 2011; Frederick et al., 2016). While climate warming would by itself result in increased rates of coastal erosion in the Arctic, coastal retreat has been accelerated by the recent loss of sea ice (Section 2.9) in combination with Arctic storm activity (Section 4.2.7). The combination of a longer open water season, increased fetch for wave build-up during storms, and warmer water and air temperatures complicates the distinction between thermal (melt-driven) and dynamical (wave-driven) erosion of Arctic coastlines.

Barnhart et al. (2014) showed how the lengthening of the open water season by factors of 1.5 to 3.0 has increased the open water fetch for autumn storms along much of the Arctic Ocean's coastline. The same authors illustrated the linkage between increased fetch and extreme values of water-level setup at Drew Point, Alaska, where the erosion rates exceed 4.5 m/y (Figure 4.9). Rolph et al. (2018) showed that, over the period 1979–2014, there was an approximate tripling of the number of wind events during open water conditions at Utqiagvik (Barrow), Alaska. Most of the increase was attributable to the increased open water season length, although the frequency of storm-related high-wind events has also shown an increase in this region (Rolph et al., 2018: fig. 8; Redilla et al., 2019: fig. 10). The U.S. Global Change Research Program (Karl et al., 2009) used the northern Alaskan coast to illustrate the risks of flooding and coastal erosion. Since the open water season offshore of northern Alaska has lengthened by one to three months in recent decades (Stroeve and Notz, 2018; Thoman and Walsh, 2019), this region highlights the fact that storms in coastal areas of the Arctic pose increasing risks regardless of whether storm activity is changing.

4.2.13.2 Future projections

Kostopoulos et al. (2018) used coastal engineering models to relate open water fetch to wave height, coastal erosion and sediment transport, all of which will impact Arctic operations, infrastructure and human activities. As the open water area of the Arctic Ocean expands in a warming climate, wind-waves as well as swell will increase (Casas-Prat and Wang, 2020). Swell from distant storms can be expected to further increase the wave energy reaching the Arctic coastline (Frederick et al., 2016).

4.2.13.3 Summary

There is widespread evidence of increased rates of coastal erosion in the Arctic. The increase in coastal erosion results from a combination of the background climate change (increasing water temperatures, longer ice-free season) and extreme weather events (storm-driven waves and swell). A continuation of changes in the background climate, including the loss of sea ice and the warming of coastal waters, is relatively certain, although there is less confidence in the future changes of storminess in the high-latitude coastal areas (Section 4.2.7). While a key metric for the rate of coastal erosion in the Arctic is the duration of the sea ice-free season, there are no clearly defined thresholds for the duration of the open water season.

4.3 Thresholds and irreversibilities

The fact that each of the past six years has been warmer in the Arctic than the warmest year (1998) of the 20th century suggests that the Arctic's climate may have entered a new regime in the early 2000s. As shown in Chapter 2, corresponding changes are apparent in sea ice, snow cover, permafrost temperatures, and other variables, indicating that the entire Arctic system is undergoing a regime shift. Arguments for a somewhat later regime shift of Arctic sea ice and its forcing by the North Pacific atmosphere and ocean have been presented by Yang et al. (2020). Other work (Reid et al., 2016) points to the 1980s as the timeframe of a more global regime shift involving temperature, snow cover and sea ice. As noted earlier, the notion of 'tipping points' (thresholds) in the Arctic system has been discussed by Lenton (2012) and Duarte et al. (2012). In the former, the likelihood of threshold exceedances was scaled to the increase of global temperature by focusing on potentially abrupt changes in Arctic sea ice, the Greenland Ice Sheet, the boreal forest, yedoma permafrost, and the Atlantic meridional overturning circulation. While the timing and even the existence of thresholds for these Arctic system components can be debated, the issue of concern here is the role of extreme events in abrupt changes or tipping points.

Based on the literature reviews in Section 4.2, it is apparent that few evaluations of extreme events in the Arctic have addressed specific thresholds and their rates of exceedance. Possible reasons for the absence of work on threshold exceedances are that (i) the key thresholds are not known and (ii) impact-related thresholds vary regionally, especially among different types of community (e.g., coastal vs. inland, urban vs. rural). Nevertheless, Lenton's (2012) selection of candidates for tipping points can serve to illustrate the differing roles of extreme events in abrupt changes related to threshold exceedances. Permafrost thaw, for example, has a clearly defined threshold (0°C) but is largely dependent on the underlying (slow-onset) change in climate rather than short-duration warm events or single snowfall events. Similarly, the Greenland Ice Sheet's accelerating mass loss likely arises from slower-onset changes in the atmosphere and ocean, although a signature of the warming climate may be the increased frequency of rapid melt events (Section 4.2.10). However, deep oceanic mixing that drives the meridional overturning circulation may be driven primarily by high-wind events over ocean areas in which weaker stratification makes the water column vulnerable to deep convection. Abrupt changes in the boreal forest may also be consequences of extreme events such as severe wildfire seasons or severe droughts spanning one or more growing seasons. The role of extreme events in sea-ice retreat appears to be more complex, as the literature surveyed in Section 4.2.9 shows that rapid ice-loss events account for most of the loss of sea ice, both historically and in model projections. While the metric for rapid ice-loss events is the year-to-year change, recent work has shown that shorter-term (multi-day) loss events account for much of the year-to-year change in the annual minimum sea-ice extent.

Finally, ecological thresholds almost certainly exist but are likely to be intertwined with thresholds at the species level. Chapter 6 refers to some of these thresholds and addresses changes and vulnerabilities of Arctic ecosystems more thoroughly. Nevertheless, there is a need for a more systematic compilation of species- and ecosystem-level thresholds that includes relevant information on the event duration. Such information would enable more quantitative assessments of the role of extreme events in the exceedance of ecological thresholds.

4.4 Summary and recommendations

The preceding review highlighted a variety of types of extreme events in the Arctic atmosphere, ocean, and cryosphere. It encompassed studies that range from systematic analyses to somewhat subjective selection of events for examination. While the published literature uses a diverse mix of criteria to identify extreme events, the review enables some conclusions about the state of knowledge of extreme events in the Arctic, including recent trends and projected changes. In an attempt to synthesize the material reviewed here, the following assessment is provided of ongoing (recent) and expected (future) changes in the occurrences of each of the 13 types of event surveyed here.

In Table 4.1, the evidence for ongoing changes is grouped into four categories: high, medium, low, and none. The confidence in future changes is grouped similarly into three categories: high, medium, and low. The ratings assigned here represent 'expert judgment' based primarily on the consistency and comprehensiveness of the relevant publications on each topic. Nevertheless, it is believed that the reviews in the previous sections provide at least a qualitative (and in some cases quantitative) justification for the ratings. The table of ratings is provided in the spirit of a similar ranking by the National Academies of Sciences (NAS, 2016) of extreme events globally in a context of attribution.

The summary in Table 4.1 conforms to this review's organization by type of extreme event. It does not include compounding of extreme events, which can occur by concurrent extreme events of different types, multiple occurrences of a particular event type, or co-occurrence with stresses not related to climate and weather. Compounding can amplify the impacts in nonlinear ways. Examples of high-impact compounding of the types of high-latitude extreme events addressed here include heatwaves and drought/wildfire, high wind and icing (freezing rain), or sea-ice loss and strong cyclones. Zscheischler et al. (2020) recently provided a framework for the study of compound extreme events, which are starting to receive attention in other regions. In one of the few high-latitude studies to address compounding, Ballinger et al. (2021) used a compounding framework to evaluate drivers of autumn and winter temperature variations in the Greenland region. More comprehensive studies of compound events in the Arctic would be timely, especially as impacts of extreme events become a focus of work by AMAP and other organizations.

Table 4.1 Assessment of evidence for recent trends or changes in extreme event types and impacts based primarily on historical information, and confidence in future changes based primarily on model projections. One, two and three dots denote low, medium and high levels of evidence (confidence), respectively. Absence of dots indicates that there is no consistent evidence for change.

	Evidence for change	Confidence in future change
Temperature	●●●	●●●
Precipitation	●	●●●
Inland flooding	●	●
Snow	●●	●●
Freezing rain	–	●●
Atmospheric blocking	●	●
Cyclones	●	●
Wind	●	●
Sea ice (rapid loss events)	●●●	●●●
Greenland Ice Sheet (melt events)	●●	●●●
Drought	–	●
Wildfire	●●	●●
Coastal erosion	●●●	●●●

The review presented here has been limited to published studies that have utilized observational data and model simulations to evaluate variations and trends in various types of extreme events in the Arctic. The assessment of historical variations and trends has emphasized documentation rather than attribution, although the discussions of future projections were based on climate models driven by changing external (anthropogenic) forcing. Kirchmeier-Young et al. (2017) have shown that extreme individual events such as the 2012 sea-ice minimum can be attributed to human influence, but attribution studies of other extreme events in the Arctic are generally lacking. Such studies of the historical variations are a priority in order to place the projected changes into a reality-based framework.

The reviews in the preceding sections generally contain only minimal discussions of thresholds and tipping points. The lack of more extensive discussion reflects the general absence of studies of thresholds in the Arctic system, including both its physical and ecological components. Potential thresholds and tipping points for abrupt changes in the Arctic have been highlighted in general surveys by Lenton (2012) and Duarte et al. (2012), but the linkages between extreme events and threshold exceedances have received little attention. Given the potential for high-impact thresholds to be reached during extreme events, the topic of thresholds in the Arctic system is emerging as a research priority.

Finally, the impacts of extreme events in the Arctic remain under-researched. As far back as the Arctic Climate Impact Assessment (ACIA, 2005), Arctic changes and their impacts have tended to be discussed largely in terms of climatic averages. This tendency is especially apparent in future projections of Arctic change. By contrast, it is extreme events rather than changes in averages that often have the greatest impacts on ecosystems and humans in the Arctic. In this regard, the topic of ecosystem impacts can serve as a convenient bridge between extreme events, thresholds, and their implications for vegetation, wildlife and humans. More generally, documentation of the impacts of extreme events on ecosystems and humans can serve to guide the priorities for further evaluation of changes of extreme events in the Arctic.

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References

Aakala, T., 2018. Forest fire histories and tree age structures in Värriö and Maltio Strict Nature Reserves, northern Finland. Boreal Environment Research, 23:209-219.

ACIA, 2005. Arctic Climate Impact Assessment. Cambridge University Press.

Alexander, L.V., X. Zhang, T.C. Peterson, J. Caesar, B. Gleason and 19 others, 2006. Global observed changes in daily climate extremes of temperature and precipitation. Journal of Geophysical Research: Atmospheres, 111:D05109, doi:10.1029/2005JD006290.

AMAP, 2011. Snow, Water, Ice and Permafrost in the Arctic (SWIPA): Climate Change and the Cryosphere. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway.

AMAP, 2017. Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2017. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway.

Arheimer, B. and G. Lindström, 2015. Climate impact on floods: changes in high flow in Sweden in the past and the future (1911–2100). Hydrology and Earth System Sciences: 19:771-784.

Arp, C.D., B.M. Jones, J.A. Schmutz, F.E. Urban and M.T. Jorgenson, 2010. Two mechanisms of aquatic and terrestrial habitat change along an Alaskan Arctic coastline. Polar Biology, 33:1629-1640.

Ballinger, T.J., J.E. Overland, M. Wang, U.S. Bhatt, E. Hanna, I. Hanssen-Bauer, S.-J. Kim, R.L. Thoman and J.E. Walsh, 2020. Surface air temperature. NOAA Arctic Report Card 2020 (R.L. Thoman, J. Richter-Menge and M.L. Druckenmiller, eds). doi:10.25923/gcw8-2z06.

Ballinger, T.J., E. Hanna, R.J. Hall, J.R. Carr, S. Brasher, E.C. Osterberg, J. Cappelen, M. Tedesco, Q. Ding and S.H. Mernild, 2021. The role of blocking circulation and emerging open water feedbacks on Greenland cold-season air temperature variability over the last century. International Journal of Climatology, 41:E2778-E2800. doi:10.1002/joc.6879.

BAMS, 2016. State of the Climate in 2015. Supplement to Bulletin of the American Meteorological Society, 97:S1-S275.

Barnes, E.A., E. Dunn-Sigouin, G. Masato and T. Woollings, 2014. Exploring recent trends in Northern Hemisphere blocking. Geophysical Research Letters, 41:638-644.

Barnhart, K.R., I. Overeem and R.S. Anderson, 2014. The effect of changing sea ice on the physical vulnerability of Arctic coasts. The Cryosphere, 8:1777-1799.

Bathiany, S., D. Notz, T. Mauritsen, V. Brovkin and G. Raedel, 2016. On the potential for abrupt Arctic winter sea-ice loss. Journal of Climate, 29:2703-2719.

Bieniek, P.A. and J.E. Walsh, 2017. Atmospheric circulation patterns associated with monthly and daily temperature and precipitation extremes in Alaska. International Journal of Climatology, 32:208-217.

Bieniek, P.A., U.S. Bhatt, J.E. Walsh, R. Lader, B. Griffith, J.K. Roach and R.L. Thoman, 2018. Assessment of Alaska rain-on-snow events using dynamical downscaling. Journal of Applied Meteorology and Climatology, 57:1847-1863.

Bieniek, P.A., U.S. Bhatt. A. York, J.E. Walsh and R. Lader, 2020. Lightning variability in dynamically downscaled simulations of Alaska's present and future summer climate. Journal of Applied Meteorology and Climatology, 59:1139-1152.

Bintanja, R. and O. Andry, 2017. Towards a rain-dominated Arctic. Nature Climate Change, 7:263-267.

Bintanja, R. and F.M. Selton, 2014. Future increases in Arctic precipitation linked to local evaporation and sea ice retreat. Nature, 509:479-482.

Boisvert, L.N., M A. Webster, A.A. Petty, T. Markus, D.H. Bromwich and R.I. Cullather, 2018. Intercomparison of precipitation estimates over the Arctic Ocean and its peripheral seas from reanalyses. Journal of Climate, 31:8441-8462.

Borzenkova, A.V. and A.B. Shmakin, 2012. Changes in snow cover thickness and daily snowfall intensity affecting the highways cleaning expenses in Russian cities [In Russian with English summary and figure captions]. Ice Snow, 2:59-70.

Box, J.E., X. Fettweis, J.C. Stroeve, M. Tedesco, D.K. Hall and K. Steffen, 2012. Greenland ice sheet albedo feedback: thermodynamics and atmospheric drivers. The Cryosphere, 6:821-839.

Briner, J., J.K. Cuzzone, J.A. Badgely, N.E. Young, E.J. Steig and 15 others, 2020. Rate of mass loss from the Greenland Ice Sheet will exceed Holocene values this century. Nature, 586:70-74.

Bring, A., I. Federova, Y. Dibike, L. Hinzman, J. Mard, S.H. Mernild, T. Prowse, O. Semenova, S.L. Stuefer and M.-K. Woo, 2016. Arctic terrestrial hydrology: A synthesis of processes, regional effects, and research challenges. Journal of Geophysical Research: Biogeosciences, 121:621-649.

Brown, R., D.V. Schuler, O. Bulygina, C. Derksen, K. Luojus, L. Mudryk, L. Wang and D. Yang, 2017. Arctic terrestrial snow cover. In: Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2017, pp. 25-64. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway.

Burn, D.H., P.H. Whitfield and M. Sharif, 2016. Identification of changes in floods and flood regimes in Canada using a peaks over threshold approach. Hydrological Processes, 30:3303-3314.

Cai, L., V.A. Alexeev, J.E. Walsh and U.S. Bhatt, 2018. Patterns, impacts, and future projections of summer variability in the Arctic from CMIP5 models. Journal of Climate, 31:9815-9833.

Casas-Prat, M. and X.L. Wang, 2020. Projections of extreme ocean waves in the Arctic and potential implications for coastal inundation and erosion. Journal of Geophysical Research: Oceans, 125:e2019JC015745.

Cattiaux, J., Y. Peings, D. Saint-Martin, N. Trou-Kechout and S.J. Vavrus, 2016. Sinuosity of mid-latitude atmospheric flow in a warming world. Geophysical Research Letters, 43:8259-8268.

Climatic Research Unit (University of East Anglia) and Met Office, no date. Temperature. www.cru.uea.ac.uk/cru/data/temperature

Cohen, J., H. Ye and J. Jones, 2015. Trends and variability in rain-on-snow events. Geophysical Research Letters, 42:7115-7122.

Cohen, J., X. Zhang, J. Francis, T. Jung, R. Kwok and 26 others, 2020. Divergent consensuses on Arctic amplification influence on midlatitude severe winter weather. Nature Climate Change, 10:20-29.

Collins, M., R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W.J. Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A.J. Weaver and M. Wehner, 2013. Long-term climate change: projections, commitments and irreversibility. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley, eds.). Cambridge University Press.

Condron, A. and I. Renfrew, 2013. The impact of polar mesoscale storms on northeast Atlantic Ocean circulation. Nature Geoscience, 6:34-37.

Condron, A., G.R. Bigg and I.A. Renfrew, 2006. Polar mesoscale cyclones in the northeast Atlantic: Comparing climatologies from ERA-40 and satellite imagery. Monthly Weather Review, 114:1518-1533.

Conway, H. and C.F. Raymond, 1993. Snow stability during rain. Journal of Glaciology, 39:635-642.

Cook, J.M., A.J. Tedstone, C. Williamson, J. McCutcheon, A.J. Hodson and 21 others, 2019. Glacier algae accelerate melt rates on the western Greenland Ice Sheet. The Cryosphere Discussions, doi.org/10.5194/tc-2019-58.

Curtis, S., A. Fair, J. Wistow, D.V. Val and K. Oven, 2017. Impact of extreme weather events and climate change for health and social care systems. Environmental Health, 16 (Suppl 1), 128, 10.1186/s12940-017-0324.

Cvijanovic, I., B.D. Santer, C. Bonfils, D.D. Lucas, J.C.H. Chiang and S. Zimmerman, 2017. Future loss of Arctic sea-ice cover could drive a substantial decrease in California's rainfall. Nature Communications, 8:1947.

Dahlke, H.E., S.W. Lyon, J.R. Stedinger, G. Rosqvist and P. Jansson, 2012. Contrasting trends in floods for two subarctic catchments in northern Sweden – does glacier presence matter? Hydrology and Earth System Sciences, 16:2123-2141.

Davini, P. and F. D'Andrea, 2016. Northern Hemisphere atmospheric blocking representation in global climate models: Twenty Years of Improvements? Journal of Climate, 29:8823-8840.

Davini, P. and F. D'Andrea, 2020. From CMIP3 to CMIP6: Northern Hemisphere atmospheric blocking simulation in present and future climate. Journal of Climate, 33:10021-10038.

Davini, P., C. Cagnazzo, S. Gualdi and A. Navarra, 2012. Bidemensional diagnostics, variability, and trends of Northern Hemisphere blocking. Journal of Climate, 25:6496-6509.

Delhasse, A., E. Hanna, C. Kittel and X. Fettweis, 2021. Brief communication: CMIP6 does not suggest any atmospheric blocking increase in summer over Greenland by 2100. International Journal of Climatology, 41:2589-2596.

Di Libetro, T, 2017. Wildfire still burning in Greenland tundra in mid-August 2017. www.climate.gov/news-features/event-tracker/wildfire-still-burning-greenland-tundra-mid-august-2017

Donat, M.G., L.V. Alexander, H. Yang, I. Durre, R. Vose, and 24 others, 2013. Updated analyses of temperature and precipitation extreme indices since the beginning of the twentieth century: The HadEX2 dataset. Journal of Geophysical Research: Atmospheres, 118:2098-2118.

Döscher, R. and T. Koenigk, 2013. Arctic rapid sea ice loss events in regional coupled climate scenario experiments. Ocean Science, 9:217-248.

Duarte, C.M., S. Agusti, P. Wassmann, J.M. Arrieta, M. Alcaraz, A. Coello, N. Marba, I.E. Hendriks, J. Holding, I. Garcia-Zarandona, E. Kritzberg and D. Vaque, 2012. Tipping elements in the Arctic marine ecosystem. Ambio, 41:44-55.

DuVivier, A.K., J.J. Cassano, S. Greco and G.D. Emmitt, 2017. A case study of observed and modeled barrier flow in the Denmark Strait in May 2015. Monthly Weather Review, 145:2385-2404.

Emmer, A., 2017. Glacier retreat and glacial lake ourburst floods (GLOFs). In: Oxford Research Encyclopedia, Natural Hazard Science (S.L. Cutter et al., eds.). Oxford University Press.

Flato, G. and M. Ananicheva, 2017. Regional drivers and projections of regional change. In: Adaptation Actions for a Changing Arctic: Perspectives from the Bering-Chukchi-Beaufort Region, pp. 89-124. Arctic Monitoring and Assessment Programme, Oslo, Norway.

Floodlist, 2019a. Russia – Irkutsk flood leave 18 dead, 8 missing. http://floodlist.com/asia/russia-irkutsk-floods-june-july-2019 [Accessed online: 12 December 2019].

Floodlist, 2019b. Russia – thousands evacuated after floods in Amur and Irkutsk. http://floodlist.com/asia/russia-floods-amur-irkutsk-july-2019 [Accessed online: 12 December 2019].

Forbes, B.C., T. Kumpula, N. Meschtyb, R. Laptander, M. Macias-Fauria and 7 others, 2016. Sea ice, rain-on-snow and tundra reindeer nomadism in Arctic Russia. Biology Letters, 12:20160466.

Frederick, J.M., M.A. Thomas, D.L. Bull, C.A. Jones and J.D. Roberts, 2016. The Arctic coastal erosion problem. Report SAND2016-9762, Sandia National Laboratories, Albuquerque, NM.

García-Lázaro, J.R., J.A. Moreno-Ruiz, D. Riano and M. Arbelo, 2018. Estimation of burned area in the northeastern Siberian boreal forest from a long-term data record (LTDR) 1982–2015 time series. Remote Sensing, 10:940.

Ge, S., D. Yang and D. Kane, 2012. Yukon River Basin long-term (1977-2006) hydrologic and climatic analysis. Hydrological Processes, 27:2475-2484.

Gibbs, A.E. and B.M. Richmond, 2015. National assessment of shoreline change – Historical shoreline change along the north coast of Alaska, U.S.-Canadian border to Icy Cape. U.S. Geological Survey Open-File Report 2015–1048. https://dx.doi.org/10.3133/ofr20151048.

Graham, R.M., L. Cohen, A.A. Petty, L.N. Boisvert, A. Rinke, S.R. Hudson, M. Nicolaus and M.A. Granskog, 2017. Increasing frequency and duration of Arctic winter warming events. Environmental Research Letters, 44:6974-6983.

Graham, R.M., P. Itkin, A. Meyer, A. Sundfjord, G. Spreen and 24 others, 2019. Winter storms accelerate the demise of sea ice in the Atlantic sector of the Arctic Ocean. Scientific Reports, 9:9222.

Gregory, J.M., S.E. George and R.S. Smith, 2020. Large and irreversible future decline of the Greenland ice-sheet. The Cryosphere, 14:4299-4322.

Groisman, P.Y., R.W. Knight, D.R. Easterling, T.R. Karl, G.C. Hegerl and V.N. Razuvaev, 2005. Trends in intense precipitation in the climate record. Journal of Climate, 18:1326-1350.

Groisman, P.Y., O.N. Bulygina, X. Yin, R.S. Vose, S.K. Gulev, I. Hanssen-Bauer and E. Førland, 2016. Recent changes in the frequency of freezing precipitation in North America and northern Eurasia. Environmental Research Letters, 11:045007.

Hanna, E., X. Fettweis, S.H. Merild, J. Cappelen, M.H. Ribergaard, C.A. Chuman, K. Steffen, L. Wood and T.L. Mote, 2014. Atmospheric and oceanic climate forcing of the exceptional Greenland ice sheet surface melt in summer 2012. International Journal of Climatology, 34:1022-1037.

Hanna, E., T.E. Cropper, P.D. Jones, A.A. Scaife and R. Allan, 2015. Recent seasonal asymmetric changes in the NAO (a marked summer decline and increased winter variability) and associated changes in the AO and Greenland Blocking Index. International Journal of Climatology, 35:2540-2554.

Hanna, E. T.E. Cropper, R.J. Hall and J. Cappelen, 2016. Greenland blocking index 1851-2015: a regional climate change signal. International Journal of Climatology, 36:4847-4861.

Hanna, E., R.J. Hall, T.E. Cropper, T.J. Ballinger, L. Wake, T. Mote and J. Cappelen, 2018a. Greenland Blocking Index daily series 1851-2015: Analysis of changes in extremes and links with North Atlantic and UK climate variability and change. International Journal of Climatology, 38:3546-3564.

Hanna, E., X. Fettweis and R.J. Hall, 2018b. Brief communication: Recent changes in summer Greenland blocking captured by none of the CMIP5 models. The Cryosphere, 12:3287-3292.

Hanna, E., J. Cappelen, X. Fettweis, S.H. Mernild, T.L. Mote, R. Mottram. K. Steffen, T.J. Ballinger and R.J. Hall, 2020a. Greenland surface air temperature changes from 1981 to 2019 and implications for future ice-sheet melt and mass-balance change. International Journal of Climatology, 41:E1336-E1352,

Hanna, E., F. Pattyn, F. Navarro, V. Favier, H. Goelzer, M.R. van den Broeke, M. Vizcaino, P.L. Whitehouse, C. Ritz, K. Bulthuis and B. Smith, 2020b. Mass balance of the ice sheets and glaciers – progress since AR5 and challenges. Earth Science Reviews, 201:102976.

Hansen, B.B., R. Aanes, I. Herfindal, J. Kohler and B.E. Sæther, 2011. Climate, icing, and wild arctic reindeer: Past relationships and future prospects. Ecology, 92:1917-1923.

Hansen, B.B., K. Isaksen, R.E. Benestad, J. Kohler, Å Ø. Pedersen, L.E. Loe, S.J. Coulson, J.O. Larsen and Ø. Varpe, 2014. Warmer and wetter characteristics and implications of an extreme weather event in the high Arctic. Environmental Research Letters, 9:114021.

Hansen, B.B., M. Gamelon, S.D. Albon, A.M. Lee, A. Stien, R.J. Irvine, B.-E. Saether, L.E. Loe, E. Ropstad, V. Veiberg and V. Grøtan, 2019. More frequent extreme climate events stabilize reindeer population dynamics. Nature Communications, 10:1616.

Harden, B.E., I.A. Renfrew and G.N. Petersen, 2011. A climatology of wintertime barrier winds off southeast Greenland. Journal of Climate, 24:4701-4717.

Hartmann, D.L., A.M.G. Klein Tank, M. Rusticucci, L.V. Alexander, S. Brönnimann, Y. Charabi, F.J. Dentener, E.J. Dlugokencky, D.R. Easterling, A. Kaplan, B.J. Soden, P.W. Thorne, M. Wild and P.M. Zhai, 2013. Observations: atmosphere and surface. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group 1 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, pp. 159-254. Cambridge University Press.

Hirabayashi, Y., R. Mahendran, S. Koirala, L. Konoshima, D. Yamazaki, S. Watanabe, H. Kim and S. Kanae, 2013. Global flood risk under climate change. Nature Climate Change, 3:816-821.

Hofer, S., A.J. Tedstone, X. Fettweis and J.L. Bamber, 2017. Decreasing cloud cover drives the recent mass loss on the Greenland Ice Sheet. Science Advances, 3:e1700584.

Holland, M.M., C.M. Bitz and B. Tremblay, 2006. Future abrupt reductions in the summer Arctic sea ice. Geophysical Research Letters, 33:L23503.

Holland, M.M., C.M Bitz, L.-B. Tremblay and D.A. Bailey, 2008. The role of natural versus forced change in future rapid summer Arctic sea ice loss. In: Arctic Sea Ice Decline: Observations, Projections, Mechanisms, and Implications. Geophysical Monograph Series, 180:133-150.

Hu, F.S., P.E. Higuera, J.E. Walsh, W.L. Chapman, P.A. Duffy, L.B. Brubaker and M. Chipman, 2010. Tundra burning in Alaska: Linkages to climatic change and sea ice retreat. Journal of Geophysical Research, 115:G04002.

Hughes, M. and J.J. Cassano, 2015. The climatological distribution of extreme Arctic winds and implications for ocean and sea ice processes. Journal of Geophysical Research, 120:7358-7377.

IPCC, 2012. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge University Press.

IPCC, 2013. Climate Change 2013: The Physical Science Basis. Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

IPCC, 2018. Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. www.ipcc.ch/sr15

IPCC, 2019. Special Report on the Ocean and Cryosphere in a Changing Climate. Intergovernmental Panel on Climate Change (IPCC).

Jeong, D.I., A.J. Cannon and X. Zhang, 2019. Projected changes in extreme freezing precipitation and design ice loads over North America based on a large ensemble of Canadian regional climate model simulations. Natural Hazards and Earth System Sciences, 19:857-872.

Jonassen, M.O., D. Chechin, A. Yu. Karpechko, C. Lüpkes, T. Spengler, A. Tepstra, T. Vihma and X. Zhang, 2020. Dynamical processes in the Arctic atmosphere. In: A.A. Kokhanovsky and C. Tomasi (eds.), Physics and Chemistry of Arctic Atmosphere. pp. 1-52. Springer Polar Sciences.

Jones, B.M., C.D. Arp, M.T. Jorgenson, K.M. Hinkel, J.A. Schmutz and P.L. Flint, 2009. Increase in the rate and uniformity of coastline erosion in Arctic Alaska. Geophysical Research Letters, 36:L03503.

Kam, J., T.R. Knutson, F. Zeng and A.T. Wittenberg, 2018. CMIP5 model-based assessment of anthropogenic influence on highly anomalous arctic warmth during November-December. Bulletin of the American Meteorological Society, 99:S34-S38.

Kane, D.L., J.P. McNamara, D. Yang, P.Q. Olsson and R.E. Gieck, 2003. An extreme rainfall/runoff event in Arctic Alaska. Journal of Hydrometeorology, 4:1220-1228.

Kanno, Y., J.E. Walsh, M.R. Abdillah, J. Yamaguchi and T. Iwasaki, 2019. Indicators and trends of polar cold airmass. Environmental Research Letters, 14:025006.

Karl, T., J. Melillo and T. Peterson (eds.), 2009. Global Climate Change Impacts in the United States. U.S. Global Change Research Program, Cambridge University Press.

Kharin, V.V., F.W. Zwiers, X. Zhang and M. Wehner, 2013. Changes in temperature and precipitation extremes in the CMIP5 ensemble. Climatic Change, 119:345-357.

Kharuk, V.I. and E.I. Ponomarev, 2017. Spatiotemporal characteristics of wildfire frequency and relative area burned in larch-dominated forests of central Siberia. Russian Journal of Ecology, 48:507-512.

King, M.D., I.A. Howat, S.G. Candela, M.J. Noh, S. Jeong, B.P.Y. Noël, M.R. van den Broeke, B. Wouters and A. Hegrete, 2020. Dynamic ice loss from the Greenland Ice Sheet driven by sustained glacier retreat. Communications Earth & Environment, 1:1.

Kirchmeier-Young, M.C., F.W. Zwiers and N.P. Gillett, 2017. Attribution of extreme events in Arctic sea ice loss. Journal of Climate, 30:553-571.

Klein, D., J.E. Walsh and M. Shulski, 2009. What killed the reindeer of St. Matthew Island? Weatherwise, 62:32-39.

Kogan, F. and W. Guo, 2016. Early twenty-first century droughts during the warmest climate. Geomatics, Natural Hazards and Risk, 7:127-137.

Kolstad, E.W., 2011. A global climatology of favourable conditions for polar lows. Quarterly Journal of the Royal Meteorological Society, 137:1749-1761.

Kolstad, E.W. and T. Bracegirdle, 2008. Marine cold-air outbreaks in the future: an assessment of IPCC AR4 model results for the Northern Hemisphere. Climate Dynamics, 30:871-885.

Kontar, Y.Y., J.C. Eichelberger, T.N. Gavrilyeva, V.F. Filippova, A.N. Savvirinova, N.I. Yananaev and S.F. Trainor, 2018. Springtime flood risk reduction in rural Arctic: A comparative study of Interior Alaska, United States and central Yakutia, Russia. Geosciences, 8:90.

Kostopoulos, D., E. Yitzhak and O.T. Gudmestad, 2018. Coastal erosion due to decreased ice coverage, associated wave action, and permafrost melting. In: Arctic Studies – A Proxy for Climate Change. Doi: 10.5772/intechopen.80604.

Koyama, T., J. Stroeve, J. Cassano and A. Crawford, 2017. Sea ice loss and Arctic cyclone activity from 1979 to 2014. Journal of Climate, 30:4735-4754.

Kumar, D., V. Mishra and A.R. Ganguly, 2015. Evaluating wind extremes in CMIP5 climate models. Climate Dynamics, 45:441-453.

Kusunoki, S., R. Mizuta and M. Hosaka, 2015. Future changes in precipitation intensity over the Arctic projected by a global atmospheric model with a 60-km grid size. Polar Science, 9:277-292.

Lader, R.T., J.E. Walsh, U.S. Bhatt and P.A. Bieniek, 2017. Projections of 21st century climate extremes for Alaska via dynamical downscaling and quantile mapping. Journal of Applied Meteorology and Climatology, 56:2393-2409.

Landgren, O.A., Y. Batrak, J.E. Haugen, E. Staylen and T. Iversen, 2019. Polar low variability and future projections for the Nordic and Barents Seas. Quarterly Journal of the Royal Meteorological Society, 145:3116-3128.

Landrum, L. and M.M. Holland, 2020. The emergence of a New Arctic: When extremes become routine. Nature Climate Change, 10:1108-1115.

Lantuit, H., P.P. Overduin, N. Couture, S. Wetterich, F.Are and 19 others, 2012. The Arctic coastal dynamics database: A new classification scheme and statistics on Arctic permafrost coastlines. Estuaries and Coasts, 35:383-400.

Lehner, B., P. Döll, J. Alcamo, T. Henrichs and F. Kaspar, 2006. Estimating the impact of global change on flood and drought risks in Europe: A continental, integrated analysis. Climatic Change, 75:273-299.

Lenton, T.M., 2012. Arctic climate tipping points. Ambio, 41:10-22.

Lewkowicz, A.G. and R.G. Way, 2019. Extremes of summer climate trigger thousands of thermokarst landslides in a High Arctic environment. Nature Communications, 10:1329.

Liu, J., J.A. Curry, H. Wang, M. Song and R.M. Horton, 2012. Impact of declining Arctic sea ice on winter snowfall. Proceedings of the National Academy of Sciences, 190:4074.

Luo, B., L. Wu, D. Luo, A. Dai and I. Simmonds, 2019. The winter midlatitude-Arctic interaction: effects of North Atlantic SST and high-latitude blocking on Arctic sea ice and Eurasian cooling. Climatic Dynamics, 52:2981-3004.

Lynch, A.H., J.A. Curry, R.D. Brunner and J.A. Maslanik, 2004. Toward an integrated assessment of the impacts of extreme wind events on Barrow, Alaska. Bulletin of the American Meteorological Society, 85:209-222.

Masrur, A., A.N. Petrov and J. DeGroote, 2018. Circumpolar spatio-temporal patterns and contributing climatic factors of wildfire activity in the Arctic tundra from 2001–2015. Environmental Research Letters, 13:01401.

Matthes, H., A. Rinke and K. Dethloff, 2015. Recent changes in Arctic temperature extremes: warm and cold spells during winter and summer. Environmental Research Letters, 11:029501.

McCabe, G., M. Clark and M. Serreze, 2001. Trends in Northern Hemisphere surface cyclone frequency and intensity. Journal of Climate, 14:2763-2768.

McLeod, J.T. and T.L. Mote, 2016. Linking interannual variability in extreme Greenland blocking episodes to the recent increase in summer melting across the Greenland ice sheet. International Journal of Climatology, 36:1484-1499.

McLeod, J.T., T.J. Ballinger and T.L. Mote, 2018. Assessing the climatic and environmental impacts of mid-tropospheric anticyclones over Alaska. International Journal of Climatology, 38:351-364.

Melillo, J., T. Richmond and G. Yohe (eds.), 2014. Climate Change Impacts in the United States. U.S. Global Change Research Program, Washington, DC.

Merkouriadi, I., B. Chang, S.R. Hudson and M.S. Granskog, 2020. Effect of frequent winter warming events (storms) and snow on sea-ice growth – a case from the Atlantic sector of the Arctic Ocean during the N-ICE2015 campaign. Annals of Glaciology, 61:164-170.

Mesquita, M., D. Atkinson and K. Hodges, 2010. Characteristics and variability of storm tracks in the Bering Sea and Alaska. Journal of Climate, 23:294-311.

Messori, G., C. Woods and R. Caballero, 2018. On the drivers of wintertime temperature extremes in the high Arctic. Journal of Climate, 31:1597-1618.

Min, S.-K., X. Xhang and F. Zwiers, 2008. Human-induced Arctic moistening. Science, 320:518-520.

Mölders, N., D. Khordakova, R. Dlugi and G. Kramm, 2016. Sustainability of wind energy under changing wind regimes – A case study. Atmospheric and Climate Sciences, 6:158-173.

Moore, G.W.K., 2013. The Novaya Zemlya Bora and its impact on Barents Sea air-sea interaction. Geophysical Research Letters, 40:3462-3467.

Moore, G.W.K., 2016. The December 2015 North Pole warming event and the increasing occurrence of such events. Nature Scientific Reports, 6:39084.

Mudryk, L., R. Brown, C. Derksen, K. Luojus and B. Decharme, 2019. Terrestrial snow cover. Bulletin of the American Meteorological Society, 100:S160-S161.

Mudryk, L., M. Santolaria-Otín, G. Krinner, M. Ménégoz, C. Derksen, C. Brutel-Vuilmet, M. Brady and R. Essery, 2020. Historical Northern Hemisphere snow cover trends and projected changes in the CMIP-6 multi-model ensemble. The Cryosphere Discussions, https://doi.org/10.5194/tc-2019-320.

NAS, 2016. Attribution of Extreme Weather Events in the Context of Climate Change. National Academies of Sciences (NAS), Engineering and Medicine, National Academies Press.

NASA Earth Observatory, no date. Arctic Fires Fill the Skies with Soot. https://earthobservatory.nasa.gov/images/145380/arctic-fires-fill-the-skies-with-soot

Natural Resources Canada, no date. Canadian National Fire Database (CNFDB). http://cwfis.cfs.nrcan.gc.ca/ha/nfdb?wbdisable=true

NOAA, no date a. Climate at a Glance: Global Haywood Plots. National Oceanic and Atmospheric Administration (NOAA). www.ncdc.noaa.gov/cag/global/haywood/asia/land

NOAA, no date b. Climate at a Glance: Statewide Time Series. National Oceanic and Atmospheric Administration (NOAA). www.ncdc.noaa.gov/cag/statewide/time-series

Noël, B., W.J. van de Berg, S. Lhermitte and M.R. van den Broeke, 2019. Rapid ablation zone expansion amplifies north Greenland mass loss. Science Advances, 5:eaaw0123.

Noer, G., Ø. Saetra, T. Lien and Y. Gusdal, 2011. A climatological study of polar lows in the Nordic Seas. Quarterly Journal of the Royal Meteorological Society, 137:1762-1772.

NSIDC, 2019. Europe's warm air spikes Greenland melting to record levels. Greenland Ice Sheet Today. National Snow and Ice Data Center, http://nsidc.org/greenland-today/2019/08/ europes-warm-air-spikes-greenland-melting-to-record-levels/

O'Gorman, P.A., 2014. Contrasting responses of mean and extreme snowfall to climate change. Nature, 512:416-418.

Olsson, T., J. Jakkila, N. Veijalainen, L. Backman, J. Kaurola and B, Vehvilainen, 2015. Impacts of climate change on temperature, precipitation and hydrology in Finland – studies using bias corrected Regional Climate Model data. Hydrology and Earth System Sciences, 19:3217-3238.

Oltmanns, M., F. Straneo, G.W.K. Moore and S H. Mernild, 2014. Strong downslope wind events in Ammassalik, Southeast Greenland. Journal of Climate, 27:977-993.

Overeem, I., R.S. Anderson, C.W. Wobus, G.D. Clow, F.E. Urban and N. Matell, 2011. Sea ice loss enhances wave action at the Arctic coast. Geophysical Research Letters, 38:L17503.

Overland, J.E. and M. Wang, 2020. The 2020 Siberian heat wave. International Journal of Climatology, 41:E2341-E2346.

Overland, J.E., J.A. Francis, E. Hanna and M. Wang, 2012. The recent shift in early summer atmospheric circulation. Geophysical Research Letters, 39:L19804.

Overland, J., E. Hanna, I. Hanssen-Bauer, S.-J. Kim, J. Walsh, M. Wang and U. S. Bhatt, 2014. Air temperature. Arctic Report Card 2014. www.arctic.noaa.gov/reportcard

Overland, J.E., M. Wang and T.J. Ballinger, 2018. Recent increased warming of the Alaskan marine Arctic due to midlatitude linkages. Advances in Atmospheric Sciences, 15:75-84.

Pan, C.G., P.B. Kirchner, J.S. Kimball, Y. Kim and J. Du, 2018. Rain-on-snow events in Alaska, their frequency and distribution from satellite observations. Environmental Research Letters, 13:075004.

Pan, X., D. Yang, K.P. Chun, J. Zhang and Y. You, 2020. Under-measured daily maximum precipitation from manual gauge observations over the northern regions. Science of the Total Environment, 715:136970.

Paquin, J.P., R. Döscher, L. Sushama and T. Koenigk, 2013. Causes and consequences of mid–21st-century rapid ice loss events simulated by the Rossby Centre regional atmosphere-ocean model. Tellus, 65:1 doi:10.3402/tellusa.v65i0.19110.

Parkinson, C.L. and J.C. Comiso, 2013. On the 2012 record low Arctic sea ice cover: Combined impact of preconditioning and an August storm. Geophysical Research Letters, 40:1356-1361.

Pattyn, F, C. Ritz, E. Hanna, X. Asay-Davis, R. DeConto, G. Durand, L. Favier, X. Fettweis, H. Goelzer, N.R. Golledge, P.K. Munneke, J.T.M. Lenaerts, S. Nowicki, A.J. Payne, A. Robinson, H. Seroussi, L.D. Trusel and M. van den Broeke, 2018. The Greenland and Antarctic ice sheets under 1.5°C global warming. Nature Climate Change, 8:1053-1061.

Peeters, B.,A.O. Pedersen, L.E. Loe, K. Isaksen, V. Veiberg, A. Stien, J. Kohler, J.-C. Gallet, R. Aanes and B. Bremset Hansen, 2019. Spatiotemporal patterns of rain-on-snow and basal ice in high Arctic Svalbard: detection of a climate-cryosphere regime shift. Environmental Research Letters, 14:015002.

Peterson, T.C., X. Zhang, M. Brunet-India and J.L. Vázquez-Aguirre, 2008. Changes in North American extremes derived from daily weather data. Journal of Geophysical Research, 113:D07113.

Petty, A.A., J.C. Stroeve, P.R. Holland, L.N. Boisvert, A.C. Bliss, N. Kimura and W.N. Meier, 2018. The Arctic sea ice cover of 2016: a year of record-low highs and higher-than-expected lows. The Cryosphere, 12:433-452.

Ponomarev, E.I., V.I. Kharuk and K.J. Ranson, 2016. Wildfire dynamics in Siberian Larch Forests. Forests, 7:125.

Pregnolato, M., A. Ford, C. Robson, V. Glenis, S. Barr and R. Dawson, 2016. Assessing urban strategies for reducing the impacts of extreme weather on infrastructure networks. Royal Society Open Science, 3:160023.

Rasmussen, E.A. and J. Turner (eds.), 2009. Polar Lows. Cambridge University Press.

Redilla, K., S.T. Pearl, P.A. Bieniek and J.E. Walsh, 2019. Wind climatology for Alaska: Historical and future. Atmospheric and Climate Sciences, 9:683-702.

Reeve, M.A. and E.W. Kolstad, 2011. The Spitsbergen South Cape tip jet. Quarterly Journal of the Royal Meteorological Society, 137:1739-1748.

Reid, P.C., R.E. Hari and 27 others, 2016. Global impacts of the 1980s regime shift. Global Change Biology, 22:682-703.

Renfrew, I.A., S.D. Outten and G.W.K. Moore, 2009. An easterly tip jet off Cape Farewell, Greenland. I: Aircraft observations. Quarterly Journal of the Royal Meteorological Society, 135:1919-1933.

Rennert, K., G. Roe, J. Putkonen and C.M. Bitz, 2008. Soil thermal and ecological impacts of rain-on-snow events in the circumpolar Arctic. Journal of Climate, 22:2302-2315.

Rinke, A., M. Maturilli, R.M Graham, H. Matthes, D. Handorf, L. Cohen, S.R. Hudson and J.C. Moore, 2017. Extreme cyclone events in the Arctic: Wintertime variability and trends. Environmental Research Letters, 12:094006.

Rogers, T.S., J.E. Walsh, M. Leonawicz and M. Lindgren, 2015. Arctic sea ice: Use of observational data and model hindcasts to refine future projections of ice extent. Polar Geography, 38:22-41.

Rojo, M., G. Noer and C. Claud, 2019. Polar Low tracks in the Norwegian Sea and the Barents Sea from 1999 until 2019. PANGAEA, https://doi.org/10.1594/PANGAEA.903058

Rolph, R.J., A.R. Mahoney, J. Walsh and P.A. Loring, 2018. Impacts of a lengthening open water season on Alaskan coastal communities: deriving locally relevant indices from large-scale datasets and community observations. The Cryosphere, 12:1779-1790.

Routson, C.C., N.P. McKay, D.S. Kaufman, M.P. Erb, H. Goosse, B.N. Shuman, J.R. Rodysill and T. Ault, 2019. Mid-latitude net precipitation decreased with Arctic warming during the Holocene. Nature, 568:83-87.

Rudeva, I. and I. Simmonds, 2015. Variability and trends of global atmospheric frontal activity and links with large-scale modes of variability. Journal of Climate, 28:3311-3330.

Rudeva, I., S.K. Gulev, I. Simmonds and N. Tilinina, 2014. The sensitivity of characteristics of cyclone activity to identification procedures in tracking algorithms. Tellus, 66A:24961.

Ruosteenoja, K., T. Vihma and A. Venäläinen, 2019. Projected changes in European and North Atlantic seasonal wind climate derived from CMIP5 simulations. Journal of Climate, 32:6467-6490.

Ryazanova, A. and N. Voropay, 2017. Droughts and excessive moisture events in southern Siberia in the late XXth - early XXIst centuries. IOP Conference Series Earth and Environmental Science, 96:012015.

Schmidt, N.M., J. Reneerkens, J.H. Christensen, M. Olesen and T. Roslin, 2019. An ecosystem-wide reproductive failure with more snow in the Arctic. PLoS Biol, 17:e3000392.

Screen, J.A. and C. Deser, 2019. Pacific Ocean variability influences the time of emergence of a seasonally ice-free Arctic Ocean. Geophysical Research Letters, 46:2222-2231.

Screen, J.A., C. Deser and L. Sun, 2015a. Reduced risk of North American cold extremes due to continued Arctic sea ice loss. Bulletin of the American Meteorological Society, 96:1489-1503.

Screen, J.A., C. Deser and L. Sun, 2015b. Projected changes in regional climate extremes arising from Arctic sea ice loss. Geophysical Research Letters, 10:984006.

Serreze, M.C., A.D. Crawford and A.P. Barrett, 2015. Extreme daily precipitation events at Spitsbergen, an Arctic island. International Journal of Climatology, 35:4574-4588.

Shevnina, E., E. Kurzeneva, V. Kovalenko and T. Vihma, 2017. Assessment of extreme flood events in changing climate for a long-term planning of socio-economic infrastructure in the Russian Arctic. Hydrology and Earth System Sciences, 21:2559-2578.

Shiklomanov, A.I., R.B. Lammers. M.A. Rawlins, L.C. Smith and T.M. Pavelsky, 2007. Temporal and spatial variations in maximum river discharge from a new Russian dataset. Journal of Geophysical Research, 112:G04S53.

Sillmann, J., V.V. Kharin, F.W. Zwiers, X. Zhang and D. Bronaugh, 2013a. Climate extremes indices in the CMIP5 multimodel ensemble: Part 1: Model evaluation in the present climate. Journal of Geophysical Research: Atmospheres, 118:1716-1733.

Sillmann, J., V.V. Kharin, F.W. Zwiers, X. Zhang and D. Bronaugh, 2013b. Climate extremes indices in the CMIP5 multimodel ensemble: Part 2. Future climate projections. Journal of Geophysical Research: Atmospheres, 118:2473-2493.

Simmonds, I. and I. Rudeva, 2012. The great Arctic cyclone of August 2012. Geophysical Research Letters, 39:L23709.

Siu, C., Z. Zhang, L. Yu, Y. Li and M. Song, 2017. Investigation of Arctic air temperature extremes at north of 60N in winter. Acta Oceanologica Sinica, 36:51-60.

Stoll, P.J., R.G. Graversen, G. Noer and K. Hodges, 2018. An objective global climatology of polar lows based on reanalysis data. Quarterly Journal of the Royal Meteorological Society, 144:2099-2117.

Stroeve, J. and D. Notz, 2018. Changing state of Arctic sea ice across all seasons. Environmental Research Letters, 13:103001.

Tamarin-Brodsky, T. and Y. Kaspi, 2017. Enhanced poleward propagation of storms under climate change. Nature Geoscience, 10:908-913.

Tedesco, M., X. Fettweis, T. Mote, J. Wahr, P. Alexander, J.E. Box and B. Wouters, 2013. Evidence and analysis of 2012 Greenland records from spaceborne observations, a regional climate model and reanalysis data. The Cryosphere, 7:615-630.

Tedesco, M., T. Mote, X. Fettweis, E. Hanna, J. Jeyaratnam, J.F. Booth, R. Datta and K. Briggs, 2016. Arctic cut-off high drives the poleward shift of a new Greenland melting record. Nature Communications, 7:11723.

Thoman, R. and J.E. Walsh, 2019. Alaska's changing environment: Documenting Alaska's physical and biological changes through observations. International Arctic Research Center, University of Alaska, Fairbanks.

Tilinina, N., S.K. Gulev and D.H. Bromwich, 2014. New view of Arctic cyclone activity from the Arctic system reanalysis. Geophysical Research Letters, 41:1766-1772.

Toreti, A., P. Naveau, M. Zampieri, A. Schindler, E. Scoccimarro, E. Xoplaki, H.A. Dijkstra, S. Gualdi and J. Luterbacher, 2013. Projections of global changes in precipitation extremes from Coupled Model Intercomparison Project Phase 5 models. Geophysical Research Letters, 40:4887-4892.

Trusel, L.D., S.B. Das, M.B. Osman, M.J. Evans, B.E. Smith, X. Fettweis, J.R. McConnell, B.P.Y. Noël and M.R. van den Broeke, 2018. Nonlinear rise in Greenland runoff in response to post-industrial Arctic warming. Nature, 564:104-108.

Tuononen, M., V.A. Sinclair and T. Vihma, 2015. A climatology of low-level jets in the mid-latitudes and polar regions of the Northern Hemisphere. Atmospheric Science Letters, 16:492-499.

Ummenhofer, C.C. and G.A. Meehl, 2017. Extreme weather and climate events with ecological relevance: a review. Philosophical Transactions of the Royal Society of London B, 372:20160135.

USGCRP, 2014. Our Changing Climate. Climate Change Impacts in the United States: The Third National Climate Assessment. U.S. Global Change Research Program, Washington, DC.

Välisuo, I., T. Vihma, R. Pirazzini and M. Schäfer, 2018. Atmospheric variables controlling inter-annual variability of surface melt in Greenland. Journal of Geophysical Research, 123:10,443-10,463.

Vavrus, S.J., F. Wang, J.E. Martin, J.A. Francis, Y. Peings and J. Cattiaux, 2017. Changes in North American atmospheric circulation and extreme weather: Influence of Arctic amplification and northern hemisphere snow cover. Journal of Climate, 30:4317-4333.

Venäläinen, A., M. Laapas, P. Pirinen, M. Horttanainen, R. Hyvönen, I. Lehtonen, P. Junila, M. Hou and H.M. Peltola, 2017. Estimation of the high spatial-resolution variability in extreme wind speeds for forestry applications. Earth System Dynamics, 8:529-545.

Veraverbeke, S., B.M. Rogers, M.J. Goulden, R.R. Jandt, C.E. Miller, E. B. Wiggins and J.T. Randerson, 2017. Lightning as a major driver of recent large fire years in North American boreal forests. Nature Climate Change, 7:529-534.

Vihma, T., 2017. Weather extremes linked to interaction of the Arctic and mid-latitudes, In: Climate Extremes: Mechanisms and Potential Prediction. Geophysical Monograph Series, 226, American Geophysical Union, pp. 39-49.

Vihma, T., J. Screen, M. Tjernström, B. Newton, X. Zhang, V. Popova, C. Deser, M. Holland and T. Prowse, 2016. The atmospheric role in the Arctic water cycle: A review on processes, past and future changes, and their impacts. Journal of Geophysical Research: Biogeosciences, 121:586-620.

Vincent, L.A. and E. Mekis, 2006. Changes in daily and extreme temperature and precipitation indices for Canada over the twentieth century. Atmosphere-Ocean, 44:177-193.

Walsh, J.E., J.E. Overland, P.Y. Groisman and B. Rudolf, 2011a. Arctic climate: Recent variations. In: Snow, Water, Ice and Permafrost in the Arctic (SWIPA): Climate Change and the Cryosphere, Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway.

Walsh, J.E., J.E. Overland, P.Y. Groisman and B. Rudolf, 2011b. Ongoing climate change in the Arctic. Ambio:40:6-16.

Wang, X., V. Swail and F. Zwiers, 2006. Climatology and extratropical cyclone activity: comparison of ERA-40 with NCEP-NCAR reanalysis for 1958-2001. Journal of Climate, 19:3145-3166.

Wang, X., Y. Feng, G. Compo, V. Swail, F. Zwiers, R. Allan and O. Sardeshmukh, 2013. Trends and low-frequency variability of extra-tropical cyclone activity in the ensemble of twentieth-century reanalyses. Climate Dynamics, 40:2775-2800.

Wang, Z., J.E. Walsh, S. Szymborski and M. Peng, 2020. Rapid Arctic sea ice loss on the synoptic time scale and related atmospheric circulation anomalies. Journal of Climate, 33:1597-1617.

Wei, T., M. Ding, B. Wu, C. Lu and S. Wang, 2016. Variations in temperature-related extreme events (1975-2014) in Ny-Ålesund, Svalbard. Atmospheric Science Letters, 17:102-108.

Wickström, S., M. Jonassen, T. Vihma and P. Uotila, 2020. Trends in cyclones in the high latitude North Atlantic during 1979-2016. Quarterly Journal of the Royal Meteorological Society, 146:762-779.

Woollings, T., D. Barriopedro, J. Methven, S.-W. Son, O. Martius, B. Harvey, J. Sillmann, A.R. Lupo and S. Seneviratne, 2018. Blocking and its response to climate change. Current Climate Change Reports, 4:287-300.

Yang, D. and D. Kane (eds.), 2020. Arctic Hydrology, Permafrost and Ecosystems. Springer.

Yang, D., D. Kane and Z. Zhang, 2005. Bias correction of long-term (1973-2014) daily precipitation data over the northern regions. Geophysical Research Letters, 32:L19501, doi:10.1029/2005GL024057.

Yang, D., Y. Zhao, R. Armstrong and D. Robinson, 2009. Yukon River streamflow response to seasonal snow cover changes. Hydrological Processes, 23:109-121.

Yang, D., X. Shi and P. Marsh, 2014. Variability and extremes of Mackenzie River daily discharge during 1973-2011. Quaternary International, 380-381:159-168.

Yang, X.-Y., G. Wang and N. Keenlyside, 2020. The Arctic sea ice extent change connected to Pacific decadal variability. The Cryosphere, 14:693-708.

Zahn, M. and H. von Storch, 2008. Tracking polar lows in CLM. Meteorologische Zeitschrift, 17:445-453.

Zahn, M. and H. von Storch, 2010. Decreased frequency of North Atlantic polar lows associated with future climate warming. Nature, 467:309-312.

Zahn, M., M. Akperov, A. Rinke, F. Feser and I.I. Mokhov, 2018. Trends of cyclone characteristics in the Arctic and their patterns from different reanalysis data. Journal of Geophysical Research: Atmospheres, 123:2737-2751.

Zappa, G., L.C. Shaffrey, K.I. Hodges, P.G. Sansom and D.B. Stephenson, 2013. A multimodel assessment of future projections of North Atlantic and European extratropical cyclones in the CMIP5 climate models. Journal of Climate, 26:5846-5862.

Zhang, J., R. Lindsay, A. Schweiger and M. Steele, 2013. The impact of an intense summer cyclone on 2012 Arctic sea ice extent. Geophysical Research Letters, 40:1-7.

Zscheischler, J. and 14 others, 2020. A typology of compound weather and climate events. Nature Reviews: Earth and Environment, 1:333-347.

5. Arctic/mid-latitude weather connectivity

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Key findings

- *Pronounced changes in the Arctic environment add a new potential driver of anomalous weather in the mid-latitudes that affects billions of people, such as stalled severe weather events, persistent hot-dry extremes/drought, and cold air outbreaks. Mechanisms include natural variability, Arctic amplification, and movement of the polar vortex.*
- *At present, there is no consensus in the meteorological community on the degree to which observed Arctic changes have increased linkages to severe mid-latitude weather events and climate. Current and possible new connections are societally relevant as continued rapid Arctic shifts are an inevitable aspect of anthropogenic global change and worthy of further prediction research.*

5.1 Introduction

Determining the degree to which recent Arctic changes influence broader hemispheric weather is a scientific challenge and an opportunity for improved extended-range weather forecasts, as noted by the recent Year of Polar Prediction (YOPP) (Jung et al., 2016) and related studies (Barnes and Screen, 2015; Overland et al., 2016; Vavrus, 2018; Cohen et al., 2020). The question of links between Arctic warming and an increase in severe weather at mid-latitudes is societally relevant because continued rapid Arctic change is seen as an inevitable aspect of anthropogenic global change (Richter-Menge et al., 2019). The public, governments, and private sector have a major interest in forecasting severe weather due to Arctic influences, whether these influences are part of historical climate patterns or caused by recent changes. Potential Arctic impacts on mid-latitude weather are considered a motivation for climate change mitigation (IPCC, 2019). This chapter reviews the current state of research on Arctic/mid-latitude connectivity mechanisms and their strength.

5.2 Arctic warming is unequivocal, substantial and ongoing

The six warmest years in the Arctic have all occurred in the past decade (Figure 5.1), and Arctic warming is now occurring at more than three times the global rate (see also Chapter 2). Global warming is linked to increasing concentrations of long-lived atmospheric greenhouse gases, especially carbon dioxide (CO_2) and methane (CH_4), attributed to the burning of fossil fuels (Hansen, 2020). The amplification of Arctic warming (also referred to as 'Arctic amplification') relative to the rest of the globe is in part related to a decrease in the amount of multi-year sea ice and associated loss of sea-ice thickness and extent (Figure 5.2). Sea-ice thickness has decreased to less than ~1 m over much of the Arctic during the past decade and a half (Schweiger et al., 2011), concomitant with a 40% reduction in summer sea-ice extent, and a shift from sea ice to open water in all seasons except winter. Currently there is a delay of more than a month in the timing of late autumn (November) sea-ice freeze-up in multiple marginal seas compared to previous decades that provides additional heating to the atmosphere (see, for example, the Chukchi/Barents seas area shown in black in Figure 5.2). While loss of sea ice is one of the components leading to Arctic amplification, other elements such as higher air temperatures through changes in radiation, heat and moisture advection from the south, and the temperature lapse rate (vertical distribution) are now considered critical (Pithan and Mauritsen, 2014; Feldl et al., 2020). Local mechanisms include loss of snow cover and sea ice leading to lower albedo (reflectivity of sunlight), atmospheric boundary layer changes, and clouds trapping near-surface heat. Remote mechanisms involve atmospheric and oceanic heat and moisture transport from the subarctic. This northward transport involves a positive feedback whereby increased heating results in further sea-ice melt that in turn enables the next warm event to travel further north. Recent studies argue that remote mechanisms have increased sea-ice disappearance during both winter and summer (Cohen et al., 2020).

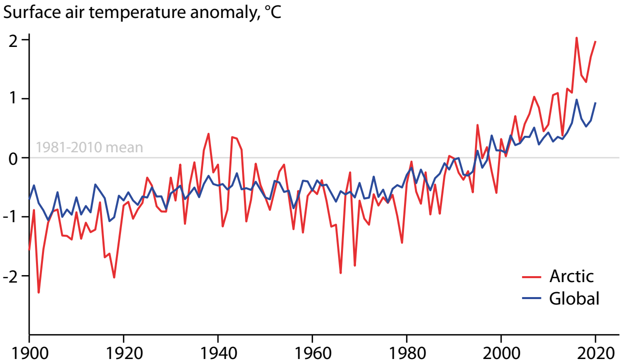

Figure 5.1 Annual mean surface air temperature anomalies for land stations located in the Arctic (60–90°N) and globally for the period 1900–2020, relative to the 1981–2010 means. Source: CRUTEM4 data are obtained from the Climate Research Unit (University of East Anglia) and the UK Met Office.

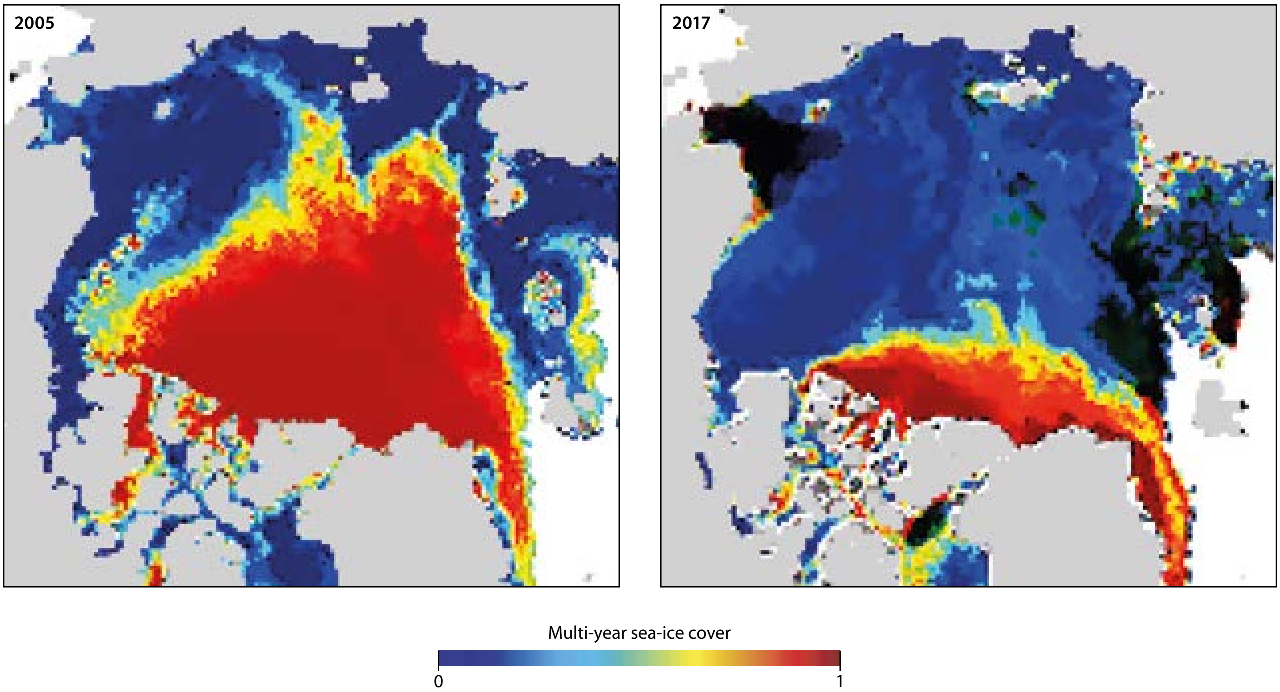

Figure 5.2 Change in the areal coverage of thick multi-year sea ice (red areas; ice that has lasted for more than one year) over the last decade and a half based on satellite data. There is a loss of 70% of sea ice volume. The black areas represent areas of delayed autumn sea-ice freeze-up. Modified from Kwok (2018).

5.3 Features of Northern Hemisphere weather

Recent studies have found that weather connectivity between the Arctic and mid-latitudes depends not only on the magnitude of Arctic amplification, but also on the location, amplitude, and movement of meanders in the polar jet stream (a belt of powerful winds in the troposphere that blow in a generally easterly direction). The meandering form of the jet stream can vary considerably in excursion and location (see Figure 5.3 for two examples). The wavy configuration moves warm air northward and cold air southward: where this occurs depends on the longitudinal positioning of the waves. Excursions to the north are referred to as ridges because they are associated with high atmospheric pressure, and those to the south as troughs because they are associated with low atmospheric pressure. While

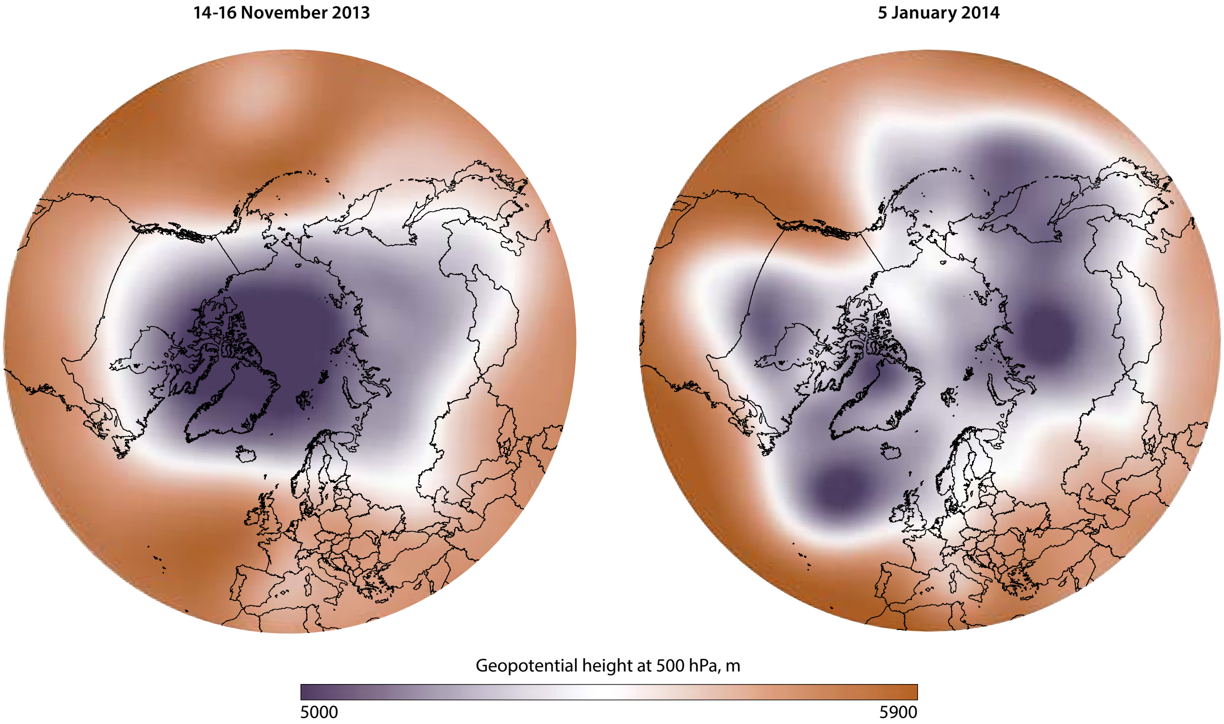

Figure 5.3 Contrasting geopotential height fields at the lower jet stream level (500 hPa) with low values in purple and the jet stream in white. A single and more west-to-east jet stream encircling the tropospheric polar vortex on 14–16 November 2013 contrasts with a wavier configuration on 5 January 2014 with multiple low height centers (dark purple). Source: NOAA Climate.gov

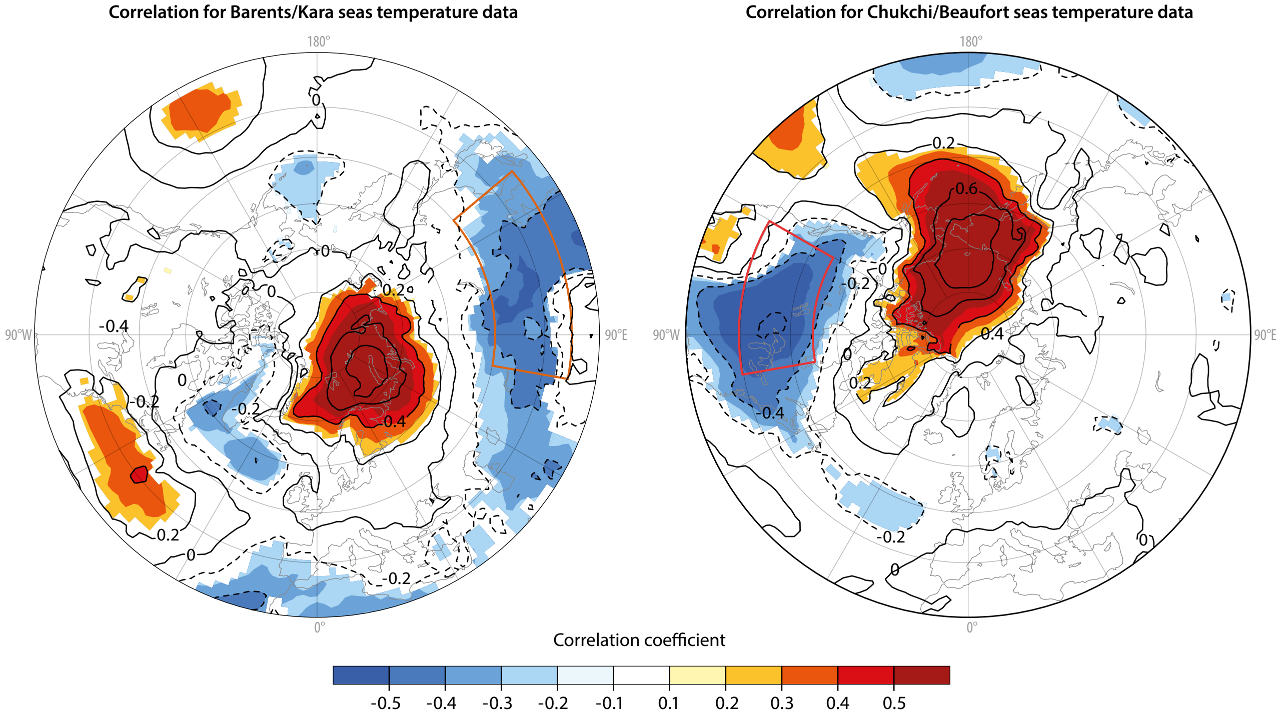

Figure 5.4 Correlation of hemispheric surface air temperatures with surface air temperatures in the Barents/Kara seas region and the Chukchi/Beaufort seas region during winter (DJF) in the period 1979/1980 to 2013/2014. Shading denotes statistical significance at the 5% level. Source: Kug et al. (2015).

Arctic amplification is ongoing every year, potential linkages between the Arctic and mid-latitude weather depend on the configuration of the jet stream in the mid/upper troposphere (5–10 km altitude) and the stratospheric polar vortex (15–40 km altitude). Potential linkages are defined here as both possible atmospheric circulation forcing by changes in the Arctic, and how variability of atmospheric circulation primarily in the Arctic (e.g., the polar vortex) can modify atmospheric circulation in mid-latitudes (e.g., cold air outbreaks).

That the location of jet stream excursions is not geographically fixed argues for the irregular occurrence of potential weather linkages, that is, showing a lack of trend or annual/seasonal cycle, despite continued Arctic amplification. Year-to-year variability reported in studies claiming weak multi-decadal trends in linkages (e.g., Kug et al., 2015; Mori et al., 2019) does suggest such irregularity. In fact, amplified Arctic warming in early winter may not in itself initiate mid-latitude weather connections, but instead can intensify such interactions by enhancing the amplitude of existing large-scale jet stream excursions and durations, and thus contribute to the establishment of stationary atmospheric wind patterns known as blocks (Woollings et al., 2018; Luo et al., 2019; Tachibana et al., 2019; Overland et al., 2021).

Wavy patterns in the jet steam lead to increased northward movement of warm air (advection) as well as southward cold advection between the subarctic and mid-latitudes in adjacent longitudinal sectors. Some metrics of jet-stream waviness have indicated an increased frequency of high-amplitude jet stream days since Arctic amplification first emerged in the mid-1990s, embedded in large, naturally occurring year-to-year winter variability (Vavrus et al., 2017). Because cold and warm events often occur simultaneously in adjacent regions, according to the longitudinal axis and amplitude of jet-stream waves as they move location, metrics based on averages over a season and across large regions tend to produce weak composite spatial or seasonal signals (Screen and Simonds, 2014; Francis, 2017). This is one source of the discrepancy evident among studies.

Three processes are potentially involved in linking the Arctic to persistent jet-stream patterns: internal atmospheric processes related to blocking processes that initiate and add to the persistence of the wavy jet-stream pattern; local warm surface temperatures often associated with loss of sea ice; and northward advection of warm air in an existing jet-stream pattern.

5.4 Living with an uncertain climate system

Of interest is the non-uniform distribution of cold and warm temperature anomalies at mid-latitudes seen in some years both in North America and central Asia that have been referred to as the paradox of 'Warm Arctic-Cold Continents' (WACC) in a warming world. Figure 5.4 shows the hemispheric year-to-year correlation of winter hemispheric surface air temperature with temperatures in the Barents/Kara seas region and Chukchi/Beaufort seas region suggesting a WACC relationship. These statistical relationships suggest that long-term (multi-decadal) warming trends over the Arctic may be causally linked to the long-term cooling trends over the continents, such as that observed over Eurasia between 1979 and 2014. However, other researchers have argued that this decadal trend in WACC is a coincidental artifact, that natural variability was cooling the continents during the same decades as sea-ice loss (McCusker et al., 2016; Ogawa et al., 2018), or that both the warm Arctic and cold continents were each caused by other processes.

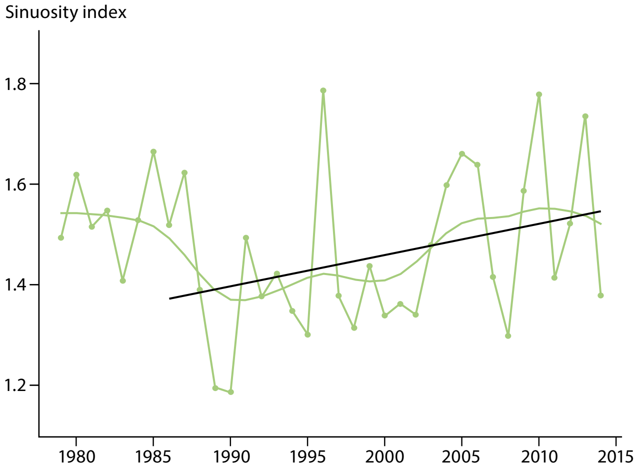

Figure 5.5 Time series of Atlantic sinuosity for the jet stream in late winter/early spring (JFM) with a five-year spline smoothing. Sinuosity is based on the north/south displacement of a line of equal geopotential height contour (500 hPa). Source: Cattiaux et al. (2016).

Although several researchers have noted that there does not appear to be a season-wide winter average impact of Arctic amplification on mid-latitudes (Screen and Simmonds, 2014; Blackport and Screen, 2020), other researchers have suggested a shorter event-scale irregular connection (week to month), mediated by a variable jet stream (Overland et al., 2016, 2021; Tachibana et al., 2019; He et al., 2020). Figure 5.5 shows that the degree of sinuosity (waviness) can vary from winter to winter. As well as emphasizing the North Atlantic year-to-year variability in the jet stream, the graphic also identifies a weak upward trend.

Reviews (Cohen et al., 2020) and international workshops, sponsored by the World Climate Research Programme's Climate and Cryosphere project (WCRP CliC), International Arctic Science Committee (IASC), and the U.S. Climate Variability and Predictability (U.S. CLIVAR) program, all resulted in divergent conclusions on the relative importance for Arctic/mid-latitude linkages between long-term Arctic changes and atmospheric internal variability, based on model simulations and observational data; a clear consensus on the lack of consensus. Multiple recent papers concluded that thermodynamic forcing due to recently sea ice-free Arctic regions is insignificant relative to internal atmospheric variability (Guan et al., 2020; McGraw and Barnes, 2020). A second group of studies links the dominance of upstream teleconnection forcing from the Atlantic that amplifies warming over the Barents/Kara seas region, regional ridging of high pressure systems, and then downstream cooling over Asia (Jin et al., 2020; Li et al., 2020; Xie et al., 2020) to a possible role for the stratosphere (Zhang et al., 2018). Other connections include tropical teleconnections (Perlwitz et al., 2015; Sigmond and Fyfe, 2016; Yamazaki et al., 2020) and land-surface influences from snow cover and soil moisture (Nakamura et al., 2019). Twenty-seven papers based on climate model simulations do not support sea-ice loss as a significant mechanism for Arctic/mid-latitude weather linkages (Liang et al., 2019; Cohen et al., 2020), while other studies suggest that models might underestimate the atmospheric response to surface and other forcings (Romanowsky et al., 2019; Smith et al., 2020). In contrast, several case studies show the importance of all three linkage mechanisms: local surface heating, temperature advection, and prior jet stream physics (Tachibana et al., 2019; Overland et al., 2021). The magnitude of potential Arctic influences remains unresolved, but it is generally accepted that possible Arctic/mid-latitude weather linkages do exist, but are not always direct, can be overwhelmed by internal variability, and are often subject to multiple, simultaneous, and time-lagged ocean-atmosphere processes.

5.5 Examples of winter Arctic/mid-latitude linkages

This section provides examples of winter Arctic/mid-latitude linkages for North America, eastern Asia, and Europe that illustrate how the connection between the Arctic and mid-latitude weather is mediated by the wavy jet stream configuration on an event timescale.

For North America, delayed freeze-up of sea ice during early winter in maritime Alaska can reinforce an in-place intrinsic jet stream pattern (Francis et al., 2017; Overland and Wang, 2018) (Figure 5.6). For example, December 2016 contrasts with December 2017. Both years experienced delayed sea-ice freeze-up with warm Alaskan temperature anomalies. In 2017, warm Alaskan temperatures reinforced the climatological wavy jet stream over North America by increasing regional pressure (geopotential thickness), with downstream cold eastern U.S. temperatures; in 2016 the more zonal (west-east) jet stream, which coincided with the strong gradient in geopotential height, was too far to the south to interact with the warm Arctic. Tachibana et al. (2019) studied the 2017 Alaska case in detail and noted atmospheric modifications from both surface heat fluxes and warm air advection. To put December 2017 into a longer context, anomalously cold December surface air temperatures over eastern North America occurred roughly twice per decade after 1990 despite continued Arctic amplification (Overland and Wang, 2018). Alaska ridging was associated with the 2017 pattern, Greenland/Baffin Bay blocking was influential in 2010, and ridging in both regions was coincident with the eastern United States cold event in 2000. There were five major cold events in the United States during the 1980s before the emergence of significant Arctic amplification; they were dominated by internal atmospheric variability. Thus, such December North American linkage events with a duration of a month or more were recently rare.

In late winter, conditions leading to persistent cold spells in central and eastern North America are often associated with an enhanced climatological tropospheric western ridge / eastern trough jet-stream pattern across the continent, initiated and maintained by stratospheric polar vortex displacements. During February 2015 and 2018, for example, a warming occurred in Alaska while cold conditions persisted in eastern or central North America (Figure 5.7a,c). Negative geopotential height anomalies (lower regional pressures) at the jet stream (500 hPa) and polar vortex (100 hPa) levels were nearly vertically collocated (Figure 5.7b,d) suggesting large-scale control of the weather pattern by the stratospheric polar vortex. Downstream (east) of the Alaskan-located

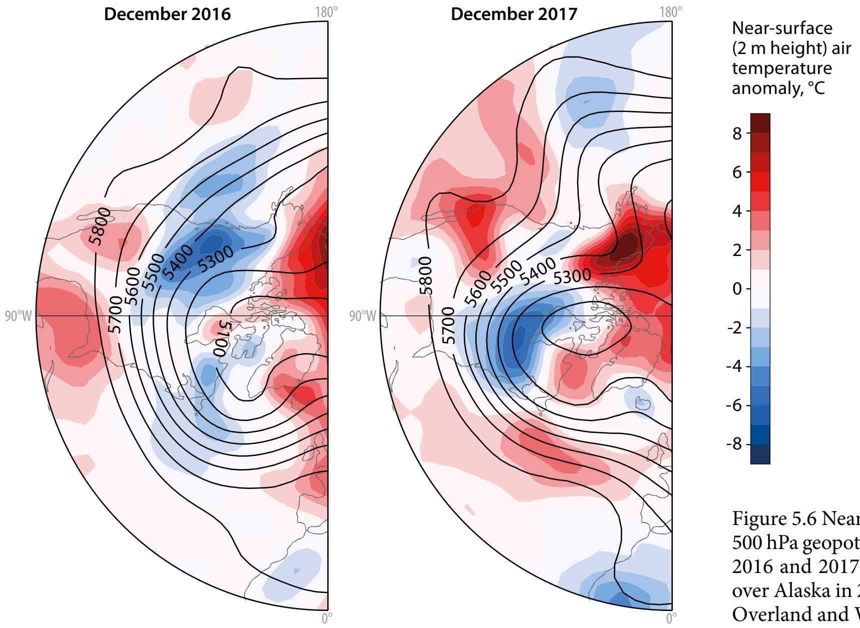

Figure 5.6 Near-surface air temperature anomalies and 500 hPa geopotential height (contour, m) for December 2016 and 2017. Note the wavy jet stream and a ridge over Alaska in 2017 and more zonal flow in 2016. After Overland and Wang (2018).

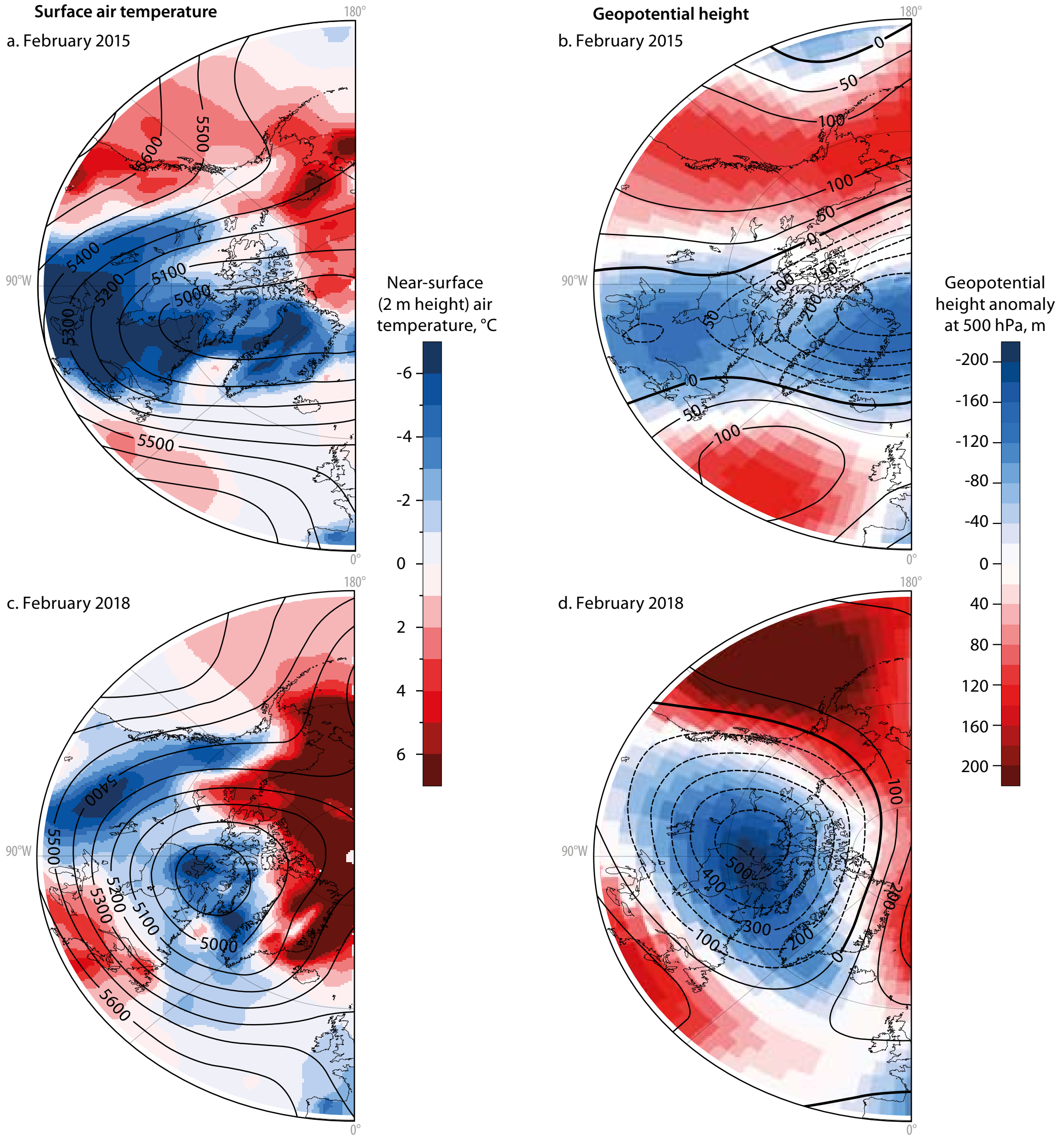

Figure 5.7 Averaged 500 hPa geopotential height (contour, m) and near-surface (2 m height) air temperature (shading, °C) for (a) February 2015 and (c) February 2018. The corresponding period geopotential height anomalies at 500 hPa (shading, m) and 100 hPa (contour, m) are shown in b and d. Data from the NCEP/NCAR reanalysis.

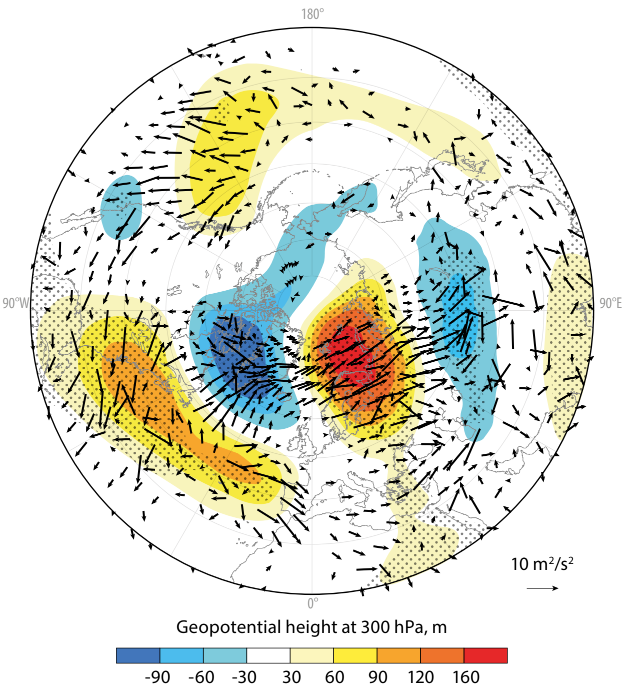

Figure 5.8 Geopotential height at 300 hPa between warm and cold Decembers over the Barents/Kara seas region. Dotted areas denote significant differences exceeding the 90% confidence level. Superimposed arrows indicate the horizontal component of wave-activity flux, a propagating packet of wave disturbances. Alternating colors show an atmospheric teleconnection, a train of geographic impacts. Source: Sato et al. (2014).

ridge, a deep trough persisted over Hudson Bay and eastern Canada, causing a prolonged and intense late-winter cold spell across central North America (Overland and Wang, 2019). In 2015, the trough was displaced east resulting in cold eastern North American temperatures (Figure 5.7a,b). Evidence suggests that late winters (February) during the Arctic amplification era (since ~1990) featured more frequent amplified tropospheric ridge-trough longwave circulation patterns over North America (Francis and Vavrus, 2015). Since 2014, the Pacific ridge has strengthened (McLeod et al., 2018); this behavior coincides with anomalously warm sea-surface temperatures in the northeastern North Pacific that favor the development of a ridge in this location (Francis et al., 2017). The position of the jet stream was important to the extra Greenland Ice Sheet melt in 2019. The tropics can also influence the polar vortex.

Several papers have noted the importance of the Barents/Kara seas region as a potential source of Asian mid-latitude weather linkages during the past decade (Zhang et al., 2018; Xie et al., 2020). Figure 5.8 shows an Atlantic-Barents/Kara seas-Asia atmospheric wave train (a connected pattern termed a 'teleconnection') correlated with warm temperatures over the Barents/Kara seas region, and the potential for cold temperature anomalies in central Asia. It is noted that there are multiple drivers of atmospheric wave trains, including Atlantic sea-surface temperatures, sea-ice loss, and atmospheric blocking by the Ural Mountains, a mountain range running north to south through western Russia. Many observational and modeling studies relate sea-ice loss to winter mid-latitude teleconnection patterns in both the troposphere and the stratosphere; see Vihma (2014), Vavrus (2018), Smith et al. (2019), and Cohen et al. (2020) for comprehensive reviews.

Some modeling studies (McCusker et al., 2016; Blackport et al., 2019) have stated that correlation between Arctic sea ice and Eurasian temperatures does not imply causation. They found no causal relationship between the multi-decadal Arctic warming and Eurasian cooling trends, suggesting that the observed trends were both driven by internal variability in the atmospheric circulation and change in external forcing. Blackport et al. (2019) presented additional physically-based evidence; based on the direction of atmospheric heat transports and lead-lag relationships, they suggested that the atmosphere is driving the sea-ice loss, and not vice versa. Kug et al. (2015), Mori et al. (2019) and He et al. (2020) suggested that climate models fail to reproduce all the complex interactions related to the atmospheric response to sea-ice loss and hence that model results should be taken with caution; other studies suggest that climate models are able to reproduce the most relevant processes (Screen and Blackport, 2019). The winter 2015–2016 Barents/Kara seas region case study shows that all three linkage mechanisms were active: local surface heating, temperature advection, and prior jet stream physics; surface heating was active over the winter period while advection occurred with episodic storm events (Overland et al., 2021).

It is an open question as to whether the recent regional mid-latitude cooling is a result of circulation changes resulting from sea-ice loss, Arctic amplification in general, natural variability, or from a combination of these processes. Certainly the atmospheric teleconnection pattern in Figure 5.8 spanning the North Atlantic, Barents/Kara seas region, Ural Mountains, to central Siberia is a major subarctic weather pattern that can be reinforced by surface temperatures and warm air advection.

In winters following low sea-ice conditions in the Barents/Kara seas, cold surge events into east Asia often result from the development of cold central Asian temperatures associated with the intensification and expansion of the Siberian High, and storm development to the east that leads to major movement of cold air to eastern Asia. Storm-scale cold surges over East Asia can thus be initiated by the sea ice and temperature anomalies over the Barents/Kara seas region. Figure 5.9 shows how such cold surges can develop (Park et al., 2011; Overland et al., 2021). Note that the wave train feature and cold reservoir over central Asia can be a monthly feature while the far eastern Asia weather event is on the synoptic-weekly time scale.

As in North America, Europe can be influenced by a shift in the stratospheric polar vortex. A major example was the latter part of the 'Beast from the East' severe weather event that brought cold air down into Europe during March 2018 (Greening and Hodgson, 2019; Overland et al., 2020). The right-hand globe in Figure 5.10 shows the jet stream pattern at 500 hPa with cold winds moving southward over Europe. The left-hand globe shows that the center of the stratospheric polar vortex was collocated over the center of the low atmospheric pressure, providing persistence to the atmospheric pattern.

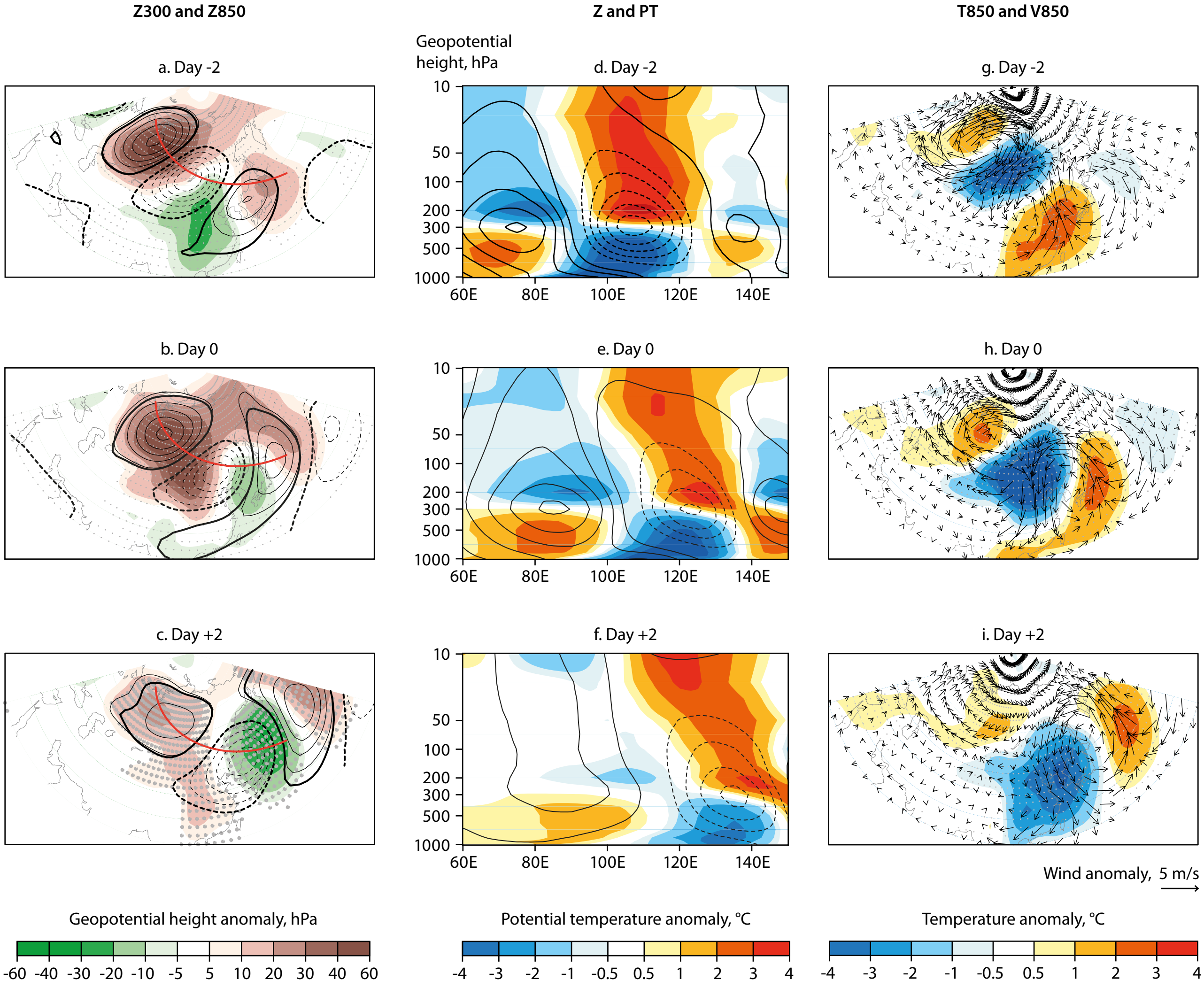

Figure 5.9 Composite anomalies of (a-c) geopotential height at 300 hPa (contour) and 850 hPa (shading), (d-f) vertical sections of geopotential height (contour) and potential temperature (shading) along the thick red lines of a-c, and (g-i) temperature anomalies (shading) and wind anomalies (vectors) at 850 hPa during day -2 to +2 relative to cold-surge occurrences. Source: Park et al. (2011).

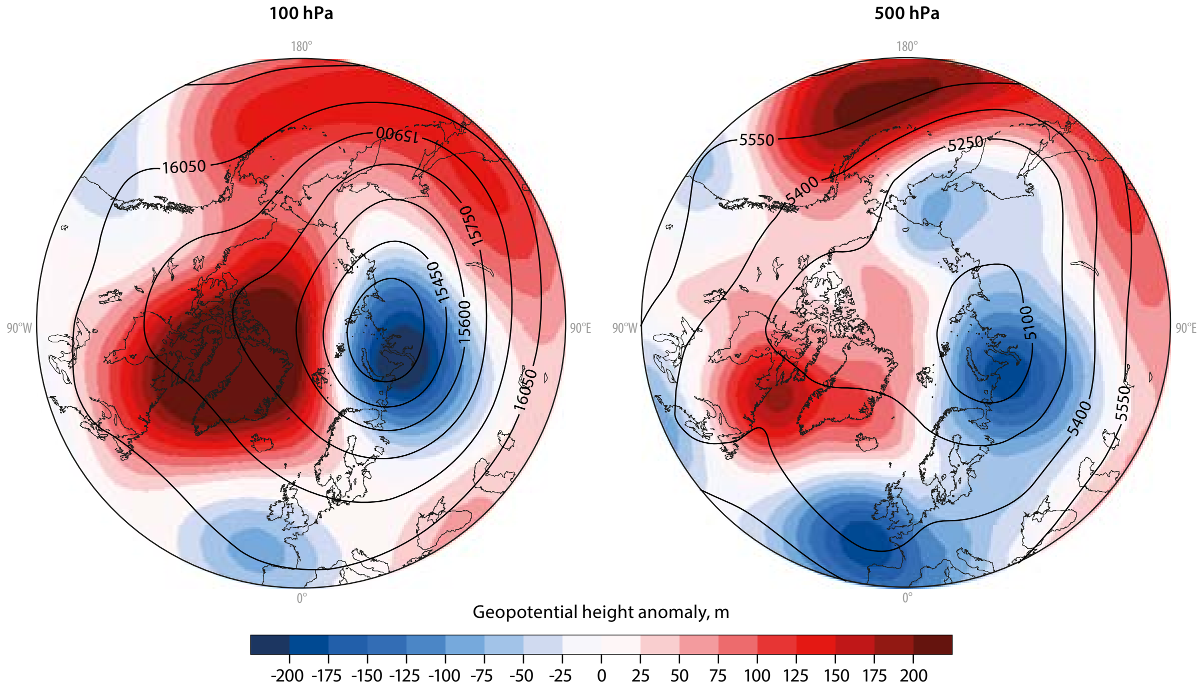

Figure 5.10 Geopotential height (contours, m) and anomaly (shading) at 100 and 500 hPa for the ‘Beast from the East’ in March 2018. The wind direction follows the contours for the jet stream bringing cold Arctic temperatures into Europe. Source: NCEP/NCAR reanalysis.

5.6 Heatwaves and summer Arctic linkages

In terms of the North American ridge-trough structure noted in Section 5.5, in some years the ridge is centered on California and associated with heat waves, extensive fires, and drought in the extended winter season (Cvijanovic et al., 2017; Swain et al., 2017; Budikova et al., 2019).

While this chapter has so far focused on the wavy jet stream pattern, it is the southern location of the west-to-east zonal pattern that was responsible for the January–April 2020 record heat wave in subarctic Siberia (Ciavarella et al., 2020; Overland and Wang, 2020).

Recent years have seen reductions in sea-ice extent, but their thermodynamic effect in summer is small as the surface temperatures of the open sea and sea ice are close to each other. The summertime north-south air temperature gradient has, however, decreased between mid-latitudes and the subarctic, with associated weakening of zonal mid-latitude atmospheric circulation (Coumou et al., 2015). Interactions between subarctic storm tracks and other remote and regional feedback processes can lead to more persistent hot-dry extremes (Screen et al., 2015; Francis, 2017; Mann et al., 2017; Coumou et al., 2018). The North American Pacific Northwest extreme heat dome of June 2021 was initiated by a southward polar vortex excursion. Recent studies point to the importance of sea ice, snow cover and soil moisture anomalies as contributors to hot summer and cold winter conditions in Eurasia (Benestad et al., 2011; Nakamura et al., 2019; Sato and Nakamura, 2019).

5.7 Observational analysis versus modeling experiments

Why do some atmospheric models not reproduce the observed links between weather patterns in the Arctic and mid-latitudes? As reviewed by an extensive group of Arctic scientists, Cohen et al. (2020) noted that "Although some model experiments support the observational evidence, most modeling results show little connection between AA [Arctic amplification] and severe mid-latitude weather. Divergent conclusions between model and observational studies, and even intra-model studies, continue to obfuscate a clear understanding of how AA processes are influencing mid-latitude weather."

Some modeling studies have shown that linkages between the Arctic and mid-latitude weather contribute to increased severity and frequency of major weather events such as stalled weather systems, extreme cold air outbreaks, and drought in North America and Eurasia. Some controlled experiments using climate models with and without Arctic sea-ice loss support these findings, whereas others find few impacts outside of the Arctic (Warner et al., 2020). That does not negate occasional extreme cold waves, but on average these extremes are tempered by the Arctic amplification warming. Discrepancies between different modeling studies may be related to sampling, but may also result from inconsistent boundary forcings or experimental protocols. The Polar Amplification Model Intercomparison Project (PAMIP) (Smith et al., 2019) aimed to address this issue by prescribing identical boundary forcings and protocols to multiple models. The first study based on PAMIP simulations (Ronalds et al., 2020) found that in response to future Arctic sea-ice loss in winter, the frequency of occurrence of the North American temperature west-east / warm-cold pattern, defined as anomalously warm

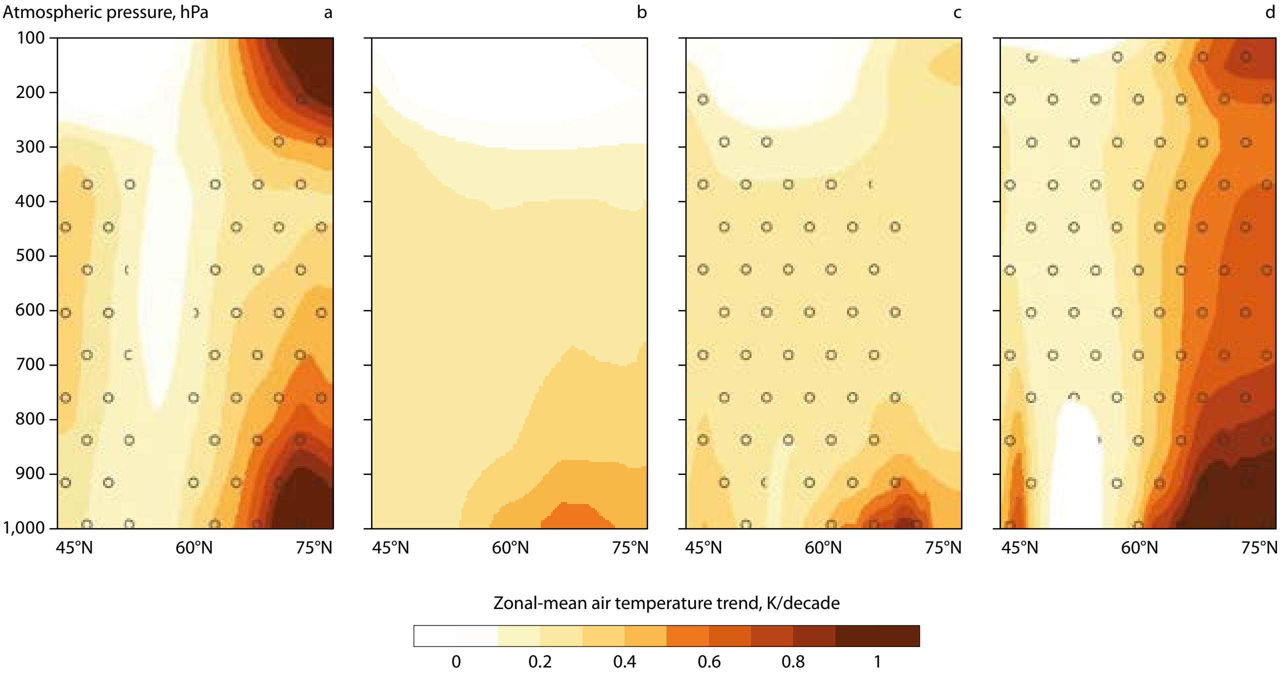

Figure 5.11. Winter (DJF) zonal-mean air-temperature trends (a) from December 1980 to February 2019 averaged over four reanalysis products (MERRA-2, ERA5, JRA-55, CFSR); (b) for the CMIP5 multi-model ensemble mean historical simulations through 2004 and RCP8.5 simulations thereafter; (c) from December 1980 to February 2019 for the AMIP multi-model mean; and (d) from December 1980 to February 2019 for the AMIP ensemble member that best matches the reanalysis mean based on pattern correlation. Stippling indicates significant trends with $p < 0.05$ after the correlation for false discovery rate was applied. From Cohen et al. (2020).

temperatures in the northwest and anomalously cold temperatures in the southeast, increases, while the frequency of anomalously cold temperatures over all of North America decreases.

Based on observations, Arctic amplification is evident throughout the troposphere, with a second maximum in the upper troposphere and stratosphere in the zonal-mean winter air-temperature trends for the Northern Hemisphere and Arctic between 1980 and 2019 (Figure 5.11a). Arctic warming simulated by the ensemble-mean Coupled Ocean-Atmosphere multi-Model Intercomparison Project-5 (CMIP5) lacks the magnitude and vertical extent of the observations (Figure 5.11b). The Atmospheric Model Intercomparison Project (AMIP) models forced with observed sea-surface temperature and sea-ice loss data are similar to those of CMIP5 (Figure 5.11c). As further noted by Cohen et al. (2020), "analysis of individual ensemble members reveals that several members closely match the distribution of observed temperature trends…; the individual ensemble member that best matches the observations is shown in Figure 5.11d". The large ensemble spread and the match shown in Figure 5.11d in models suggests that simulated and observed differences could be due to natural variability in different ensemble runs, consistent with observations (Overland and Wang, 2018).

However, the possibility that the models are deficient in representing some wavy jet stream dynamics, such as atmospheric blocking events (Tibaldi and Molteni, 2018; Woollings et al., 2018), cannot be excluded. Modeling the links between Arctic amplification and mid-latitude weather remains contentious in the Arctic community, and is important for further work.

5.8 Putting it all together: An intermittent phenomenon

At present there is no consensus in the meteorological community on the degree to which observed Arctic amplification has direct connections to mid-latitude extreme weather events. Although a wavy jet stream (Figure 5.3 right) drives both cold and warm air advection across the subarctic at any given time, the seasonal and regional means show little evidence of strong average seasonal influence relative to background global warming. While climate models do provide a closer look at specific physical processes, not all important Arctic dynamic processes in the troposphere (Vihma et al., 2014), stratosphere (Romanowsky et al., 2019), and land surface layer (Nakamura et al., 2019) are sufficiently represented.

Case studies do suggest specific weather linkage events over North America, Europe, and eastern Asia, downstream of Alaska and to the south and east of the Barents/Kara seas and the Ural Mountains. From these examples it does not appear that Arctic amplification is the direct cause of the weather linkages, but that a warmer Arctic, associated with the jet stream and movement of the stratospheric polar vortex over subarctic continents, can reinforce intrinsic natural jet-stream variability. Although environmental managers and the wider public would like a clear answer to the question of how the new Arctic changes will influence mid-latitude weather, the issue is complex due to the multiple physical processes involved and their interactions. A notable conclusion of this review is that there are many historical naturally occurring Arctic/mid-latitude connections, such as stratospheric polar vortex disruptions, that require more attention with analogs for future prediction of severe weather events. The relevance of forecasting extreme mid-latitude weather events supports continued research on Arctic linkages.

References

Barnes, E.A. and J.A. Screen, 2015. The impact of Arctic warming on the midlatitude jet-stream: Can it? Has it? Will it? WIREs Climate Change, 6:277-286.

Benestad, R., R. Senan, M. Balmaseda, L. Ferranti, Y.J. Orsolini and A. Melsom, 2011. Sensitivity of T_{2m} to Arctic sea ice. Tellus A, 63:324-337.

Blackport, R. and J.A. Screen, 2020. Insignificant effect of Arctic amplification on the amplitude of midlatitude atmospheric waves. Science Advances, 6:eaay2880.

Blackport, R., J.A. Screen, K. van der Wiel and R. Bintanja, 2019. Minimal influence of reduced Arctic sea ice on coincident cold winters in mid-latitudes. Nature Climate Change, 9:697-704.

Budikova, D., T.W. Ford and T.J. Ballinger, 2019. United States heat wave frequency and Arctic Ocean marginal sea ice variability. Journal of Geophysical Research: Atmospheres, 124:6247-6264.

Cattiaux, J., Y. Peings, D. Saint-Martin, N. Trou-Kechout and S.J. Vavrus, 2016. Sinuosity of midlatitude atmospheric flow in a warming world. Geophysical Research Letters, 43:8259-8268.

Ciavarella, A., D. Cotterill, P. Stott, S. Kew, S. Philip, G. Jan van Oldenborgh, A. Skålevåg, P. Lorenz, Y. Robin, F. Otto, M. Hauser, S.I. Seneviratne, F. Lehner and O. Zolina, 2020. Prolonged Siberian heat of 2020. www.worldweatherattribution.org/wp-content/uploads/WWA-Prolonged-heat-Siberia-2020.pdf

Cohen, J., X. Zhang, J. Francis and 29 others, 2020. Divergent consensuses on Arctic amplification influence on midlatitude severe winter weather. Nature Climate Change, 10:20-29.

Coumou, D., J. Lehmann and J. Beckmann, 2015. The weakening summer circulation in the Northern Hemisphere mid-latitudes. Science, 348:6232.

Coumou, D., G. Di Capua, S. Vavrus, L. Wang and S. Wang, 2018. The influence of Arctic amplification on mid-latitude summer circulation. Nature Communications, 9:2959.

Cvijanovic, I., B.D. Santer, C. Bonfils, D.D. Lucas, J.C.H. Chiang and S. Zimmerman, 2017. Future loss of Arctic sea-ice cover could drive a substantial decrease in California's rainfall. Nature Communications, 8:1947.

Feldl, N., S. Po-Chedley, H.K.A. Singh, S. Hay and P.J. Kushner, 2020. Sea ice and atmospheric circulation shape the high-latitude lapse rate feedback. npj Climate and Atmospheric Science, 3:41.

Francis, J.A., 2017. Why are Arctic linkages to extreme weather still up in the air? Bulletin of the American Meteorological Society, 98:2551-2557.

Francis, J.A. and S.J. Vavrus, 2015. Evidence for a wavier jet stream in response to rapid Arctic warming. Environmental Research Letters, 10:014005.

Francis, J.A., S.J. Vavrus and J. Cohen, 2017. Amplified Arctic warming and mid-latitude weather: New perspectives on emerging connections. WIREs Climate Change, 8:e474.

Greening, K. and A. Hodgson, 2019. Atmospheric analysis of the cold late February and early March 2018 over the UK. Weather, 74:79-85.

Guan, W., X. Jiang, X. Ren, G. Chen and Q. Ding, 2020. Role of atmospheric variability in driving the "warm-Arctic, cold-continent" pattern over the North America sector and sea ice variability over the Chukchi-Bering Sea. Geophysical Research Letters, 47:e2020GL088599.

Hansen, J., 2020. Climate Models vs Real World. www.columbia.edu/~jeh1/mailings/2020/20200203_ModelsVsWorld.pdf

He, S., X. Xu, T. Furevik and Y. Gao, 2020. Eurasian cooling linked to the vertical distribution of Arctic warming. Geophysical Research Letters, 47:e2020GL087212.

IPCC, 2019. IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Intergovernmental Panel on Climate Change (IPCC). www.ipcc.ch/srocc/chapter/technical-summary

Jin, C., B. Wang, Y.-M. Yang and J. Liu, 2020. "Warm Arctic-cold Siberia" as an internal mode instigated by North Atlantic warming. Geophysical Research Letters, 47:e2019GL086248.

Jung, T., N.D. Gordon, P. Bauer, D.H. Bromwich, M. Chevallier and 21 others, 2016. Advancing polar prediction capabilities on daily to seasonal time scales. Bulletin of the American Meteorological Society, 14:1631-1647.

Kug, J.-S., J.-H. Jeong, Y.-S. Jang, B.-M. Kim, C.K. Folland, S.-K. Min and S.-W. Son, 2015. Two distinct influences of Arctic warming on cold winters over North America and East Asia. Nature Geoscience, 8:759-762.

Kwok, R., 2018. Arctic sea ice thickness, volume, and multiyear ice coverage: losses and coupled variability (1958–2018). Environmental Research Letters, 13:105005.

Li, M., D. Luo, I. Simmonds, A. Dai, L. Zhong and Y. Yao, 2020. Anchoring of atmospheric teleconnection patterns by Arctic Sea ice loss and its link to winter cold anomalies in East Asia. International Journal of Climatology, 41:547-558.

Liang, X., M. Losch, L. Nerger, L. Mu, Q. Yang and C. Liu, 2019. Using sea surface temperature observations to constrain upper ocean properties in an Arctic sea ice-ocean data assimilation system. Journal of Geophysical Research: Oceans, 124:4727-4743.

Luo, D., X. Chen, J. Overland, I. Simmonds, Y. Wu and P. Zhang, 2019. Weakened potential vorticity barrier linked to Arctic sea-ice loss and increased mid-latitude cold extremes. Journal of Climate, 32:4235-4261.

Mann, M., S. Rahmstorf, K. Kornhuber, B.A. Steinman, S.K. Miller and D. Coumou, 2017. Influence of anthropogenic climate change on planetary wave resonance and extreme weather events. Scientific Reports, 7:45242.

McCusker, K., J. Fyfe and M. Sigmond, 2016. Twenty-five winters of unexpected Eurasian cooling unlikely due to Arctic sea-ice loss. Nature Geoscience, 3:838-842.

McGraw, M.C. and E.A. Barnes, 2020. New insights on subseasonal Arctic-midlatitude causal connections from a regularized regression model. Journal of Climate, 33:213-228.

McLeod, J.T., T.J. Ballinger and T.L. Mote, 2018. Assessing the climatic and environmental impacts of mid-tropospheric anticyclones over Alaska. International Journal of Climatology, 38:351-364.

Mori, M., Y. Kosaka, M. Watanabe, H. Nakamura and M. Kimoto, 2019. A reconciled estimate of the influence of Arctic sea-ice loss on recent Eurasian cooling. Nature Climate Change, 9:123-129.

Nakamura, T., K. Yamazaki, T. Sato and J. Ukita, 2019. Memory effects of Eurasian land processes cause enhanced cooling in response to sea ice loss. Nature Communications, 10:5111.

Ogawa, F., N. Keenlyside, Y. Gao, T. Koenigk, S. Yang, L. Suo, T. Wang, G. Gastineau, T. Nakamura, H. Nam Cheung, N.-E. Omrani, J. Ukita and V. Semenov, 2018. Evaluating impacts of recent Arctic sea ice loss on the Northern Hemisphere winter climate change. Geophysical Research Letters, 45:3255-3263.

Overland, J.E. and M. Wang, 2018. Arctic-midlatitude weather linkages in North America. Polar Science, 16:1-9.

Overland, J.E. and M. Wang, 2019. Impact of the winter polar vortex on greater North America. International Journal of Climatology, 39:5815-5821.

Overland, J. and M. Wang, 2020. The 2020 Siberian Heat Wave. International Journal of Climatology, 41:E2341-E2346.

Overland, J.E., K. Dethloff, J.A. Francis, R.J. Hall, E. Hanna, S.-J. Kim, J.A. Screen, T.G. Shepherd and T. Vihma, 2016. Nonlinear response of mid-latitude weather to the changing Arctic. Nature Climate Change, 6:992-999.

Overland, J., R. Hall, E. Hanna, A. Karpechko, T. Vihma, M. Wang and X. Zhang, 2020. The polar vortex and extreme weather: the beast from the east in winter 2018. Atmosphere, 11:664.

Overland, J.E., T.J. Ballinger, J. Cohen, J.A. Francis, E. Hanna, R. Jaiser, B.-M. Kim, S.-J. Kim, J. Ukita, T. Vihma, M. Wang and X. Zhang, 2021. How do intermittency and simultaneous processes obfuscate the Arctic influence on midlatitude winter extreme weather events? Environmental Research Letters, 16:4.

Park, T., C. Ho and S. Yang, 2011. Relationship between the Arctic Oscillation and cold surges over East Asia. Journal of Climate, 24:68-83.

Perlwitz, J., M. Hoerling and R. Dole, 2015. Arctic tropospheric warming: causes and linkages to lower latitudes. Journal of Climate, 28:2154-2167.

Pithan, F. and T. Mauritsen, 2014. Arctic amplification dominated by temperature feedbacks in contemporary climate models. Nature Geoscience, 7:181-184.

Richter-Menge, J., M.L. Druckenmiller and M. Jeffries (eds.), 2019. Arctic Report Card: Tracking recent environmental changes relative to historical records. www.arctic.noaa.gov/Report-Card

Romanowsky, E., D. Handorf, R. Jaiser, I. Wohltmann, W. Dorn, J. Ukita, J. Cohen, K. Dethloff and M. Rex, 2019. The role of stratospheric ozone for Arctic-midlatitude linkages. Scientific Reports, 9:7962.

Ronalds, B., E.A. Barnes, R. Eade, Y. Peings and M. Sigmond, 2020. North Pacific zonal wind response to sea ice loss in the Polar Amplification Model Intercomparison Project and its downstream implications. Climate Dynamics, 55:1779-1792.

Sato, T. and T. Nakamura, 2019. Intensification of hot Eurasian summers by climate change and land-atmosphere interactions. Scientific Reports, 9:10866.

Sato, K., J. Inoue and M. Watanabe, 2014. Influence of the Gulf Stream on the Barents Sea ice retreat and Eurasian coldness during early winter. Environmental Research Letters, 9:084009.

Schweiger, A., R. Lindsay, J. Zhang, M. Steele and H. Stern, 2011. Uncertainty in modeled arctic sea ice volume. Journal of Geophysical Research: Oceans, 116: doi:10.1029/2011JC007084.

Screen, J.A. and R. Blackport, 2019. Is sea-ice-driven Eurasian cooling too weak in models? Nature Climate Change, 9:934-936.

Screen, J.A. and I. Simmonds, 2014. Amplified mid-latitude planetary waves favour particular regional weather extremes. Nature Climate Change, 4:704-709.

Screen, J.A., C. Deser and L. Sun, 2015. Projected changes in regional climate extremes arising from Arctic sea ice loss. Environmental Research Letters, 10:084006.

Sigmond, M. and J. Fyfe, 2016. Tropical Pacific impacts on cooling North American winters. Nature Climate Change, 6:970-974.

Smith, D.M., J.A. Screen, C. Deser, J. Cohen, J. Fyfe, J. Garcia-Serrano, T. Jung, V. Kattsov, D. Matei, R. Msadek, Y. Peings, M. Sigmond, J. Ukita, J.-H. Yoon and X. Zhang, 2019. The Polar Amplification Model Intercomparison Project (PAMIP) contribution to CMIP6: investigating the causes and consequences of polar amplification. Geoscientific Model Development, 12:1139-1164.

Smith, D.M., A. Scaife, R. Eade, P. Athanasiadis, A. Bellucci and 34 others, 2020. North Atlantic climate far more predictable than models imply. Nature, 583:796-800.

Swain, D.L., D. Singh, D.E. Horton, J.S. Mankin, T.C. Ballard and N.S. Diffenbaugh, 2017. Remote linkages to anomalous winter atmospheric ridging over the northeastern Pacific. Journal of Geophysical Research: Atmospheres, 122:12194-12209.

Tachibana, Y., K.K. Komatsu, V.A. Alexeev, L. Cai and Y. Ando, 2019. Warm hole in Pacific Arctic sea ice cover forced mid-latitude Northern Hemisphere cooling during winter 2017-18. Scientific Reports, 9:5567.

Tibaldi, S. and F. Molteni, 2018. Atmospheric blocking in observation and models. Oxford Research Encyclopedia, Climate Science.

Vavrus, S.J., 2018. The influence of Arctic amplification on mid-latitude weather and climate. Current Climate Change Reports, 4:238-249.

Vavrus, S.J., F. Wang, J.E. Martin, J.A. Francis, Y. Peings and J. Cattiaux, 2017. Changes in North American atmospheric circulation and extreme weather: Influence of Arctic Amplification and Northern Hemisphere snow cover. Journal of Climate, 30:4317-4333.

Vihma, T., 2014. Effects of Arctic sea ice decline on weather and climate: A review. Surveys in Geophysics, 35:1175-1214.

Vihma, T., R. Pirazzini, I. Fer, I.A. Renfrew, J. Sedlar, M. Tjernström, C. Lüpkes, T. Nygård, D. Notz, J. Weiss, D. Marsan, B. Cheng, G. Birnbaum, S. Gerland, D. Chechin and J.C. Gascard, 2014. Advances in understanding and parameterization of small-scale physical processes in the marine Arctic climate system: a review. Atmospheric Chemistry and Physics, 14:9403-9450.

Warner, J.L., J.A. Screen and A.A. Scaife, 2020. Links between Barents-Kara sea ice and the extratropical atmospheric circulation explained by internal variability and tropical forcing. Geophysical Research Letters, 47:e2019GL085679.

Woollings, T., D. Barriopedro, J. Methven, S.-W. Son, O. Martius, B. Harvey, J. Sillmann, A.R. Lupo and S. Seneviratne, 2018. Blocking and its response to climate change. Current Climate Change Reports, 4:287-300.

Xie, Y., G. Wu., Y. Liu and J. Huang, 2020. Eurasian cooling linked with Arctic warming: insights from PV dynamics. Journal of Climate, 33:2627-2644.

Yamazaki, K., T. Nakamura, J. Ukita and K. Hoshi, 2020. A tropospheric pathway of the stratospheric quasi-biennial oscillation (QBO) impact on the boreal winter polar vortex. Atmospheric Chemistry and Physics, 20:5111-5127.

Zhang, P., Y. Wu, I.R. Simpson, K.L. Smith, X. Zhang, B. De and P. Callaghan, 2018. A stratospheric pathway linking a colder Siberia to Barents-Kara Sea sea ice loss. Science Advances, 4:7.

6. Arctic climate and ecosystem linkages: impacts and feedbacks

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Key findings

- *Ecosystems across the Arctic are undergoing fundamental changes in their structure and function. These changes impact all species, including humans, living in the Arctic and beyond.*
- *The rapid pace of Arctic ecosystem change requires immediate action to document what is being lost and what is being created as unique ecosystems are disappearing and the cryosphere is shrinking. The unique ecosystems of the remaining perennial sea-ice cover, ice shelves and epishelf lakes, and the Greenland Ice Sheet are among the priorities for documentation.*
- *Ecosystem impacts of the rapidly changing cryosphere are observed throughout the Arctic, altering the productivity, seasonality, distribution and interactions of species in terrestrial, coastal, and marine ecosystems. Changes in sea-ice extent and seasonality, snow cover on land and sea ice, tundra greening and browning, and the rapid loss of perennial ice and the Greenland Ice Sheet result in fundamental ecosystem changes that affect the cycling of carbon and greenhouse gases. Adaptation requires coordinated climate-ecosystem monitoring at key locations, building on existing monitoring efforts in combination with community-driven monitoring that uses Indigenous and local knowledge.*
- *Extreme events exacerbate transitions already under way from climate warming and sea-ice changes, triggering further impacts on terrestrial, coastal, and marine ecosystems. For example, extreme precipitation events and a generally increasing rain-to-snow ratio affect the structure and function of terrestrial ecosystems. Permafrost thaw, impacting exchanges of greenhouse gases, is also influenced by accelerated collapses and thermokarst erosion associated with extreme precipitation.*
- *In marine ecosystems, primary productivity continues to increase due to complex changes in nutrient and light conditions. Predicting the future productivity of the Arctic Ocean requires a better understanding of the changing production associated with the sea ice and water column, the cycling of nutrients, and the adaptive capacity of primary producers to changing conditions.*
- *Significant emissions of methane from tundra, freshwater, and near-coastal sediments remain a major global source of greenhouse warming and new findings add hitherto unrecognized processes, such as subglacial outflow of gases, to the portfolio of source components in the Arctic. None of these, however, change previous total natural emission estimates for the Arctic when considering the inherent variability and uncertainty ranges.*
- *The Arctic gateways that connect the Arctic Ocean to the Pacific and Atlantic oceans are experiencing major ecosystem shifts. Warming, acidification, and massive die-offs of bird species are some of the recent changes in the Beaufort Sea. In the Barents Sea, expansion of the Atlantic domain has resulted in widespread shifts in species distribution and abundance.*
- *Changes in coastal ecosystems, intensified by extreme events, affect coastal communities that are increasingly vulnerable to coastal erosion through wave and storm action. Adaptation and mitigation measures for impacted communities are essential.*

6.1 Introduction

The aim of this chapter is to investigate climate-ecosystem linkages in terms of impacts and feedbacks. Whereas climate impacts on Arctic ecosystems are widespread and span all trophic levels, ecosystem feedbacks to the climate system are inherent to the biogeochemical cycling of greenhouse gases and exchanges of heat and water.

Within food webs, climate feedbacks take place at the lower trophic levels, via gas uptake (autotrophic production), respiration, and potential sequestration through sedimentation and accumulation of carbon biomass in soils and sediments. The focus of this chapter is therefore on ecosystem processes and components that influence the biogeochemical cycling of greenhouse gases and surface energy exchanges, i.e., impacts and feedbacks. Recent assessments of climate change impacts on Arctic marine and terrestrial ecosystems provide a comprehensive analysis of ecosystem impacts across all trophic levels (AMAP, 2011, 2017; CAFF, 2013, 2017) and a recent review and upcoming AMAP assessment on short-lived climate forcers deal specifically with other radiatively active gases and aerosols (Abbatt et al., 2019; AMAP, in press). The chapter follows a coupled approach to assess ecosystem-climate connections, and provides a review and analysis of new science since the SWIPA 2017 (Snow, Water, Ice and Permafrost in the Arctic) report (AMAP, 2017).

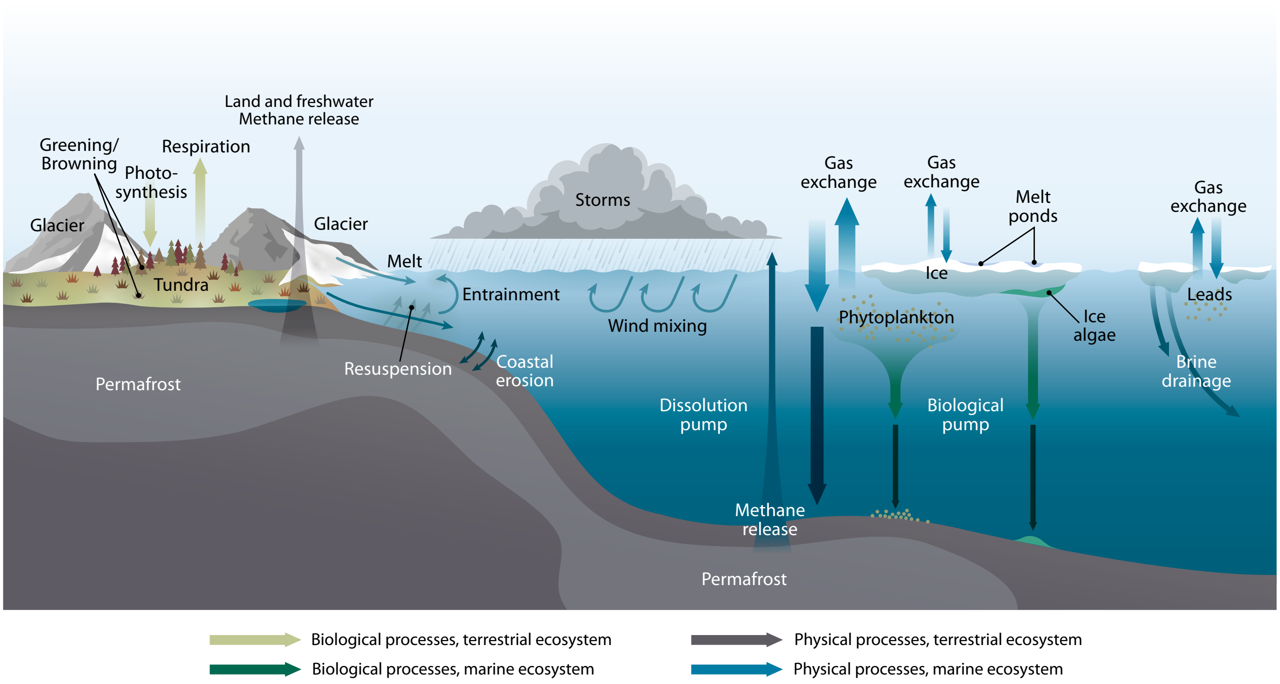

Figure 6.1 Schematic illustration of the key biogeochemical processes affecting the cycling of carbon dioxide and methane in Arctic terrestrial, coastal and marine ecosystems.

The terrestrial, freshwater, and marine environments host major atmospheric exchanges of carbon in the form of the greenhouse gases carbon dioxide (CO_2) and methane (CH_4). The annual atmospheric exchanges are very small, on a mass basis, compared with the vast stocks of organic material in the Arctic environment. Stocks in permafrost soils alone amount to ~1300 Gt C (Hugelius et al., 2014) and in subsea permafrost ~560 Gt C (170–740, 90% confidence interval; Sayedi et al., 2020). The oceans store even larger amounts of carbon, with estimates of ~38,000 Gt C in the form of dissolved inorganic carbon for the World Ocean (Sarmiento and Gruber, 2006; Friedlingstein et al., 2020). Hence, there is potential for much greater exchanges with the atmosphere, giving rise to concern as atmospheric CO_2 concentrations continue to rise and the Arctic continues to warm (Abram et al., 2019; Meredith et al., 2019). As climate regulators, land-based environments are prone to vegetation changes that may affect the structure and composition of the terrestrial cover which in turn affect energy exchanges. Seawater has a heat capacity four times greater than air, making the oceans large heat reservoirs within the climate system. Conversely, because gas is more soluble in cold water than warm water, the cold Arctic Ocean can retain larger quantities of climatically-active gases than temperate waters. The seasonality of Arctic ecosystems, notably the presence and duration of sea ice, lake ice, and terrestrial/sea-ice snow cover are also sensitive variables in a warming climate, causing feedbacks in terms of energy and gas exchange. Taken together, these mechanisms characterize the multiple ways in which Arctic ecosystems interact with climate, as summarized in Figure 6.1, and are addressed in the following sections.

6.2 Impacts of change

6.2.1 Air and sea temperature impacts

Observational records show that Arctic warming has accelerated since 2005 and that the greatest increases in air temperature are occurring over the Arctic Ocean, especially during October through May (Box et al., 2019; see Chapter 2). In terms of annual averages, Arctic Ocean near-surface air temperatures increased by 4–6°C between 1971 and 2019. Sea-surface temperatures between 1982 and 2018 also show an increasing trend, influenced by air temperature, water vapor, sea-ice concentrations and, regionally, advection from neighboring seas (Carvalho and Wang, 2020). The repercussions of Arctic warming are observed on land and in the ocean, and impacts range from thawing permafrost to sea-ice losses and ecosystem-wide restructuring.

6.2.1.1 Arctic greening and browning

The tundra biome has seen widespread greening over the past few decades due to an increased growth of shrubs in response to longer and warmer summers (Berner et al., 2020; Myers-Smith et al., 2020). This Arctic greening has been observed through long-term ecological monitoring programs, as shrubs have become taller and more abundant, and also as a spectral response in remotely-sensed vegetation indices (Elmendorf et al., 2012; Post et al., 2013). However, the majority of the Arctic has seen little change in spectral greenness despite an increase in summer warmth (Berner et al., 2020). This may be due to, among other factors, nutrient and moisture limitation or grazing and trampling by herbivores (Berner et al., 2020).

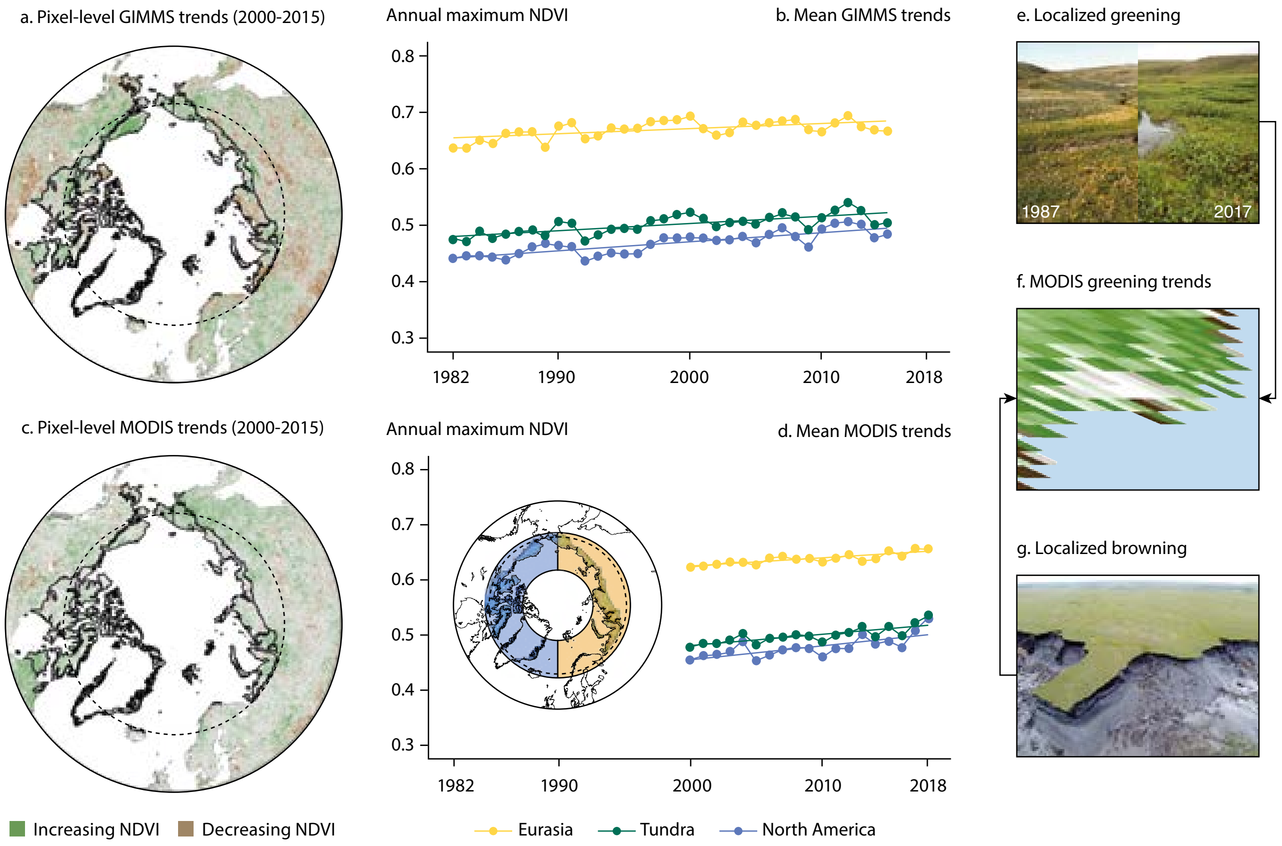

Figure 6.2 Apparent Arctic greening, which varies across space and time and among satellite datasets, is driven by actual *in-situ* change and, in part, by challenges associated with satellite data interpretation and integration. From a–d, Trends in maximum normalized differential vegetation index (NDVI) vary spatio-temporally, and the magnitude of change depends on the satellite imagery analyzed (a and c, data subsetted to temporally overlapping years; b and d, data from the Global Inventory Modeling and Mapping Studies dataset from AVHRR GIMMS3gv1 1982 to 2015, and MODIS MOD13A1v6 2000 to 2018). From e–g, Regional trends may summarize localized greening, for example shrub encroachment (e) and browning such as permafrost thaw (g) occurring at the pixel scale on Qikiqtaruk–Herschel Island in the Canadian Arctic (f). NDVI trends (a and c) were calculated using robust regression (Theil–Sen estimator) in the Google Earth Engine 130. The dashed line indicates the Arctic Circle and the green 'tundra' line (b and d) indicates the Arctic tundra region from the Circumpolar Arctic Vegetation Map (www.geobotany.uaf.edu/cavm). The inset map in (d) indicates the regions for the mean trends for the 'Eurasia' and 'North America' polygons. From: Myers-Smith et al. (2020).

Herbivore-plant interactions are complex, however, and may also increase plant nitrogen concentrations and plant quality (Mosbacher et al., 2019). The resulting higher carbon and nitrogen stocks and Leaf Area Index (LAI) can lead to higher photosynthetic activity and subsequently to greater ecosystem carbon sink strength, even with low temperatures and short growing seasons (López-Blanco et al., 2020).

Nevertheless, there are parts of the Arctic where the spectral greening trend has weakened, or even reversed; a process called Arctic browning (Phoenix and Bjerke, 2016). Observations of spectral browning are fewer than those of greening, but more complex in origin since causes of spectral browning include spatially non-uniform impacts such as extreme winter events (i.e., rain-on-snow and frost droughts) and pest outbreaks (Bjerke et al., 2014; Lund et al., 2017). Other possible contributory factors include delayed onset of snowmelt and increases in standing surface water (Bhatt et al., 2017). While the overall response of the tundra biome to increasing summer temperatures is one of increasing growth, it remains unclear whether winter warming, a potential driver of Arctic browning, may become more important and weaken the greening trend in the future (Figure 6.2).

Arctic vegetation represents just a thin layer between the atmosphere and the soil, but plays a key role in biogeophysical feedbacks. Changes in Arctic vegetation growth and biomass can alter the exchange of energy, and therefore climate. Locally, shrubs shade the ground from incoming solar radiation and influence heat transfer, which is why permafrost soils beneath shrubs remain colder than in their absence (Blok et al., 2010). Shrubs also enhance evapotranspiration, which – through the dissipation of energy as latent heat – can cause a cooling effect and enhance cloud formation (Rydsaa et al., 2017). However, these effects are bound by simultaneously opposing processes. Shrub expansion reduces the albedo of the landscape, which results in increased absorption of solar radiation and may offset the cooling from shading. The presence of tall vegetation protruding from the highly reflective snow cover decreases surface albedo (Loranty et al., 2018). However, taller shrubs capture more snow, which increases the insulation of the ground in winter, effectively warming the soil. A sufficiently thick snow cover can trigger permafrost thaw and surface subsidence (Jafarov et al., 2018). A thicker winter snowpack, through its warming effect on soil temperatures, can also lead to higher heterotrophic respiration, resulting in possible overall ecosystem carbon loss (López-Blanco et al., 2018). Ultimately, the biogeophysical and climatic feedbacks depend on the integrated response of the ecosystem to multiple forcings.

6.2.1.2 Arctic Ocean warming and freshening

The Arctic Ocean is experiencing widespread temperature increases, with direct impacts on the sea ice ecosystem (see Section 6.2.4), the dissolution of gases and associated processes such as ocean acidification, and the physiology and ecology of a wide range of organisms. Temperature affects all aspects of the lifecycle of marine species, including reproduction, prey-predator interactions, and range extensions (see Michel, 2013; AMAP, 2017). Through its effect on the freshwater balance and sea-ice loss, warming also has opposing effects on the surface stratification of the Arctic Ocean. Sea-surface temperatures in summer show significant warming trends for the past four decades in most Arctic regions, with large increases in eastern Baffin Bay and the Beaufort, Chukchi, and Laptev Seas (Timmermans and Ladd, 2019; Carvalho and Wang, 2020). Direct and indirect changes associated with warming are reshaping the ecosystems and food webs of the Arctic Ocean.

Warming of the marine ecosystem in a given region of the Arctic Ocean can occur in two major ways. First, the strength and poleward penetration of ocean currents that bring warm waters from the North Pacific and Atlantic oceans are modified by climate change (Polyakov et al., 2017, 2020). Second, seasonal solar heating during summer warms the upper ocean once the ice has melted (Timmermans et al., 2018). These two mechanisms have different drivers (e.g., shifting winds *versus* Arctic amplification) and their relative importance will vary across different parts of the Arctic Ocean, with their additive influence being greatest in peripheral areas. Their impacts on the marine ecosystem differ because they affect different vertical horizons of the water column (i.e., the upper mixed layer *versus* a thicker extent of the water column) and because ocean currents also transport nutrients and organisms from lower latitudes, while solar heating only affects local temperature and, to a certain extent, vertical stratification. Solar heating also paves the way for range expansions, but for organisms of the lower food web this expansion is presumably much slower when currents do not assist (Oziel et al., 2020), and for upper trophic levels it is principally made possible by sea-ice reductions (Stafford, 2019; Lefort et al., 2020).

Warming can affect the lower food web in two major, non-mutually exclusive ways. First, based on ecological theory, organisms that are well-adapted to low temperatures may be supplanted by other species that are better adapted to temperate conditions, thereby altering dominance patterns and the food available to consumers, up to fish, birds and marine mammals (e.g., Beaugrand, 2015; Beaugrand et al., 2019). Second, warming alters the physiological rates and function of all organisms, whether these are 'historical' big players that succeed in maintaining their dominance or new ones that recently gained a competitive edge (e.g., Hoppe et al., 2018a).

Many Arctic species are considered to be adapted to low temperatures with presumably limited capacity to adapt to temperatures exceeding optimal conditions for growth and reproduction, making them vulnerable to temperature increases. Phytoplankton, which form the base of marine food webs, and microbes (e.g., archaea, bacteria) involved in the cycling of key elements in marine biogeochemical cycles are harbingers of change as they respond rapidly to environmental forcings. A comparison of thermal thresholds for Arctic phytoplankton species suggests that sub-optimal temperature conditions, i.e., temperatures higher than the thermal optimum, already occur in the surface ocean layer at 70°N and will extend northward as the Arctic continues to warm, impacting phytoplankton dynamics and community structure (Coello-Camba and Agustí, 2017).

Under seasonally ice-free conditions, Arctic phytoplankton tend to concentrate in productive subsurface layers once the water column stratifies and nitrogen has been depleted at the surface (e.g., Martin et al., 2010; Zhuang et al., 2020). These layers are typically dominated by the genus *Micromonas* offshore, a dominant phytoplankton group in the Arctic Ocean (Lovejoy et al., 2007; Marquardt et al., 2016), and by the cosmopolitan diatom *Chaetoceros gelidus* in coastal areas (CAFF, 2017; Benner et al., 2019; Schiffrine et al., 2020). It is noteworthy that *M. polaris* and a *C. gelidus* strain isolated from the coastal Beaufort Sea currently share the same temperature optimum (6°C) for growth (Benner et al., 2019; Schiffrine et al., 2020) and that this optimum almost systematically exceeds the temperature of subsurface layers throughout summer and autumn in this region (generally <1°C, Schiffrine et al., 2020). Because these layers are largely isolated from the surface by the stratification, their temperatures seldom track those of the surface ocean, which seasonally warms from near-freezing to 10°C or slightly more (Schiffrine et al., 2020). It follows that climate-driven warming of subsurface phytoplankton layers can be expected to be much slower and weaker than at the surface and to have a positive impact on the growth of *M. polaris* and *C. gelidus* for the foreseeable future.

The ocean surface layer is much more prone to seasonal and long-term climate warming than the subsurface, which may have negative consequences for currently dominant polar species. However, the recent evidence of wide thermal adaptation capacity in *M. polaris* (Benner et al., 2019) implies a new paradigm with respect to the adaptive response of phytoplankton communities to ongoing changes, suggesting a better potential to adapt to warming ocean temperature than previously assumed. Moreover, the growth rate of *M. polaris* cells that did not undergo multi-generational adaptation was the same at 2°C and 13°C, with a small reduction relative to the 6°C optimum (Benner et al., 2019).

Although knowledge of species-specific adaptive capacity and temperature impacts on community interactions is still limited, the high temperature plasticity found in a key Arctic phytoplankton group (*M. polaris*; Benner et al., 2019) suggests that factors other than a direct impact of temperature (e.g., nutrient and light availability) prevail in controlling phytoplankton community structure and production in the changing Arctic. Changes in phytoplankton community composition have been related to freshening and strengthening of surface stratification, with potential for system-wide changes as the ocean continues to warm (AMAP, 2017). Recent studies also show synergistic responses to multiple factors that are influenced by climate change (e.g., temperature, acidification conditions, salinity), with ensuing impacts on phytoplankton functional groups, diversity and physiology (Hoppe et al., 2018a; Sugie et al., 2020).

Temperature-dependent physiological changes may affect a host of biogeochemically relevant properties, including growth rates, the balance between gross primary production and respiration and the chemical composition of phytoplankton. Changes in growth rate can further modify the timing and duration of the spring bloom, a key event in the Arctic Ocean productive cycle. A shifting balance between gross primary production and respiration can impact the amount of organic matter channeled into the upper food web and the size of the biological pump that contributes to reduce the CO_2 burden of the atmosphere. Finally, changes in the elemental composition (or elemental stoichiometry) of primary producers can modulate their nutritional value for consumers and the efficiency of the biological CO_2 pump (e.g., Schiffrine et al., 2020).

Because the Arctic Ocean is strongly influenced by advection from the Pacific and Atlantic Oceans, the distribution of these water masses and their associated biophysicochemical characteristics plays a critical role in structuring the marine ecosystem. The inflow shelves of the Arctic Ocean (*sensu* Carmack and Wassmann, 2006) are subject to considerable advection from peripheral seas, but impacts of ongoing changes reach the central basins (Polyakov et al., 2020). In the Pacific Arctic, waters from the Pacific Ocean flow into the Bering, Chukchi and Beaufort Seas, and further influence the Beaufort Gyre and Canada Basin. In the Eastern Atlantic sector of the Arctic, Atlantic water enters through two branches east and west of Svalbard. In the Western Atlantic sector, water enters the Labrador Sea and eastern Baffin Bay as it flows north with the West Greenland Current. Wide-ranging ecosystem changes resulting from the increasing influence of Atlantic and Pacific advection to the Arctic Ocean are discussed in Box 6.1.

These ecosystem changes also impact local communities. The emerging risk of toxin-producing algal blooms in the Arctic was highlighted in the SWIPA 2017 assessment (AMAP, 2017), supported by evidence of algal toxins in marine mammal species in the Pacific Arctic (Lefebvre et al., 2016). Since then, the recent occurrence of toxin-producing algal blooms has been documented in the Pacific Arctic region (Anderson et al., 2018) and is a cause for concern for food safety. Toxin-producing algal species are already present in the Arctic; for example, the genus *Pseudo-nitzschia*, which includes domoic acid producers, is widespread from the Beaufort Sea through the Canadian Arctic Archipelago and Baffin Bay (Percopo et al., 2016). Warming and freshening of the ocean is expected to provide more suitable conditions for the development of toxin-producing algal blooms in the future. Therefore, there is a need to establish the factors that influence the distribution, growth, and toxicity of toxin-producing algae in the Arctic. In 2019, the National Oceanic and Atmospheric Administration (NOAA) reported unusual mortality events for gray whales and several seal species (ringed, bearded, spotted) after hundreds of individuals were found stranded and washed up on Alaskan shores over a period of several months (NOAA, 2019). Seabirds

Box 6.1 The changing nature of the Arctic Ocean

The Arctic Ocean is influenced by its neighbors, the Pacific and Atlantic oceans. This connectivity influences the distribution of water properties and species carried by ocean currents as they enter the Arctic Ocean. This connectivity is changing. There is an increase in Pacific and Atlantic water inflow into the Arctic Ocean, causing widespread alterations in ocean properties and ecosystems, collectively referred to as borealization of the Arctic Ocean (see Polyakov et al., 2020). These changes co-exist and combine with other direct and indirect impacts of climate warming to alter the fundamental nature of the Arctic Ocean.

Over the past decade, the increase in Pacific waters entering the Arctic Ocean through the Bering Strait (Woodgate et al., 2018) together with unusually warm years has resulted in ecosystem-wide reorganization in the Bering and Chukchi seas. These changes, summarized by Huntington et al. (2020), affect all trophic levels from the flow of energy and materials to primary producers to the distribution and abundance of fish, seabird and marine mammal species (also see Box 6.2).

Atlantification, or the increasing influence of Atlantic waters in the Barents Sea and Eurasian Sector of the Arctic Ocean, is also receiving renewed interest due to its importance for sea ice, ocean properties (Polyakov et al., 2017, 2020; Asbjørnsen et al., 2020), and ecosystem structure (e.g., Neukermans et al., 2018; Oziel et al., 2020). First introduced in a study linking Atlantic heat transport to the declining sea-ice cover of the Barents Sea (Årthun et al., 2012), the term atlantification is often used interchangeably with the more encompassing term borealization in ecological studies (e.g., Fossheim et al., 2015; Frainer et al., 2017). Increasing Atlantic inflow into the Arctic Ocean pushes the polar temperature front northeastward in the Barents Sea, triggering widespread and fundamental ecosystem changes. As warm Atlantic waters reach further into the Arctic Ocean, changes in ecosystem structure are taking place, including changes in the phenology and composition of plankton communities, poleward advection of temperate species such as the coccolithophore *Emiliana huxleyi*, and a longer open water period allowing for Atlantic-type autumn blooms (Oziel et al., 2017, 2020; Neukermans et al., 2018). Northern range expansions of boreal species of invertebrates, fish and marine mammals are also documented (Haug et al., 2017). Among these, there are numerous commercial species such as mackerel (*Scomber scombrus*), cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), Greenland halibut (*Reinhardtius hippoglossoides*), redfish (*Sebastes* spp.) and shrimp (*Pandalus borealis*). Some species expanding their distribution range are considered to have reached their northernmost limit, whereas others such as capelin (*Mallotus villosus*), redfish, minke whale (*Balaenoptera acutorostrata*) and harp seal (*Pagophilus groenlandicus*) can extend their range further into the Arctic Ocean. There is also evidence of borealization of marine food webs in eastern Baffin Bay, revealed by a recent analysis of zooplankton communities showing a shift, over the past decade, towards a dominance of the small Atlantic zooplankton species *Calanus finmarchicus* (Møller and Nielsen, 2020).

throughout the region have also experienced widespread die-offs in the Bering and Chukchi seas (see also Box 6.2), numbering in the thousands in summer 2019 (USFWS, 2019). The presence of toxin-producing algae has been implicated at least in part in all of these mortality events, yet little is known about their spatio-temporal distribution across the Arctic region.

6.2.1.3 CO_2 exchanges and feedbacks

Biogeochemical feedbacks from the terrestrial and marine ecosystems to the atmosphere depend on a variety of physical and chemical factors, as well as biological processes that drive the uptake of gases (i.e., mainly photosynthesis) and their release (i.e., respiration) back to the atmosphere, or their sequestration in sediments. This chapter focuses on biological impacts and feedbacks rather than on physical and chemical processes that influence gas dissolution and exchange, and which play important roles in the Arctic. For example, the temperature dependency of gas dissolution in the ocean favors CO_2 dissolution, and acidification conditions, in cold Arctic waters. Conversely, the frozen landscape and seascape limit gas exchange with the atmosphere, thereby intensifying the seasonality of atmosphere-ocean interactions.

From a biological perspective, CO_2 exchanges result from a balance between the amount of CO_2 taken up from the atmosphere or ocean through photosynthesis (representing gross primary production) and respiration, which returns CO_2 to the atmosphere (or ocean). For carbon budgets, respiration includes the whole community respiration, which combines that of autotrophs (e.g., photosynthetic organisms) and all other organisms (heterotrophs) including decomposers of plant litter and soil carbon, or sinking algae and organic matter in the ocean. It is the imbalance between these opposing processes that represents the ecosystem biogeochemical feedback to the climate system.

In the terrestrial biome, vegetation growth will only increase the net CO_2 uptake from the atmosphere if the change in respiration remains smaller than the increase in gross primary production. Long-term eddy covariance studies have shown that increases in gross primary production and respiration largely cancel each other out during the growing season and that the change in the balance of these two opposing fluxes remains small (Parmentier et al., 2011; Lund et al., 2012; López-Blanco et al., 2017). Differences in nutrient conditions have also been shown to have overriding effects on the impacts of climate alone on the tundra ecosystem growing-season CO_2 exchange (López-Blanco et al., 2020). Due to high interannual and spatial variability, it remains challenging to extrapolate a trend in CO_2 exchange from individual sites. Pan-Arctic syntheses of carbon fluxes suggest that the Arctic terrestrial region is a sink of CO_2 during the growing season (McGuire et al., 2012), yet the strongest warming is in more recent years observed during the cold season (e.g., Christensen et al., 2020). When wintertime respiration is included and likely following an increasing trend due to this warming, the permafrost region may already be a source of CO_2 (Natali et al., 2019).

Arctic warming may not necessarily lead to a widespread increase in gross primary production in the terrestrial biome as otherwise may be assumed from an overall greening trend. Vegetation damage by extreme winter events, one of the main drivers of Arctic browning, is believed to cause a decrease in gross primary production (Parmentier et al., 2018; Treharne et al., 2018). The importance of these events at the regional scale remains largely unknown, but initial studies from permafrost-free areas in the subarctic show a significant impact on gross primary production at local sites (Parmentier et al., 2018; Treharne et al., 2018). Compensatory growth in the next year may offset these local effects (Bokhorst et al., 2011) and nutrients may in turn regulate such a response (López-Blanco et al., 2020). In the long term, it is conceivable that there may be further causal effects if shrub cover is strongly reduced, especially in the permafrost region. Manipulation experiments have shown that the removal of shrubs can lead to permafrost collapse and an increase in methane emissions (Nauta et al., 2014). These events may also happen without shrub interference and cause severe changes in vegetation composition as well as carbon and nitrogen stocks and, ultimately, tundra carbon and greenhouse gas balance (Christensen et al., 2020). Trophic interaction within the ecosystems, for example grazing by herbivores, can also change the vegetation markedly (Mosbacher et al., 2019), in turn affecting carbon fluxes (Falk et al., 2015). The interlinked ecosystem impacts on methane emissions may in some cases drive Arctic biogeochemical feedbacks, as discussed in Section 6.2.2.

The spatial and temporal distributions of CO_2 fluxes in the Arctic Ocean and its adjacent seas are not fully understood due to limited observational coverage, the complexity and heterogeneity of the different Arctic domains, and the rapid ongoing changes. In a recent study, Yasunaka et al. (2018) accounted for spatial heterogeneity by using a self-organizing map technique to estimate monthly air–sea CO_2 fluxes in the Arctic Ocean and its adjacent seas over an 18-year time series from January 1997 to December 2014. They estimated the annual Arctic Ocean CO_2 uptake at 180±130 Tg C, in agreement with a coupled atmosphere–ocean estimate of 153±14 Tg C/y (Manizza et al., 2019), and corresponding to approximately 10% of the World Ocean total. A recent ice–ocean biogeochemical coupled model estimates that the annual net carbon uptake for the Arctic Ocean increased from 110 Tg C/y to 135 Tg C/y between 1980 and 2015 (Mortenson et al., 2020).

These studies also show high regional variability in CO_2 uptake decadal trends, with both increases and decreases in different Arctic domains (e.g., an increasing trend in the Greenland Sea *versus* a decreasing trend in the Chukchi Sea; Yasunaka et al., 2018), and a lack of consistent response of the CO_2 sink to sea-ice declines (Manizza et al., 2019). Increases in the Arctic Ocean CO_2 sink during years of extreme sea-ice loss were not commensurate with changes in sea ice. Rather, changes in the Arctic Ocean CO_2 sink are attributed to a complex interplay of factors that may act differently in different Arctic regions, including winds, stratification, primary production and ocean–atmosphere exchanges. The complexity of the physical processes of CO_2 exchange associated with sea ice can be illustrated by concurrent effects of the sea-ice cover which dampens air–ocean CO_2 exchanges leading to undersaturated conditions in under-ice surface waters, leads and openings in the ice cover increasing air–ocean CO_2 fluxes (Nomura et al., 2018) which are further intensified by storms (Fransson et al., 2017), and brine expulsion during ice formation impacting CO_2 fluxes at the regional scale (Grimm et al., 2016). All of these components of the cryosphere are changing and need to be considered in biogeochemical models (Lannuzel et al., 2020). An additional consideration for the future role of the Arctic Ocean as a carbon sink is linked to its freshwater budget, based on observations in Canada Basin and Marakov Basin where dissolved inorganic carbon decreased over recent decades despite increasing atmospheric CO_2 concentrations (Woosley and Millero, 2020).

Trends, status and potential ecological impacts of ocean acidification in the Arctic are well described in a recent synthesis (AMAP, 2018) and therefore are not discussed in detail in this chapter. The Arctic Ocean is particularly vulnerable to acidification due to a combination of low temperatures, which increase gas dissolution in the water, a high freshwater contribution, and the advection of Pacific waters through the Bering Strait. Superimposed on these factors, biological CO_2 uptake in the ice or water and its export to depth, remineralization of organic matter, sea-ice freezing and melt impacts via brine rejection, and freshwater input influence ocean chemistry and acidification, resulting in a mosaic of conditions that vary on seasonal and interannual timescales, as well as regionally.

Most ecological impacts of ocean acidification are inferred from species-specific experiments or modeling studies. Natural phytoplankton assemblages from the Arctic and subarctic show resilience to acidification under a range of light conditions, with no significant change in primary production or community composition (Hoppe et al., 2018b). Given the high extreme seasonality experienced by Arctic phytoplankton, resilience to changing conditions, including acidification, can be an important tool in terms of evolutionary success. Temperature plasticity of key Arctic phytoplankton species (Benner et al., 2019) also points towards the same conclusion.

In situ measurements show low aragonite saturation (linked to ocean acidification) in fjords of Svalbard, largely due to freshwater input, with conditions nearing the threshold for carbonate shell formation in the pteropod *Limacina helicina* (Bednaršek et al., 2014; Fransson et al., 2016). Evidence of widespread shell dissolution for the same species is reported in the coastal Beaufort Sea (Niemi et al., 2021). In the western Arctic Ocean, a northward expansion and deepening of acidifying conditions after the 1990s has been largely associated with increased Pacific water transport (Qi et al., 2017). Conversely, freshwater runoff from rivers and organic matter remineralization are considered key factors for persistent acidification conditions on eastern Siberian shelves (Semiletov et al., 2016). Collectively, these findings highlight different driving factors for acidification conditions regionally, as well as the importance of high climatic and oceanic variability through seasonality and ocean circulation.

6.2.2 Thawing permafrost

6.2.2.1 Permafrost and methane

The Arctic is a source of methane. This relatively short-lived but potent greenhouse gas is produced by methanogenic bacteria in the anoxic part of the soil, below the water table. Above the water table, in the aerobic part of the soil, methane can be consumed by other microorganisms, i.e., methanotrophs. The activity of both methanogens and methanotrophs is temperature sensitive, but their relative importance depends on whether the water table is close to or above the surface (Olefeldt et al., 2013). This is why the primary sources of methane in the Arctic are lakes and wetlands. Lakes and wetlands are estimated to emit 11–41 Tg CH_4/y and 16.5–19 Tg CH_4/y, respectively (McGuire et al., 2012; Saunois et al., 2016; Wik et al., 2016). These broad estimates remain unchanged since the AMAP assessment on methane (AMAP, 2015) and SWIPA 2017 (AMAP, 2017).

Large temporal and spatial uncertainties still exist in these estimates and they embrace many possible new observations of surprising fluxes. The areal extent of wetlands and small lakes and ponds is poorly constrained, which may lead to a double-counting of emissions that inflates budget estimates (Thornton et al., 2016). Atmospheric methane is oxidized in dry upland soils, which may lower estimates when included in models (Oh et al., 2020). Recently, glacial outflow of methane has been identified as a hitherto unknown source of atmospheric methane in the terrestrial domain (Christiansen and Jørgensen, 2018; Lamarche-Gagnon et al., 2019). The winter period is also under-sampled, even though the cold season may account for up to half of the annual emissions (Treat et al., 2018). Short-lived pulses caused by freeze-thaw actions can contribute significantly to cold season emissions, but observations remain sparse (Mastepanov et al., 2013; Pirk et al., 2017; Raz-Yaseef et al., 2017). Improved mapping of Arctic landscapes and year-round monitoring is necessary to better constrain budget estimates. It remains clear, however, that all the above-listed emissions are currently within the uncertainty ranges of the broad estimates of total Arctic emissions from earlier assessment budgets (e.g., AMAP, 2015, 2017).

Several studies indicate significant sources of methane in the Arctic Ocean, with budget estimates as high as 17 Tg CH_4/y (Damm et al., 2010; Shakhova et al., 2010, 2014; Kort et al., 2012). Gas hydrates represent a large potential source of methane from the ocean floor (Kretschmer et al., 2015), and may be vulnerable to climate change. While gas plumes from gas hydrates have been reported to be widespread off the coast of Spitsbergen, the water column is hundreds of meters deep and, since it acts as an efficient filter (Sparrow et al., 2018), these releases of methane do not influence the atmosphere (Myhre et al., 2016). In the shallow waters of the Laptev Sea, it has been shown that methane released upon the degradation of subsea permafrost is quickly oxidized in the overlying sediment, limiting the potential for large increases of methane to reach the water column (Overduin et al., 2015). Model studies also indicate that gas hydrates respond slowly to climate change, since warming at the sea surface (e.g., due to sea-ice decline) takes centuries and up to a millennium to penetrate to depths where gas hydrates are located (Parmentier et al., 2013; Archer, 2015; Kretschmer et al., 2015). Atmospheric measurements conducted near the East Siberian, Laptev and Chukchi seas indicate that previous bottom-up estimates overestimated the importance of the East Siberian Shelf Seas as a present-day methane source by as much as a factor of 4 or 5 (Berchet et al., 2016; Thornton et al., 2016; Tohjima et al., 2021). A recent estimate of methane fluxes in the East Siberian, Laptev and Chukchi seas finds emissions of approximately 3 Tg CH_4/y, and a minor overall contribution from bubbling since it is constrained to very small areas (Thornton et al., 2020). Taken together, these studies indicate that the Arctic Ocean may not be the rapidly changing or large source of methane previously feared as a potentially considerable feedback to the atmosphere (Shakhova et al., 2010, 2014).

6.2.2.2 Permafrost, precipitation and snow cover

The increase in global permafrost temperature follows the Arctic amplification of air temperature increase in the Northern Hemisphere (Biskaborn et al., 2019). In the discontinuous permafrost zone, however, air temperatures have remained statistically unchanged and increased permafrost temperatures are linked to increasing snow thickness (Biskaborn et al., 2019).

Vegetation influences snow depth, through preferential distribution, and leads to complex spatial heterogeneity in permafrost. Talik formation under shrub patches may be one of the key mechanisms creating permafrost discontinuities and could lead to permafrost degradation even in the absence of warming (Jafarov et al., 2018). Modeling experiments indicate that for the same snow cover, a drainage effect can modify ground temperatures to a depth of 1 m by up to 2°C, affecting permafrost stability under the same climate forcing (Martin et al., 2019). Ground temperatures are sensitive to snow-pack properties, however, both observations of snow-pack microstructure, especially in early and mid-winter (Gouttevin et al., 2018), and its representation in models is a topic that requires more attention (Gouttevin et al., 2018; Marchand et al., 2018; Biskaborn et al., 2019).

Precipitation has also been observed to play a role in permafrost instability. Increased thaw slump activity in the Qinghai-Tibet Plateau over the past 10 years is linked, along with anomalously high air temperatures, to abundant precipitation during the thaw season (Luo et al., 2019). Intense precipitation combined with already thawing permafrost is deemed to have played a triggering role in a debris slide in northern Iceland (Sæmundsson et al., 2018) and thermokarst erosion in northeast Greenland (Christensen et al., 2020). The frequency of such events is expected to increase. In some regions, for example in Canada and Alaska, the relative importance of precipitation or anomalous warm summer temperatures is still unclear (Kokelj et al., 2017; Rudy et al., 2017; Fraser et al., 2018; Swanson and Nolan, 2018). However, the combination of abrupt warming, heavy precipitation and snow pack can result in extreme slope failure events over large areas as was seen in Greenland in 2016 (Abermann et al., 2019). The prominent intensification of retrogressive thaw slumps on Banks Island, in the Canadian Beaufort Sea, over the past decade has been attributed to a succession of exceptionally warm summers and probably anomalously heavy rainfall (Rudy et al., 2017). This shows similarities with increasing river-bank erosion and thermokarst erosion development in the Zackenberg Research Station area, northeast Greenland (Christensen et al., 2020). Simulations also indicate, however, that increased local summer precipitation may lead to an increase in soil cooling, i.e., stabilizing permafrost (Guo and Wang, 2017), suggesting that, as for snow cover, the timing and intensity of rainfall occurrence is key to the impact. This issue deserves special attention as precipitation is expected to intensify (Bintanja and Andry, 2017).

6.2.3 Precipitation and snow-cover impacts

Models project an increase in precipitation over the Arctic Ocean and surrounding land masses, and a shift in the respective contributions of snow and rain over the coming decades (see Chapter 3). Changes in precipitation affect ecosystems and biogeochemical climate feedbacks mainly through impacts on radiative transfer, the hydrological cycle and freshwater budget, all of which have important consequences for autotrophic carbon uptake and its export and sequestration.

Concomitant with projections of increasing precipitation for the Arctic, model simulations show that the interannual variability in precipitation will also increase (Bintanja et al., 2020). The anticipated effect of these combined changes is an increase in the frequency of seasons and years with excessive precipitation, with associated impacts on ecosystems (e.g., Assmann et al., 2019).

Snow cover can affect primary production in vascular plants through multiple processes and interactions which also depend on location and climate (López-Blanco et al., 2018, 2020; Xiong et al., 2019). Reduced snow accumulation in winter and earlier snowmelt can advance the onset of the growing season as the ground surface becomes exposed to solar radiation. However, this is not necessarily synonymous with increased productivity, and may lead to accelerated rates of local extinctions (Niittynen et al., 2018), increased frost damage (Liu et al., 2018), reduced moisture due to evapotranspiration and reduced total amount of derived water available. An increase in the duration of the growing season is documented for the Russian subarctic, associated with a decrease in the number of days with freezing temperatures (Zveryaev and Arkhipkin, 2019). In Alaska, a 29-year satellite record (1988–2016) shows a mean regional trend of earlier snow-cover disappearance, despite large regional variations and extreme warm years having anomalously early dates of snow disappearance (Pan et al., 2020). Increased density of *in-situ* observation networks and reduced uncertainties in the satellite- and model-derived geospatial records are needed to better understand regional responses (Pan et al., 2020). Strong regional gradients and significant non-linear relationships were observed between snow distribution, snow-water equivalent, and vegetation greenness and timing in northeastern Greenland (Pedersen et al., 2018). Greater snow depths result in potentially later snow-free conditions and increased water from the melting snow available for the growing season. This has been shown to have varying effects on above- and below-ground biomass, resulting in biomass changes and mitigation of drought stress effects (Liu et al., 2018).

Recent studies show that wet winters can delay the vegetation growing season at high latitudes. This delay has been associated with a decline in growing degree-days based on soil temperatures, suggesting that the effects of heat exposure on vegetation growth is strongly modulated by winter precipitation (Yun et al., 2018). The date of snowmelt in the Arctic is considered of pivotal importance for the phenology (Assmann et al., 2019) as well as the total annual terrestrial ecosystem carbon uptake (e.g., Lund et al., 2012). Complex interactions ensue for the subsequent growing season, and affect key ecosystem processes such as spring phenology through impacted physical parameters such as soil moisture conditions (Jin et al., 2019).

6.2.3.1 Snow on sea ice

The largest trend in precipitation increase in the Arctic over the past four decades is observed over the Arctic Ocean (see Chapter 2). Arguably, the most widely known effect of snow on sea ice on ecosystem processes and atmospheric feedbacks is through radiative balance. Snow cover strongly attenuates light transmission through the snow-ice matrix, reducing the light available for primary producers within and under the sea ice. Snow also reflects a large fraction of the incoming solar radiation back to the atmosphere, the so-called albedo effect, creating a direct feedback to the atmosphere which acts to effectively cool the land or ocean surface. The decreasing albedo effect with the decline in sea ice (see IPCC, 2019), and its positive feedback loop as more solar radiation is absorbed at the ice-free ocean surface, is largely responsible for the accelerated Arctic warming.

Snow on sea ice affects the structure and composition of ice-associated communities and the lifecycle at higher trophic levels, such as ringed seals (*Pusa hispida*) which use snow-covered lairs for reproduction and rearing (see CAFF, 2013). Owing to its strong insulating properties, snow on sea ice also influences the rate of ice growth in the autumn, whereas in spring, snowmelt affects the export of organic material from the sea ice as meltwater percolates through connected brine channels. There is, therefore, an important seasonal component to the effects of snow on sea ice on Arctic marine ecosystem processes, implying that a shift in precipitation in the autumn/winter or in spring will have different, and possibly opposite, impacts on primary producers and food webs. For example, increased snow precipitation in the autumn/winter can reduce the overall ice thickness attained during the ice growth period (autumn to spring) due to reduced ice growth rates (Graham et al., 2019). This can lead to suitable conditions for an earlier onset of the ice algal bloom or for under-ice blooms in the following spring, when solar radiation returns, with ensuing consequences for nutrient dynamics and primary productivity (see Section 6.2.4). The timing of snowmelt also impacts the export of ice algae and sea ice-pelagic-benthic coupling (Lalande et al., 2019). Another effect of a thick snow cover, combined with thinner sea ice, is through flooding and the development of snow-ice formation (Rösel et al., 2018) and associated communities (Fernández-Méndez et al., 2018). These conditions, common in the Antarctic but rarely observed in the Arctic, are likely to become more widespread as the ice thins and precipitation increases (Granskog et al., 2018).

Because the distribution and dynamics of the snow cover is different between the rather uniform first-year ice and the heavily ridged multiyear ice, the influence of snow on ecosystem processes varies between the two ice types. Snow accumulation near ice ridges, a common feature of multiyear ice, offers suitable habitat for seals and other mammals whose life cycle depends on the sea ice. Multi-scale changes in snow distribution on sea ice, which constitute one of the many effects of the replacement of multiyear by first-year ice, are very likely to impact the location and timing of sea-ice and under-ice production (see Section 6.2.4) and possibly ice habitat usage by higher trophic levels.

6.2.3.2 Rain events

Precipitation type can have important impacts on and consequences for the biogeochemical cycling of climatically active gases in marine and terrestrial ecosystems. Excessive rain events may trigger erosional processes in thawing permafrost environments, causing substantial landscape change with associated impacts on greenhouse gas exchanges (Rudy et al., 2017; Christensen et al., 2020; also see Section 6.2.2.2). Of importance, the type of precipitation (rain or snow, freezing rain) needs to be considered in a seasonal context. In the ocean, the impact of rain events on sea ice during the spring productive period can lead to rapid drainage of the brine channels and rapid sinking export to the sea floor of the carbon biomass accumulated in the ice during the ice algal growth period (Fortier et al., 2002; AMAP, 2013). The consequences of rain events for ice algal growth dynamics and export will depend on the timing with respect to the ice algal growth period. A rain event during the initial growth period could compromise the establishment of sea-ice algal communities as cells are flushed from the ice, whereas later in the season the impact will be on export pathways of the biomass accumulated with the sea ice (Michel et al., 2006; AMAP, 2017) and on sea ice-pelagic-benthic coupling, a key process in the structuring of Arctic marine ecosystems (e.g., Grebmeier et al., 2018). The impact of rain *versus* snow precipitation in autumn when the sea-ice cover is forming does not appear to have been studied but would presumably be completely different than during the spring/summer productive period.

6.2.4 Impacts of sea-ice changes

The decline in sea ice affects Arctic marine ecosystems through direct and indirect impacts that can act synergistically or in opposing ways, and have widespread repercussions throughout the food web. Decreases in sea-ice extent and shortening of the ice-covered period expose the Arctic Ocean to larger open water areas and extend the open water period during the spring and autumn seasons. These changes increase light penetration in the water column, favoring phytoplankton growth. Furthermore, the thinning of the ice cover and the shift from multiyear ice to first-year ice impact sea-ice and under-ice productivity and diversity.

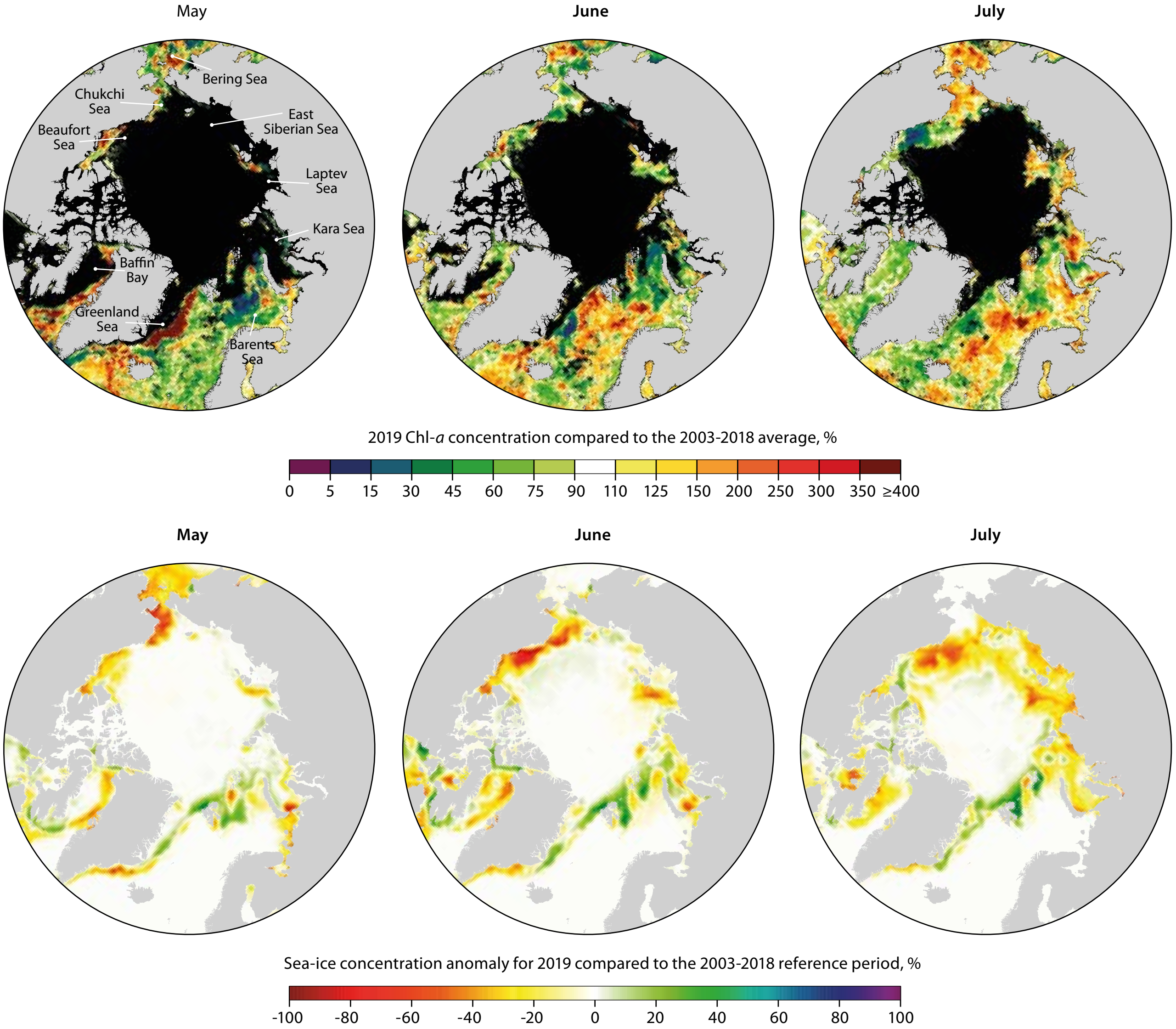

Figure 6.3 Mean monthly chlorophyll-*a* (Chl-*a*) concentrations during 2019, shown as a percentage of the 2003–2018 average for May, June, and July. Sea-ice concentration anomalies in 2019 (compared to a 2003–2018 mean reference period) for May, June, and July. Adapted from Frey et al. (2019).

Satellite ocean color sensors provide synoptic-scale estimates of chlorophyll biomass upon the seasonal degradation of sea-ice cover (Figure 6.3). In turn, satellite-based chlorophyll concentrations can be incorporated into estimates of primary production during open water conditions.

Estimates of annual and summer monthly maximum pan-Arctic net primary production for the period 1998–2015 show an increase of approximately 47% in the spring and summer months, as a result of the increase in surface area of open waters during summer and a longer phytoplankton growth season (Kahru et al., 2016). A recent analysis by Lewis et al. (2020) for the period 1998–2018 showed a 58% increase in primary production. They attributed the increase in production over the past decade to nutrient fluxes rather than an expansion of open water areas, the latter being the key driver for primary production a decade earlier. An increasing trend in primary production over the past two decades, ranging from 2 to 13 g C/m^2/y per decade, has been observed in all Arctic regions, with maximum increases in the Eurasian Arctic and Barents Sea (Figure 6.4).

Earlier breakup of sea ice in spring alters the timing of the phytoplankton spring bloom as well as its magnitude and productivity. Earlier sea-ice melt, close to the summer solstice in the High Arctic, provides favorable light conditions for phytoplankton growth. Satellite-based estimates show a northward expansion and increase in productivity of the spring phytoplankton bloom, which occurs following the ice breakup, in the High Arctic region (>75°N) (Renaut et al., 2018). Due to the combination of low light conditions at high latitude and extensive sea-ice cover, this region was previously considered unsuitable for the development of open water phytoplankton blooms. This change therefore represents a fundamental shift from ice-associated to open water production.

Changes in the phenology and spatial distribution of primary producers (phytoplankton and ice algae) profoundly impact energy transfers to higher trophic levels in the marine Arctic. In the past, the timing of the spring phytoplankton bloom was tightly linked to the timing of sea-ice melt and the release of light limitation associated with the presence of the sea-ice cover (see Kovacs and Michel, 2011; AMAP, 2017). In the Arctic,

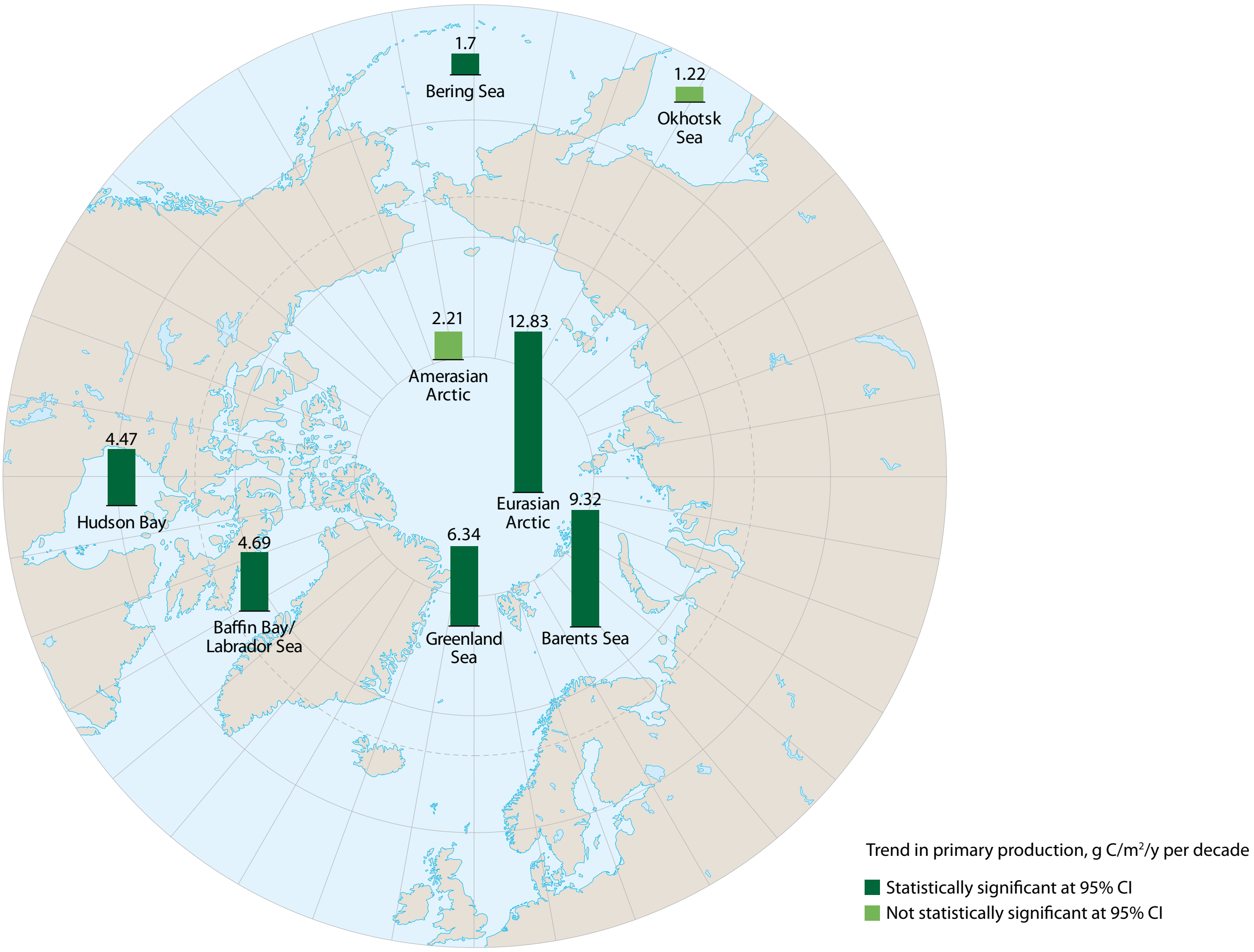

Figure 6.4 Linear trends in summer (March–September) primary production estimated from satellite ocean color in eight Arctic regions over an 18-year time series from 2003 to 2020 (Mann-Kendall test for trends). Adapted from Frey et al. (2020).

where primary production occurs over a short sunlit period, the synchronization between herbivorous zooplankton and primary producers is essential to their reproductive success. In various Arctic regions, large variations in the abundance of key zooplankton species such as *Calanus glacialis* have been ascribed to match/mismatch impacts associated with earlier sea-ice melt and increased variability in the timing of sea-ice melt or retreat, with evidence of cascading impacts on carnivorous zooplankton, fish species, birds and benthos (Dezutter et al., 2019).

The first SWIPA assessment predicted an increase in the frequency and prevalence of autumn phytoplankton blooms as a result of longer open water periods associated with the decline in sea ice (AMAP, 2011). This prediction was later corroborated (Ardyna et al., 2014), as documented in the subsequent SWIPA assessment (AMAP, 2017), and there is now accumulating evidence that longer open water periods, together with increased wind mixing in ice-free waters, trigger frequent phytoplankton autumn bloom occurrence (Nishino et al., 2015; Waga et al., 2019). Ecosystem responses are also being documented. In the Chukchi Sea, the pivotal Arctic zooplankton species *C. glacialis* can respond rapidly to the wind-induced autumn bloom, indicating that episodic increases in primary production and changes in the timing of phytoplankton blooms are effectively cascading through the ecosystem and affect the seasonality of pelagic species (Fujiwara et al., 2018). Fundamental changes in ecosystem structure and a shift from benthic- to pelagic-dominated systems are associated with the rapid sea-ice decline in the Pacific Arctic (Grebmeier et al., 2018).

Another important change in phytoplankton phenology in the Arctic concerns the occurrence of under-ice blooms (see AMAP, 2017). Thinning of the ice cover, increasing melt-pond area as multiyear ice is replaced by first-year ice, and leads which act as windows into the ocean in a more dynamic ice pack, contribute to the development of under-ice blooms (Assmy et al., 2017; Horvat et al., 2017). Under-ice blooms shift the timing of water column production to earlier in the season, depleting surface waters of the nutrients that fuel the subsequent typical spring/summer diatom bloom, unless nutrients are replenished through mixing. The dynamics of under-ice blooms are still poorly understood, with accumulating evidence of *in situ* growth at low light intensities or under a dynamic sea-ice cover (Assmy et al., 2017; Boles et al., 2020), and advection from neighboring open water areas (Johnsen et al., 2018). Since under-ice blooms are not captured by satellite imagery, satellite-derived estimates of primary production in open waters may significantly underestimate total primary production in the Arctic Ocean (Arrigo et al., 2014; Hill et al., 2018a). Production within the ice or associated with deep chlorophyll-*a* maxima is also missing from satellite-derived primary production estimates.

The cycling of carbon and other key elements in the ocean also depends on 'who is there', i.e., functional phytoplankton groups that have distinct biogeochemical roles. For example, diatoms play a key role in carbon export to depth in contrast to the prymnesiophyte *Phaeocystis pouchetii* (Reigstad and Wassmann, 2007; Lalande et al., 2019), although mineral ballasting has recently been proposed as a mechanism enhancing under-ice export for the latter (Wollenburg et al., 2018). Both groups are responsible for productive blooms in the Arctic and their respective occurrence will influence the biogeochemical cycling of carbon and other elements (e.g., Assmy et al., 2017).

The sea-ice declines and transition from a perennial multiyear-ice cover to a seasonal first-year ice cover directly impact ice algal production, ice-associated communities and the cycling of ice-produced organic carbon (e.g., Fernández-Méndez et al., 2018; Underwood et al., 2019). Ice algae play a key role in Arctic marine food webs, for example, by providing essential fatty acids that are not synthesized by zooplankton (e.g., Kohlbach et al., 2016, 2019). The overall response of ice algal communities to changes in sea ice remains elusive, largely due to the cumulative influences and complexity of several factors including the seasonality of ice formation and melt, sea-ice biogeochemistry, and key processes taking place at the atmosphere-ice-ocean interface, such as nutrient fluxes, snow dynamics and melt pond distribution (e.g., Sørensen et al., 2017; Hancke et al., 2018; Lannuzel et al., 2020).

The shift from multiyear ice to first-year ice has wide-ranging consequences for ecosystem-climate processes and feedbacks, most of which are poorly quantified. The biogeochemistry of the two ice types is very different. Multiyear ice is thicker, contains much less brine (fresher), and is much less porous than first-year ice (see Petrich and Eicken, 2009). All of these factors and the perennial nature of multiyear ice contribute to its fundamental role in atmosphere-ocean exchanges (Islam et al., 2017). Recent characterization of sea-ice communities in a variety of habitats including hummocks (Lange et al., 2017), ice ridges and the snow-ice interface (Fernández-Méndez et al., 2018) show that these can be ecological hot spots. With a more dynamic ice pack and increasing snow cover, it has been hypothesized that the snow-ice interface habitat may become more prevalent in the future (Fernández-Méndez et al., 2018). A recent study across the Arctic Ocean also shows that the diversity of sea-ice communities is higher in multiyear ice compared to first-year ice, pointing to a loss of biodiversity as seasonal (first-year) sea ice replaces the perennial (multiyear) Arctic sea-ice cover (Hop et al., 2020). Because different species act differently in the cycling of key elements, it is reasonable to anticipate changes in ice-associated biological-climate feedbacks. The shift from multiyear ice to first-year ice is also expected to impact the cycling of carbon and other elements in the ocean surface layer. Based on recent experimental evidence using natural communities, Underwood et al. (2019) showed that the carbon-rich bottom-ice biological layer in first-year ice fuels surface-water microbial communities, resulting in increases in bacterial respiration. Results also show that a spectrum of substrates provided by seasonal sea-ice melt is selectively utilized by different bacterioplankton taxa, leading to changes in microbial community composition. In the context of the shifting ice cover from multiyear ice to first-year ice, this new evidence points to increases in the remineralization of organic material at ice-water interfaces, impacting the cycling of carbon and key elements in the first-year ice-dominated future Arctic Ocean.

Early spring oceanographic observations of the ice-covered Arctic Ocean are notoriously difficult to obtain from ships or manned ice-camp platforms, and autonomous measurements can help fill this gap (e.g., Hill et al., 2018b; Boles et al., 2020). These studies provide solid evidence that light availability is sufficient to support high phytoplankton growth rates underneath the seasonal sea-ice cover (Hill et al., 2018b) and that multiple under-ice blooms can occur (Boles et al., 2020). Autonomous observatories capable of providing measurements in ice-covered conditions over a complete annual cycle are essential in order to fill the existing gap between ship, ice-camp, and satellite-based observations. The high seasonal, annual and interannual variability of biogeochemical and ecological processes in the Arctic Ocean, and its amplification, together with high spatial heterogeneity, attest to the need for continuous measurements (Boles et al., 2020).

Given the paucity of sea-ice and under-ice data to inform bloom dynamics in the context of ongoing sea-ice changes, numerical modeling can offer additional insights. A recent model intercomparison of ice-algal production in four Arctic regions for the period 1980–2009 (Watanabe et al., 2019) shows a wide range of annual production estimates among models and a lack of inter-model agreement with respect to the magnitude and direction of trends across regions. The high interannual variability in ice-associated production is proposed as an explanatory factor for the divergence in trend estimates, highlighting the need for multi-annual time series of *in situ* measurements of ice-algal production throughout the productive season.

Finally, changes in Arctic sea-ice export can influence phytoplankton phenology in downstream ecosystems through their effect on water column stratification. In the Greenland Sea, a time-series analysis for the period 2002–2018 shows that earlier (later) phytoplankton blooms coincide with reduced (increased) sea-ice export (Mayot et al., 2020). These results highlight the importance of the connectivity between the Arctic Ocean and receiving ecosystems in Baffin Bay and the subarctic North Atlantic. Despite the high interannual and decadal variability in sea-ice export in Fram Strait (e.g., Smedsrud et al., 2017), a recent study shows a significant decrease in sea-ice volume export over the past two decades (Spreen et al., 2020). Such a trend can have important implications for phytoplankton bloom dynamics in outflow regions.

6.2.5 Impacts of land-ice mass declines and riverine input

The Arctic Ocean holds about 1% of the world's seawater but receives 11% of the global freshwater runoff (McClelland et al., 2012). The seasonal input of freshwater from ice melt and rivers is a characteristic feature of the Arctic, leading to salinity stratification and estuarine-type circulation in the ocean. As land ice melts, permafrost thaws and precipitation and runoff patterns change, the extensive Arctic coasts are receiving more freshwater and its associated dissolved and particulate inorganic and organic matter. This intensifies the freshwater cycle of the

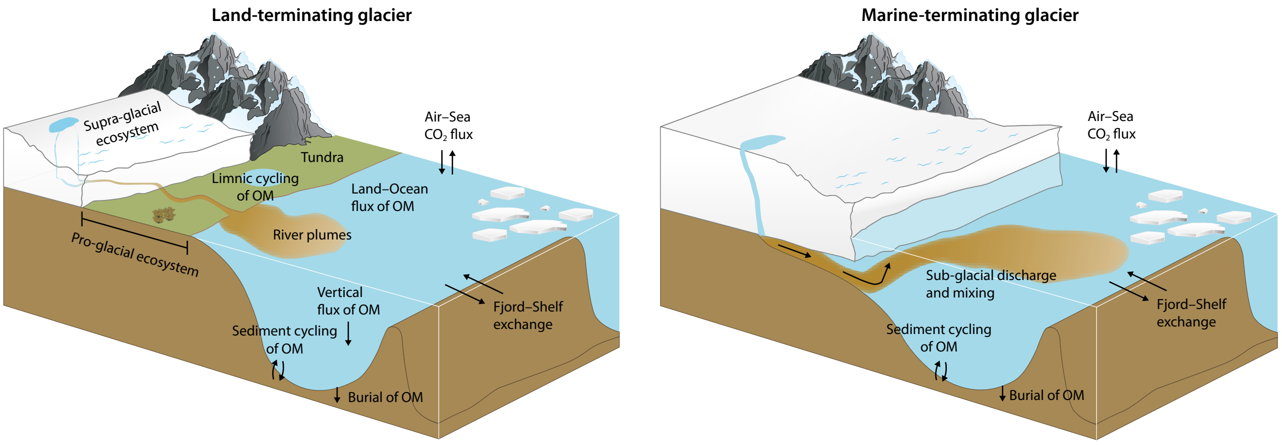

Figure 6.5 Comparison of coastal ecosystem impact and organic matter (OM) processes from land-terminating and marine-terminating glaciers.

Arctic Ocean and results in a closer coupling between land and sea in the coastal zone with likely consequences for element cycling and ecosystems. Thus, the impact of climate change in the coastal ocean is different from that in the open ocean.

The volume of land ice continues to decrease across the Arctic (Moon et al., 2018). The Greenland Ice Sheet is a key component of the Northern Hemisphere land ice and contributes 37% (or 247 Gt/y) of the annual global loss of land ice, followed by Antarctica (29%) and the other glaciers and ice caps that account for the rest (Bamber et al., 2018). Glacial meltwater is often characterized by a high sediment load made up of silt-sized particles generated from glacial erosion of the bedrock. Particles limit light penetration in coastal water and thus influence the distribution of primary producers (Murray et al., 2015). The distribution of meltwater and the associated particles result in distinct local gradients in pelagic and benthic species composition (Wlodarska-Kowalczuk and Pearson, 2004; Arimitsu et al., 2016; Balmonte et al., 2020). Overall, glacier meltwater is not considered to be nutrient-rich, however, it does contain dissolved silicate and iron at concentrations above the marine background (Hopwood et al., 2020), which could stimulate primary production under limiting conditions for these elements. In fjords where meltwater input is through glacial rivers (Figure 6.5 left), a distinct nutrient-poor surface layer is formed, where mixing and nutrient replenishment is limited (Holding et al., 2019; Randelhoff et al., 2020). In contrast, sub-glacial discharge from marine-terminating glaciers (Figure 6.5 right) can increase vertical mixing and replenish nutrients such as nitrate, thereby stimulating primary production (Meire et al., 2017; Cape et al., 2018), and provide foraging ‘hot spots’ for seabirds (Urbanski et al., 2017) and seals (Hamilton et al., 2016). Glacial meltwater thus impacts the seasonal and spatial distribution of light and nutrients essential for marine primary production in complex ways and the specific outcome is modified by numerous local factors such as glacial morphology, shelf-water mass properties and exchange, sill depth, tide, wind regimes and sea-ice cover (Hopwood et al., 2020). In addition to the effect on light and nutrient availability, glacial meltwater also transports organic matter to the coastal ocean. At a global scale, land ice holds a substantial amount of organic carbon. Although part of the exported carbon can be of ancient origin (Hood et al., 2015), the surface of glaciers, ice caps and the ice sheet hosts a dynamic and reactive organic carbon system (Wadham et al., 2019). As a result, concentrations of dissolved organic carbon in glacial meltwater may be low but the bioavailability can be high (Wadham et al., 2019). The fate and bioavailability of the particulate fraction, which is estimated to be the dominant fraction in meltwater from the Greenland Ice Sheet (Lawson et al., 2014), is far less known.

Whereas glaciers and ice sheets can dominate catchments in Greenland, Canada, Alaska and archipelagoes such as Svalbard and Franz Joseph Land, tundra dominates on the Eurasian and American continents, with catchments extending far beyond the Arctic region. Discharge from the largest Arctic rivers is increasing and peaks earlier in summer (Holmes et al., 2018). The carbon content in the large Eurasian rivers can be ten-fold higher than in glacial meltwater and the particulate fraction, which only constitutes about 10% of the total carbon load, can reflect the mobilization of carbon from thawing permafrost (Wild et al., 2019). In regions such as the East Siberian Shelf, where the terrestrial carbon load is high, the coastal waters become over-saturated with CO_2 (Anderson et al., 2009), indicating an important feedback mechanism where part of the carbon mobilized from thawing permafrost soils or eroding coastlines can be released to the atmosphere as CO_2. As a consequence of the high CO_2 levels, the East Siberian Shelf can also be a ‘hot spot’ for ocean acidification (Semiletov et al., 2016; also see Section 6.2.1.3), with potential consequences for carbonate shell-forming organisms.

In conclusion, it is well established that freshwater from rivers or glaciers is a key driver of seasonal and spatial variation in biogeochemical cycling and ecosystem structure and function in the coastal ocean. Although the mechanistic understanding of the importance of freshwater for the Arctic Ocean has increased tremendously in the past decade, important challenges remain. One challenge concerns spatial variation in the fate of allochthonous carbon in the coastal ocean: what fraction is incorporated into the marine food web (Bell et al., 2016; McGovern et al., 2020), buried in sediments or remineralized and released as CO_2 (Schuur et al., 2015) across the very different shelf systems in the Arctic. Another challenge is the limited knowledge about the combined effect of different drivers, such as runoff and changing sea-ice cover, on coastal ecosystems and their diversity.

Box 6.2 Extreme weather affects tundra carbon exchange in northeastern Greenland

Two independent examples from northeastern Greenland demonstrate how extreme precipitation patterns can have severe implications for High Arctic ecosystems (Figure 6.6). The events stand out in a 23-year record of continued observations of a wide range of ecosystem parameters and provide an early warning of conditions projected to increase. In 2015, a quarter of the average annual precipitation fell during a nine-day intensive rain event during August. This ranked as the highest daily precipitation during the 1996–2018 period and caused a strong reduction in solar radiation, decreasing CO_2 uptake by 18–23 g C/m^2 over the course of the event. This reduction in CO_2 uptake is comparable to typical annual carbon budgets in Arctic tundra (Christensen et al., 2020), almost shifting the ecosystem from a sink to a source of CO_2 in the middle of the growing season. In a different type of event, but also occurring due to changing weather patterns, an extreme snowmelt season in 2018 triggered a dramatic gully thermokarst causing rapid transformation in ecosystem functioning, from consistent annual ecosystem CO_2 uptake and low methane exchange to highly elevated methane release, a net outflux of CO_2, and substantial export of organic carbon downstream as riverine and coastal input (Christensen et al., 2020). In addition to climate warming alone, a more frequent occurrence of extreme weather patterns is expected to have large implications for otherwise undisturbed tundra ecosystems, including their elemental transport and carbon interactions with the atmosphere and ocean.

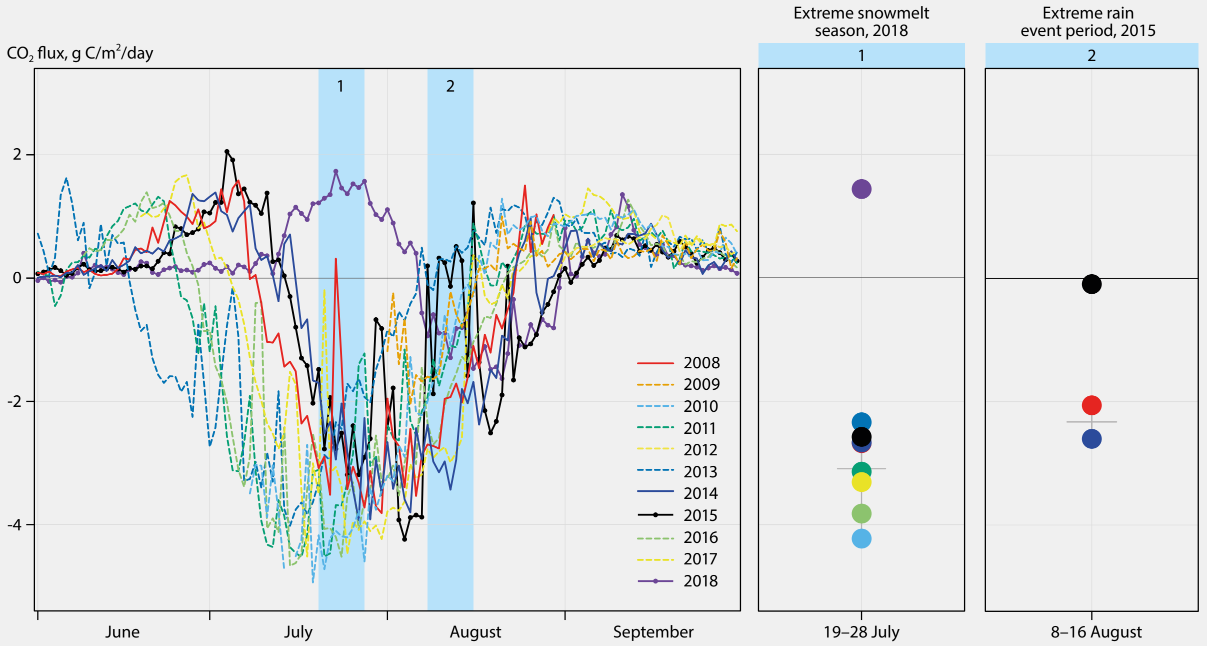

Figure 6.6 Daily land-atmosphere exchange of CO_2 fluxes 2008–2018 from the eddy covariance site located at the fen ecosystem in Zackenberg, Greenland. The 2015 and 2018 time series are highlighted with solid lines and symbol markers, along with other years with similar seasonality (2008 and 2014, solid lines only). Other years are shown with dashed lines. Blue areas highlight the extreme snowmelt season in 2018 and the rain event period in 2015. The two panels compare the 9-day average CO_2 exchange in 2015 and 2018 with other years during the extreme snowmelt event and extreme rain event. During this time series, interannual variability is clearly superseded by the extreme events in 2015 and 2018. From Christensen et al. (2020).

6.2.6 Extreme events

Extreme events such as storms are becoming more frequent in the Arctic, and are expected to continue to increase in frequency and intensity (see Chapter 4). Because extreme events superimpose on existing trends, current knowledge of their impacts on ecosystems is largely based on case studies. Case studies of extreme events in a terrestrial ecosystem (northeastern Greenland, Box 6.2) and a marine ecosystem (Bering Sea, Box 6.3) are presented here. Extreme events taking place outside the Arctic, such as extratropical cyclones, can also affect seasonal resident species in the Arctic, for example, migratory seabirds. An analysis by Guéry et al. (2019) of decadal time series of breeding populations of common eider (*Somateria mollissima*) in northern Canada (16-year time series) and Svalbard (19-year time series) found a negative correlation between winter extratropical cyclone activity and female eider survival. They also pointed to different regional mechanisms linking extratropical storms and female eider survival, and suggested that these events offer an explanation for the relationship between the North Atlantic Oscillation and seabird survival in the North Atlantic (Guéry et al., 2019).

6.3 Future projections and feedbacks to climate

The future direction of biogeochemical climate feedbacks in Arctic ecosystems depends on the balance of key processes regulating heat transfer and storage (including evapotranspiration), and climatically-active gas exchanges within the atmosphere-ocean-land system. The direction of the Arctic carbon sink depends on

Box 6.3 The extreme low ice year of 2017–2018 in the Bering Sea

The extreme high temperatures and record low ice cover in the Bering Sea during winter 2017–2018 resulted in widespread ecosystem changes brought about by multiple physical drivers and feedbacks, and affecting all trophic levels (Duffy-Anderson et al., 2019; Stabeno et al., 2019; Huntington et al., 2020). Impacts of low sea-ice cover had been documented for the southern part of the Bering Sea but did not previously extend to the northern region. In 2017–2018, the near absence of the winter sea-ice cover (two days at sea-ice areal concentrations of >10%) weakened surface-water stratification, delaying the spring phytoplankton bloom. Cascading up the food web, the zooplankton was dominated by small zooplankton species rather than the lipid-rich large zooplankton species that provide an important food source for fish and seabirds. Ripple effects on seabirds included low seabird abundances at sea, low reproductive success, and summer die-offs. Initial analysis pointed to starvation as the cause of seabird die-offs in the Bering and Chukchi Seas (USFWS, 2019). Impacts differed between species, possibly linked to life history and diet; for example, thick-billed murre (*Uria lomvia*), a species whose diet normally includes substantial lipid-rich zooplankton, was strongly affected by the ecosystem-wide changes. The abundance and distribution of fish species also showed marked changes, associated with the near absence of the thermal barrier between the southern and northern regions, i.e., the 'cold pool', a shelf region where summer bottom temperatures are <2°C (Stabeno and Bell, 2019). These conditions favored a northward expansion in the distribution of walleye pollock (*Gadus chalcogrammus*) and Pacific cod (*G. macrocephalus*).

It was hypothesized that the extreme warm and low ice year of 2018, combined with changes in benthic communities, will result or may have already resulted in a fundamental change from a benthic-dominated to a pelagic-dominated ecosystem in the northern Bering Sea (Grebmeier et al., 2018). Many of the ecological impacts associated with the extreme events of 2017–2018 have subsequently been observed during the low ice year of 2019 (Stabeno et al., 2019). Thus, it is likely that extreme events act to accelerate the transition already set in motion by climate warming and sea-ice changes across Arctic marine ecosystems.

the balance between greenhouse gas uptake and sequestration, and release into the atmosphere. The former depends on photosynthetic uptake of carbon and its export to depth or accumulation in soils in the marine and terrestrial biomes. The latter depends primarily on permafrost carbon loss and microbial remineralization of organic material.

Future projections for Arctic warming indicate that the central Arctic Ocean will experience the strongest warming. Temperature increases up to 11°C in winter, by mid-century, are projected by the CMIP6 models under scenario SSP5-8.5 (see Chapter 3).

Projections of winter CO_2 fluxes estimated for the permafrost region under model scenarios RCP4.5 and RCP8.5 against the 2003–2017 baseline years are presented in Figure 6.7. A synthesis of regional and global-scale biogeochemical models suggests that under RCP4.5, a moderate warming scenario, increased litter input into the soil from vegetation growth may offset permafrost carbon loss, whereas the latter dominates under the high warming scenario of RCP8.5 (McGuire et al., 2018). However, in both scenarios the model uncertainty remains large and processes such as vegetation damage from

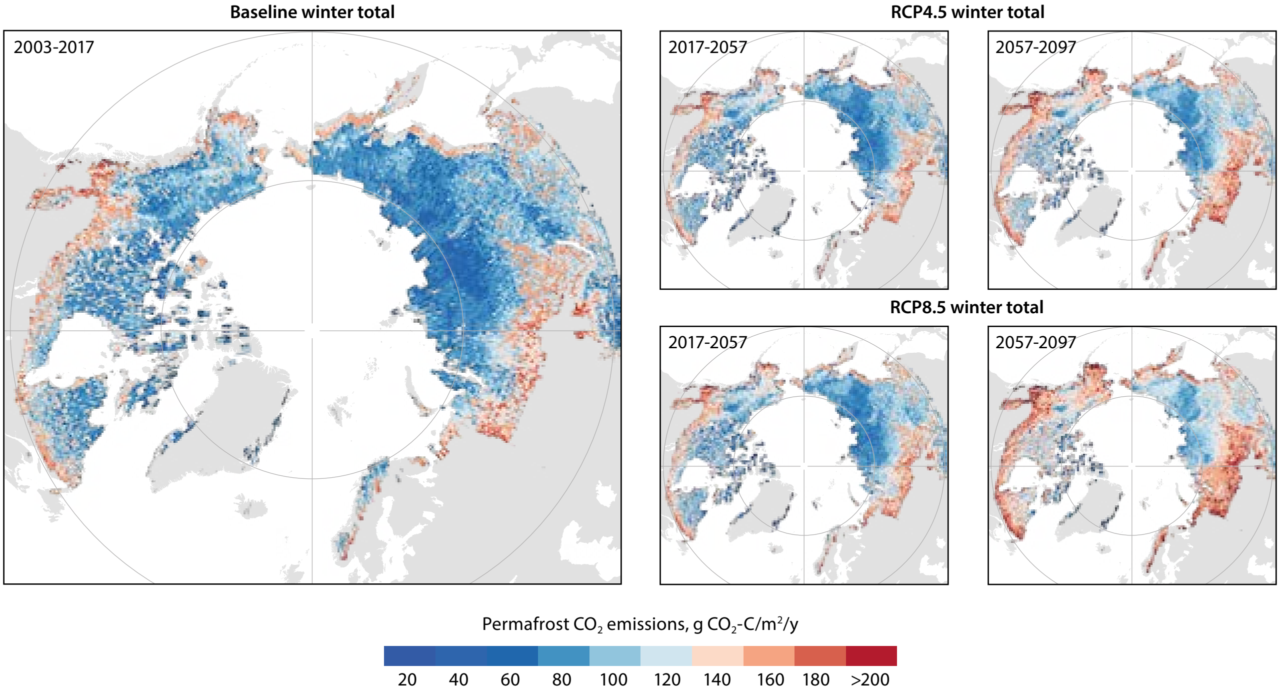

Figure 6.7 Pan-Arctic winter CO_2 emissions under current and future climate scenarios. Average annual winter (October–April) CO_2 emissions estimated for the permafrost region for the baseline years 2003–2017, and cumulative winter CO_2 fluxes under RCP4.5 and RCP8.5 scenarios over an 80-year period (2017–2057 and 2057–2097). Fluxes are reported on an annual basis. From Natali et al. (2019).

extreme winter events and abrupt permafrost thaw are not included (Parmentier et al., 2018; Turetsky et al., 2020).

The future greenhouse gas balance associated with Arctic land masses depends largely on surface wetness. If the Arctic is warming and getting wetter, an increase in methane emissions can be expected. If the Arctic is warming and drying, methane oxidation and aerobic respiration of carbon will dominate, and thawed carbon will primarily be released to the atmosphere as CO_2. At present, it remains highly uncertain which one of the two scenarios is most likely. To reduce the uncertainty, it is necessary to improve the monitoring and simulation of surface hydrology, the ecology of winter processes, extreme events, nutrient interactions, greening and browning, and permafrost thaw dynamics.

Recent modeling, based on RCP8.5, of the magnitude and phenology of sea-ice associated primary production along a latitudinal gradient from 59° to 83°N shows a non-linear response of sea-ice associated biological communities to warming (Tedesco et al., 2019). Shifts in phenology are shown at all latitudes and are strongest at latitudes south of 70°N, whereas the largest increases in ice-associated production are realized at latitudes north of 75°N. The modelled results reflect the overall complexity of the response of the sea-ice biological ecosystem to warming and sea-ice changes. Sea-ice associated primary production is largely dependent on trade-offs between shortening of the ice-covered season and ice extent at lower latitudes and a short growing season at higher latitudes, the important role of nutrient supply, also highlighted in earlier models (Popova et al., 2012; Vancoppenolle et al., 2013), and adaptive strategies within sea-ice communities.

Current model intercomparisons (Watanabe et al., 2019) point to significant challenges in achieving confident validation of annual sea-ice production estimates, largely due to limited observational data and multi-annual to decadal time series. The widespread changes in the phenology, magnitude, and type of primary production taking place in the Arctic are expected to continue, and probably accelerate in the future, given current model projections. Yet, many of the components contributing to the total primary production of the Arctic Ocean are very poorly constrained, including subsurface chlorophyll maxima, under-ice blooms, and sea-ice production. In addition, little is known about remineralization and export processes, which are key players in climate feedbacks. These limitations are exacerbated by (i) the rapidity and magnitude of ecosystem changes; (ii) the regionality of ecosystem responses; (iii) the complexity and changing connectivity with coastal ecosystems and neighboring oceans; and (iv) the evolving character of the terrestrial-ocean-atmosphere connections.

Taken together, the potential Arctic ecosystem feedbacks in a climate context should be seen in comparison to all forcing factors, including anthropogenic emissions. Here it is clear, especially in the case of methane emissions, that anthropogenic forcing still far outweighs even the most dramatic scenarios for changing natural emissions. In other words, emissions cuts worldwide will continue to have a much stronger influence on climate development than natural feedbacks (AMAP, 2015; Christensen et al., 2019).

6.4 Summary and recommendations

Since the SWIPA 2017 assessment (AMAP, 2017), widespread ecosystem impacts of climate change have continued to alter the nature of the Arctic. In both the marine and terrestrial domains, fundamental changes in ecosystem structure and functioning have already taken place and are continuing at a rapid pace. These ecosystem changes, in turn, induce feedbacks to the climate system, many of which are yet poorly quantified. Although people living in the Arctic are at the forefront of the changes observed, the impacts reach far beyond the Arctic, owing to the connectivity of the region within the Earth's atmosphere-ocean system and the exchanges of energy and greenhouse gases between land, ocean and the atmosphere. A major challenge emerging from this review and facing the scientific community, as well as Arctic communities and policymakers, is the rapidity of Arctic ecosystem changes and the increase in frequency and magnitude of extreme events. Despite more scientific efforts over the past decade, there is still insufficient consistency and spatio-temporal coverage in the observational database to adequately quantify ecosystem processes and their changes. Maintaining long time series of observational data on key ecosystem variables, accompanied by process studies, is pivotal for informing and validating predictive modeling efforts and to reduce model uncertainties. Such predictions are, in turn, necessary for readiness and adaptation to future conditions.

To conclude:

- Ecosystem feedbacks to the climate system are poorly constrained, requiring a better understanding of the direction and magnitude of key ecosystem-climate feedback processes of carbon uptake, export, storage, and remineralization, all of which are influenced by climate change.
- The intensification of the exchanges of heat and freshwater both over land and in the ocean causes changes in key forcings such as air and sea temperatures, stratification and mixing, the type of precipitation, and the frequency of extreme events, impacting all ecosystem components.
- The transition towards more extreme precipitation events and weather patterns acts on top of warming, prompting further ecosystem changes in both marine and terrestrial environments. The resulting impacts are expected to, or may already, exceed ecological thresholds.
- The wide-ranging impacts of the rapidly changing cryosphere on ecosystems and climate require immediate attention. Research on key drivers, responses and vulnerabilities using a combination of approaches ranging from small-scale experiments to autonomous observations and Earth observation systems, fully integrated with process-based modeling, is essential.
- The continued consistency and maintenance of long time series through monitoring is pivotal to document the changing behavior of key drivers for ecosystem functioning. A coordinated monitoring network of synergistic ecosystem-climate observatories at key locations is essential to inform ongoing changes, model projections and adaptation to climate change.

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References

Abbatt, J.P.D., W.R. Leaitch, A.A. Aliabadi, A.K. Bertram, J.-P. Blanchet and 65 others, 2019. Overview paper: New insights into aerosol and climate in the Arctic. Atmospheric Chemistry and Physics, 19:2527-2560.

Abermann, J., M. Eckerstorfer, E. Malnes and B.U. Hansen, 2019. A large wet snow avalanche cycle in West Greenland quantified using remote sensing and in situ observations. Natural Hazards, 97:517-534.

Abram, N., J.-P. Gattuso, A. Prakash, L. Cheng, M.P. Chidichimo, S. Crate, H. Enomoto, M. Garschagen, N. Gruber, S. Harper, E. Holland, R.M. Kudela, J. Rice, K. Steffen and K. von Schuckmann, 2019. Framing and context of the report. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate.

AMAP, 2011. Snow, Water, Ice and Permafrost in the Arctic (SWIPA): Climate Change and the Cryosphere. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway.

AMAP, 2013. AMAP Assessment 2013: Arctic Ocean Acidification. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway.

AMAP, 2015. AMAP Assessment 2015: Methane as an Arctic climate forcer. Arctic Monitoring and Assessment Programme (AMAP). Oslo, Norway.

AMAP, 2017. Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2017. Arctic Monitoring and Assessment Programme (AMAP). Oslo, Norway.

AMAP, 2018. AMAP Assessment 2018: Arctic Ocean Acidification. Arctic Monitoring and Assessment Programme (AMAP). Tromsø, Norway.

AMAP, in press. AMAP Assessment 2021: Impacts of Short-lived Climate Forcers on Arctic Climate, Air Quality, and Human Health. Arctic Monitoring and Assessment Programme (AMAP). Tromsø, Norway.

Anderson, L.G., S. Jutterstrom, S. Hjalmarsson, I. Wahlstrom and I.P. Semiletov, 2009. Out-gassing of CO_2 from Siberian Shelf seas by terrestrial organic matter decomposition. Geophysical Research Letters, 36:L20601.

Anderson, D.M., M.L. Richlen and K.A. Lefebvre, 2018. Harmful algal blooms in the Arctic. In: Arctic Report Card 2018, www.arctic.noaa.gov/Report-Card

Archer, D., 2015. A model of the methane cycle, permafrost, and hydrology of the Siberian continental margin. Biogeosciences, 12:2953-2974.

Ardyna, M., M. Babin, M. Gosselin, E. Devred, L. Rainville and J.-É. Tremblay, 2014. Recent Arctic Ocean sea ice loss triggers novel fall phytoplankton blooms. Geophysical Research Letters, 41:6207-6212.

Arimitsu, M., J. Piatt and F. Mueter, 2016. Influence of glacier runoff on ecosystem structure in Gulf of Alaska fjords. Marine Ecology Progress Series, 560:19-40.

Arrigo, K.R., D.K Perovich, R.S. Pickart, Z.W. Brown, G.L. Van Dijken, K.E. Lowry, M.M. Mills, M.A. Palmer, W.M. Balch, N.R. Bates, C.R. Benitez-Nelson, E. Brownlee, K.E. Frey, S.R. Laney, J. Mathis, A. Matsuoka, B.G. Mitchell, G.W.K. Moore, R.A. Reynolds, H.M. Sosik and J.H. Swift, 2014. Phytoplankton blooms beneath the sea ice in the Chukchi sea. Deep Sea Research II, 105:1-16.

Årthun, M.A., T. Eldevik, L.H. Smedsrud, Ø. Skagseth and R.B. Ingvaldsen, 2012. Quantifying the influence of Atlantic heat on Barents sea ice variability and retreat. Journal of Climate, 25:4736-4743.

Asbjørnsen, H., M. Årthun, Ø. Skagseth and T. Eldevik, 2020. Mechanisms underlying recent Arctic Atlantification. Geophysical Research Letters, 47:e2020GL088036.

Assmann, J.J., I.H. Myers-Smith, A.B. Phillimore, A.D. Bjorkman, R.E. Ennos, J.S. Prevey, G.H.R. Henry, N.M. Schmidt and R.D. Hollister, 2019. Local snow melt and temperature – but not regional sea ice – explain variation in spring phenology in coastal Arctic tundra. Global Change Biology, 25:2258- 2274.

Assmy, P., M. Fernández-Méndez, P. Duarte, A. Meyer, A. Randelhoff and 36 others, 2017. Leads in Arctic pack ice enable early phytoplankton blooms below snow-covered sea ice. Scientific Reports, 7:40850.

Balmonte, J.P., H. Hasler-Sheetal, R.N. Glud, T.J. Andersen, M.K. Sejr, M. Middelboe, A. Teske and C. Arnosti, 2020. Sharp contrasts between freshwater and marine microbial enzymatic capabilities, community composition, and DOM pools in a NE Greenland fjord. Limnology and Oceanography, 65:77-95.

Bamber, J.L., R.M. Westaway, B. Marzeion and B. Wouters, 2018. The land ice contribution to sea level during the satellite era. Environmental Research Letters, 13:063008.

Beaugrand, G., 2015. Theoretical basis for predicting climate-induced abrupt shifts in the oceans. Philosophical Transactions of the Royal Society B, 370:20130264.

Beaugrand, G., A. Conversi, A. Atkinson, J. Cloern, S. Chiba, S. Fonda-Umani, R. R. Kirby, C. H. Greene, E. Goberville, S.A. Otto, P.C. Reid, L. Stemmann and M. Edwards, 2019. Prediction of unprecedented biological shifts in the global ocean. Nature Climate Change, 9:237-243.

Bednaršek, N., G.A. Tarling, D.C.E. Bakker, S. Fielding and R.A. Feely, 2014. Dissolution dominating calcification process in polar pteropods close to the point of aragonite undersaturation. PLoS ONE, 9: e109183.

Bell, L.E., B.A. Bluhm and K. Iken, 2016. Influence of terrestrial organic matter in marine food webs of the Beaufort Sea shelf and slope. Marine Ecology Progress Series, 550:1-24.

Benner, I., A.J. Irwin and Z.V. Finkel, 2019. Capacity of the common Arctic picoeukaryote *Micromonas* to adapt to a warming ocean. Limnology and Oceanography Letters, 5:221-227.

Berchet, A., P. Bousquet, I. Pison, R. Locatelli, F. Chevallier, J.-D. Paris, E.J. Dlugokencky, T. Laurila, J. Hatakka, Y. Viisanen, D.E.J. Doug, E. Nisbet, R. Fisher, J. France, D. Lowry, V. Ivakhov and O. Hermansen, 2016. Atmospheric constraints on the methane emissions from the East Siberian Shelf. Atmospheric Chemistry and Physics, 16:4147-4157.

Berner, L.T., R. Massey, P. Jantz, B.C. Forbes, M. Macias-Fauria, I. Myers-Smith, T. Kumpula, G. Gauthier, L. Andreu-Hayles, B.V. Gaglioti, P. Burns, P. Zetterberg, R. D'Arrigo and S.J. Goetz, 2020. Summer warming explains widespread but not uniform greening in the Arctic tundra biome. Nature Communications, 11:4621.

Bhatt, U.S., D.A. Walker, M.K. Raynolds, P.A. Bieniek, H.E. Epstein, J.C. Comiso, J.E. Pinzon, C.J. Tucker, M. Steele, W. Ermold and J. Zhang, 2017. Changing seasonality of panarctic tundra vegetation in relationship to climatic variables. Environmental Research Letters, 12:055003.

Bintanja, R. and O. Andry, 2017. Towards a rain-dominated Arctic. Nature Climate Change, 7:263-267.

Bintanja, R., K. van der Wiel, E.C. van der Linden, J. Reusen, L. Bogerd, F. Krikken and F.M. Selten, 2020. Strong future increases in Arctic precipitation variability linked to poleward moisture transport. Science Advances, 6:eaax6869.

Biskaborn, B.K., S.L. Smith, J. Noetzli, H. Matthes, G. Vieira and 43 others, 2019. Permafrost is warming at a global scale. Nature Communications, 10:264.

Bjerke, J.W., S.R. Karlsen, K.A. Høgda, E. Malnes, J.U. Jepsen, S. Lovibond, D. Vikhamar-Schuler and H. Tømmervik, 2014. Record-low primary productivity and high plant damage in the Nordic Arctic Region in 2012 caused by multiple weather events and pest outbreaks. Environmental Research Letters, 9:084006.

Blok, D., M.P.D. Heijmans, G. Schaepman-Strub, A.V. Kononov, T.C. Maximov and F. Berendse, 2010. Shrub expansion may reduce summer permafrost thaw in Siberian tundra. Global Change Biology, 16:1296-1305.

Bokhorst, S., J.W. Bjerke, L.E. Street, T.V. Callaghan and G.K. Phoenix, 2011. Impacts of multiple extreme winter warming events on sub-Arctic heathland: phenology, reproduction, growth, and CO_2 flux responses. Global Change Biology, 17:2817-2830.

Boles, E., C. Provost, V. Garçon, C. Bertosio, M. Athanase, Z. Koenig and N. Sennéchael, 2020. Under-ice phytoplankton blooms in the central Arctic Ocean: Insights from the first biogeochemical IAOOS platform drift in 2017. Journal of Geophysical Research: Oceans, 125:e2019JC015608.

Box, J.E., W.T. Colgan, T.R. Christensen, N.M. Schmidt, M. Lund, F.-J.W. Parmentier, R. Brown, U.S. Bhatt, E.S. Euskirchen, V.E. Romanovsky, J.E. Walsh, J.E. Overland, M. Wang, R.W. Corell, W.N.Meier, B. Wouters, S. Mernild, J. Mård, J. Pawlak and M.S. Olsen, 2019. Key indicators of Arctic climate change: 1971-2017. Environmental Research Letters, 14:045010.

CAFF, 2013. Arctic Biodiversity Assessment. Status and trends in Arctic biodiversity. Conservation of Arctic Flora and Fauna, Akureyri, Iceland.

CAFF, 2017. State of the Arctic Marine Biodiversity: Key Findings and Advice for Monitoring. Conservation of Arctic Flora and Fauna International Secretariat, Akureyri, Iceland.

Cape, M.R., F. Straneo, N. Beaird, R.M. Bundy and M.A. Charette, 2018. Nutrient release to oceans from buoyancy-driven upwelling at Greenland tidewater glaciers. Nature Geoscience, 12:34-39.

Carmack, E. and P. Wassmann, 2006. Food webs and physical-biological coupling on pan-Arctic shelves: Unifying concepts and comprehensive perspectives. Progress in Oceanography, 71:446-477.

Carvalho, K.S. and S. Wang, 2020. Sea surface temperature variability in the Arctic Ocean and its marginal seas in a changing climate: Patterns and mechanisms. Global and Planetary Change, 93:103265.

Christensen, T.R., V.K. Arora, M. Gauss, L. Höglund-Isaksson and F.-J.W. Parmentier, 2019. Tracing the climate signal: mitigation of anthropogenic methane emissions can outweigh a large Arctic natural emission increase. Scientific Reports, 9:1146.

Christensen, T.R., M. Lund, K. Skov, J. Abermann, E. López-Blanco, J. Scheller, M. Scheel, M. Jackowicz-Korczynski, M.J. Murphy and M. Mastepanov, 2020. Multiple ecosystem effects of extreme weather events in the Arctic. Ecosystems, 24:122-136.

Christiansen, J.R. and C.J. Jørgensen, 2018. First observation of direct methane emission to the atmosphere from the subglacial domain of the Greenland Ice Sheet. Scientific Reports, 8:16623.

Coello-Camba, A. and S. Agustí, 2017. Thermal thresholds of phytoplankton growth in polar waters and their consequences for a warming polar ocean. Frontiers in Marine Science, 4:168.

Damm, E., E. Helmke, S. Thoms, U. Schauer, E. Nöthig, K. Bakker and R.P. Kiene, 2010. Methane production in aerobic oligotrophic surface water in the central Arctic Ocean. Biogeosciences, 7:1099-1108.

Dezutter, T., C. Lalande, C. Dufresne, G. Darnis and L. Fortier, 2019. Mismatch between microalgae and herbivorous copepods due to the record sea ice minimum extent of 2012 and the late sea ice break-up of 2013 in the Beaufort Sea. Progress in Oceanography, 173:66-77.

Duffy-Anderson, J.T., P. Stabeno, A.G. Andrews, K. Cieciel, A. Deary, E. Farley, C. Fugate, C. Harpold, R. Heintz, D. Kimmel, K. Kuletz, J. Lamb, M. Paquin, S. Porter, L. Rogers, A. Spear and E. Yasumiishi, 2019. Responses of the northern Bering Sea and southeastern Bering Sea pelagic ecosystems following record-breaking low winter sea ice. Geophysical Research Letters, 46:9833-9842.

Elmendorf, S.C., G.H.R. Henry, R.D. Hollister, R.G. Björk, N. Boulanger-Lapointe and 42 others, 2012. Plot-scale evidence of tundra vegetation change and links to recent summer warming. Nature Climate Change, 2:453-457.

Falk, J.M., N.M. Schmidt, T.R. Christensen and L. Strom, 2015. Large herbivore grazing affects the vegetation structure and greenhouse gas balance in a High Arctic mire. Environmental Research Letters, 10:045001.

Fernández-Méndez, M., L.M. Olsen, H.M. Kauko, A. Meyer, A. Rösel, I. Merkouriadi, C.J. Mundy, J.K. Ehn, A. Johansson, P.M. Wagner, Å. Ervik, B.K. Sorrell, P. Duarte, A. Wold, H. Hop and P. Assmy, 2018. Algal hot spots in a changing Arctic Ocean: Sea-ice ridges and the snow-ice interface. Frontiers in Marine Science, 5:75.

Fortier, M., L. Fortier, C. Michel and L. Legendre, 2002. Climatic and biological forcing of the vertical flux of biogenic particles under seasonal arctic sea ice. Marine Ecology Progress Series, 225: 1-16.

Fossheim, M., R. Primicerio, E. Johannesen, R.B. Ingvaldsen, M.M. Aschan and A.V. Dolgov, 2015. Recent warming leads to a rapid borealization of fish communities in the Arctic. Nature Climate Change, 5:673-677.

Frainer, A., R. Primicerio, S. Kortsch, M. Aune, A.V. Dolgov, M. Fossheim and M.M. Aschan, 2017. Climate-driven changes in functional biogeography of Arctic marine fish communities. Proceedings of the National Academy of Sciences, 114:12202-12207.

Fransson, A., M. Chierici, H. Hop, H. Findlay, S. Kristiansen and A. Wold, 2016. Late winter-to-summer change in ocean acidification state in Kongsfjorden, with implications for calcifying organisms. Polar Biology, 39:1841-1857.

Fransson, A., M. Chierici, I. Skjelvan, A. Olsen, P. Assmy, A. Peterson, G. Spreen and B. Ward, 2017. Effect of sea-ice and biogeochemical processes and storms on under-ice water CO_2 during the winter-spring transition in the high Arctic Ocean: implications for sea-air CO_2 fluxes. Journal of Geophysical Research: Oceans, 122:5566-5587.

Fraser, R., S. Kokelj, T. Lantz, M. McFarlane-Winchester, I. Olthof and D. Lacelle, 2018. Climate sensitivity of High Arctic permafrost terrain demonstrated by widespread ice-wedge thermokarst on Banks Island. Remote Sensing, 10:954.

Frey, K.E., J.C. Comiso, L.W. Cooper, J.M. Grebmeier and L.V. Stock, 2019. Arctic Ocean primary productivity: the response of marine algae to climate warming and sea ice decline. In: Richter-Menge, J., M.L. Druckenmiller and M. Jeffries (eds.). Arctic Report Card 2019. www.arctic.noaa.gov/Report-Card

Frey, K.E., J.C. Comiso, L.W. Cooper, J.M. Grebmeier and L.V. Stock, 2020. Arctic Ocean primary productivity: the response of marine algae to climate warming and sea ice decline. In: Thoman, R.L., J. Richter-Menge and M.L. Druckenmiller (eds.). Arctic Report Card 2020, Arctic Report Card 2019. www.arctic.noaa.gov/Report-Card

Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Hauck and 81 others, 2020. Global Carbon Budget 2020. Earth System Science Data, 12:3269-3340.

Fujiwara, A., S. Nishino, K. Matsuno, J. Onodera, Y. Kawaguchi, T. Hirawake, K. Suzuki, J. Inoue and T. Kikuchi, 2018. Changes in phytoplankton community structure during wind-induced fall bloom on the central Chukchi shelf. Polar Biology, 41:1279-1295.

Gouttevin, I., M. Langer, H. Löwe, J. Boike, M. Proksch and M. Schneebeli, 2018. Observation and modelling of snow at a polygonal tundra permafrost site: spatial variability and thermal implications. The Cryosphere, 12:3693-3717.

Graham, R.M., P. Itkin, A. Meyer, A. Sundfjord, G. Spreen and 24 others, 2019. Winter storms accelerate the demise of sea ice in the Atlantic sector of the Arctic Ocean. Scientific Reports, 9:9222.

Granskog, M.A., I. Fer, A. Rinke and H. Steen, 2018. Atmosphere-ice-ocean-ecosystem processes in a thinner Arctic sea ice regime: The Norwegian Young Sea ICE (N-ICE2015) Expedition. Journal of Geophysical Research: Oceans, 123:1586-1594.

Grebmeier, J.M., K.E. Frey, L.W. Cooper and M. Kędra, 2018. Trends in benthic macrofaunal populations, seasonal sea ice persistence, and bottom water temperatures in the Bering Strait region. Oceanography, 31:136-151.

Grimm, R., D. Notz, R.N.Glud, S. Rysgaard and K.D. Six, 2016. Assessment of the sea-ice carbon pump: insights from a three-dimensional ocean-sea-ice-biogeochemical model (MPIOM/HAMOCC). Elementa: Science of the Anthropocene, 4:000136.

Guéry, L., S. Descamps, K.I. Hodges, R. Pradel, B. Moe, S.A. Hanssen, K.E. Erikstad, G.W. Gabrielsen, H.G. Gilchrist, S. Jenouvrier and J. Bêty, 2019. Winter extratropical cyclone influence on seabird survival: variation between and within common eider *Somateria mollissima* populations. Marine Ecology Progress Series, 627:155-170.

Guo, D. and H. Wang, 2017. Simulated historical (1901-2010) changes in the permafrost extent and active layer thickness in the northern hemisphere. Journal of Geophysical Research: Atmospheres, 122:12,285-12,295.

Hamilton, C., C. Lydersen, R. Ims and K. Kovacs, 2016. Coastal habitat use by ringed seals *Pusa hispida* following a regional sea-ice collapse: importance of glacial refugia in a changing Arctic. Marine Ecology Progress Series, 545:261-277.

Hancke, K., L.C. Lund-Hansen, M.L. Lamara, S.H. Pedersen, M.D. King, P. Andersen and B.K. Sorrell, 2018. Extreme low light requirement for algae growth underneath sea ice: a case study from Station Nord, NE Greenland. Journal of Geophysical Research: Oceans, 123:985-1000.

Haug, T., B. Bogstad, M. Chierici, H. Gjøsæter, E.H. Hallfredsson, A. Høines, A.H. Hoel, R.B. Ingvaldsen, L.L. Jørgensen, T. Knutsen, H. Loeng, L. Naustvoll, I. Røttingen and K. Sunnanå, 2017. Future harvest of living resources in the Arctic Ocean north of the Nordic and Barents Seas: a review of possibilities and constraints. Fisheries Research, 188:38-57.

Hill, V., M. Ardyna, S.H. Lee and D.E. Varela, 2018a. Decadal trends in phytoplankton production in the Pacific Arctic Region from 1950 to 2012. Deep Sea Research II, 152:82-94.

Hill, V.J., B. Light, M. Steele and R.C. Zimmerman, 2018b. Light availability and phytoplankton growth beneath Arctic sea ice: integrating observations and modeling. Journal of Geophysical Research: Oceans, 123:3651-3667.

Holding, J.M., S. Markager, T. Juul-Pedersen, M.L. Paulsen, E.F. Møller, L. Meire and M.K. Sejr, 2019. Seasonal and spatial patterns of primary production in a high-latitude fjord affected by Greenland Ice Sheet run-off. Biogeosciences, 16:3777-3792.

Holmes, R.M., A.I. Shiklomanov, A. Suslova, M. Tretiakov, J.W. McClelland, R.G.M. Spencer and S.E. Tank, 2018. River discharge. In: Arctic Report Card 2018, www.arctic.noaa.gov/Report-Card

Hood, E., T. Battin, J. Fellman, S. O'Neel and R. Spencer, 2015. Storage and release of organic carbon from glaciers and ice sheets. Nature Geoscience, 8:91-96.

Hop, H., M. Vihtakari, B.A. Bluhm, P. Assmy, M. Poulin, R. Gradinger, I. Peeken, C. von Quillfeldt, L.M. Olsen, L. Zhitina and I.A.Melnikov, 2020. Changes in sea-ice protist diversity with declining sea ice in the Arctic Ocean from the 1980s to 2010s. Frontiers in Marine Science, 7:243.

Hoppe, C.J.M., C.M. Flintropand and B. Rost, 2018a. The Arctic picoeukaryote *Micromonas pusilla* benefits synergistically from warming and ocean acidification. Biogeosciences, 15:4353-4365.

Hoppe, C.J.M., K.K.E. Wolf, N. Schuback, P.D. Tortell and B. Rost, 2018b. Compensation of ocean acidification effects in Arctic phytoplankton assemblages. Nature Climate Change, 8:529-533.

Hopwood, M.J., D. Carroll, T. Dunse, A. Hodson, J.M. Holding, J.L. Iriarte, S. Ribeiro, E.P. Achterberg, C. Cantoni, D.F. Carlson, M. Chierici, J.S. Clarke, S. Cozzi, A. Fransson, T. Juul-Pedersen, M.H.S. Winding and L. Meire, 2020. Review article: How does glacier discharge affect marine biogeochemistry and primary production in the Arctic? The Cryosphere, 14:1347-1383.

Horvat, C., D.R. Jones, S. Iams, D. Schroeder, D. Flocco and D. Feltham, 2017. The frequency and extent of sub-ice phytoplankton blooms in the Arctic Ocean. Science Advances, 3:e1601191.

Hugelius, G., J. Strauss, S. Zubrzycki, J.W. Harden, E.A.G. Schuur, C.L. Ping, L. Schirrmeister, G. Grosse, G.J. Michaelson, C.D. Koven, J.A. O'Donnel, B. Elberling, U. Mishra, P. Camill, Z. Yu, J. Palmtag and P. Kuhry, 2014. Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps. Biogeosciences, 11:6573-6593.

Huntington, H.P., S.L. Danielson, F.K. Wiese, M. Baker, P. Boveng, J.J. Citta, A. DeRobertis, D.M.S. Dickson, E. Farley, J.C. George, K. Iken, D.G. Kimmel, K. Kuletz, C. Ladd, R. Levine, L. Quakenbush, P. Stabeno, K.M. Stafford, D. Stockwell and C. Wilson, 2020. Evidence suggests potential transformation of the Pacific Arctic ecosystem is underway. Nature Climate Change, 10:342-348.

IPCC, 2019. IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Pörtner, H.-O., D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N.M. Weyer (eds.).

Islam, F., M.D. DeGrandpre, C.M. Beatty, M.-L. Timmermans, R.A. Krishfield, J.M. Toole and S.R. Laney, 2017. Sea surface $p\mathrm{CO}_2$ and O_2 dynamics in the partially ice-covered Arctic Ocean. Journal of Geophysical Research: Oceans, 122:1425-1438.

Jafarov, E.E., E.T. Coon, D.R. Harp, C.J. Wilson, S.L. Painter, A.L. Atchley and V.E. Romanovsky, 2018. Modeling the role of preferential snow accumulation in through talik development and hillslope groundwater flow in a transitional permafrost landscape. Environmental Research Letters, 13:105006.

Jin, H., A.M. Jönsson, C. Olsson, J. Lindström, P. Jönsson and L. Eklundh, 2019. New satellite-based estimates show significant trends in spring phenology and complex sensitivities to temperature and precipitation at northern European latitudes. International Journal of Biometeorology, 63:763-775.

Johnsen, G., M. Norli, M. Moline, I. Robbins, C. von Quillfeldt, K. Sørensen, F. Cottier and J. Berge, 2018. The advective origin of an under-ice spring bloom in the Arctic Ocean using multiple observational platforms. Polar Biology, 41:1197-1216.

Kahru, M., Z. Lee, B.G. Mitchell and C.D. Nevison, 2016. Effects of sea ice cover on satellite-detected primary production in the Arctic Ocean. Biology Letters, 12:20160223.

Kohlbach, D., M. Graeve, B.A. Lange, D. Carmen, I. Peeken and H. Flores, 2016. The importance of ice algae-produced carbon in the central Arctic Ocean ecosystem: Food web relationships revealed by lipid and stable isotope analyses. Limnology and Oceanography, 61:2027-2044.

Kohlbach, D., S.H. Ferguson, T.A. Brown and C. Michel, 2019. Landfast sea ice-benthic coupling during spring and potential impacts of system changes on food web dynamics in Eclipse Sound, Canadian Arctic. Marine Ecology Progress Series, 627:33-48.

Kokelj, S.V., T.C. Lantz, J. Tunnicliffe, R. Segal and D. Lacelle, 2017. Climate-driven thaw of permafrost preserved glacial landscapes, northwestern Canada. Geology, 45:371-374.

Kort, E.A., S.C. Wofsy, B.C. Daube, M. Diao, J.W. Elkins, R.S. Gao, E.J. Hintsa, D.F. Hurst, R. Jimenez, F.L. Moore, J.R. Spackman and M.A. Zondlo, 2012. Atmospheric observations of Arctic Ocean methane emissions up to 82° north. Nature Geoscience, 5:318-321.

Kovacs, K. and C. Michel, 2011. Biological impacts of changes to sea ice in the Arctic. In: Snow, Water, Ice and Permafrost in the Arctic (SWIPA): Climate Change and the Cryosphere. pp. 9-32 – 9-51. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway.

Kretschmer, K., A. Biastoch, L. Rüpke and E. Burwicz, 2015. Modeling the fate of methane hydrates under global warming. Global Biogeochemical Cycles, 29:610-625.

Lalande, C., E.-M. Nöthig and L. Fortier, 2019. Algal export in the Arctic Ocean in times of global warming. Geophysical Research Letters, 46:5959-5967.

Lamarche-Gagnon, G., J.L. Wadham, B.S. Lollar, S. Arndt, P. Fietzek, A.D. Beaton, A.J. Tedstone, J. Telling, E.A. Bagshaw, R.R. Hawkings, T.J. Kohler, J.D. Zarsky, M.C. Mowlem, A.M. Anesio and M. Stibal, 2019. Greenland melt drives continuous export of methane from the ice-sheet bed. Nature, 565:73-90.

Lange, B.A., H. Flores, C. Michel, J.F. Beckers, A. Bublitz, J.A. Casey, G. Castellani, I. Hatam, A. Reppchen, S.A. Rudolph and C. Haas, 2017. Pan-Arctic sea ice-algal chl a biomass and suitable habitat are largely underestimated for multi-year ice. Global Change Biology, 23:4581-4597.

Lannuzel, D., L. Tedesco, M. van Leeuwe, K. Campbell, H. Flores, B. Delille, L. Miller, J. Stefels, P. Assmy, J. Bowman, K. Brown, G. Castellani, M. Chierici, O. Crabeck, E. Damm, B. Else, A. Fransson, F. Fripiat, N.-X. Geilfus, C. Jacques, E. Jones, H. Kaartokallio, M. Kotovitch, K. Meiners, S. Moreau, D. Nomura, I. Peeken, J.-M.Rintala, N. Steiner, J.-L. Tison, M. Vancoppenolle, F. Van der Linden, M. Vichi and P. Wongpan, 2020. The future of Arctic sea-ice biogeochemistry and ice-associated ecosystems. Nature Climate Change, 10:983-992.

Lawson, E.C., J.L. Wadham, M. Tranter, M. Stibal, G.P. Lis, C.E.H. Butler, J. Laybourn-Parry, P. Nienow, D. Chandler and P. Dewsbury, 2014. Greenland Ice Sheet exports labile organic carbon to the Arctic oceans. Biogeosciences, 11:4015-4028.

Lefebvre, K.A., L. Quakenbush, E. Frame, K.B. Huntington, G. Sheffield, R. Stimmelmayr, A. Bryan, A. Kendrick, H. Ziel, T. Goldstein, J.A. Snyder, T. Gelatt, F. Gulland, B. Dickerson and V. Gill, 2016. Prevalence of algal toxins in Alaskan marine mammals foraging in a changing arctic and subarctic environment. Harmful Algae, 55:13-24.

Lefort, K.J., C.J. Garroway and S.H. Ferguson, 2020. Killer whale abundance and predicted narwhal consumption in the Canadian Arctic. Global Change Biology, 26:4276-4283.

Lewis, K.M., G.L. van Dijken and K.R. Arrigo, 2020. Changes in phytoplankton concentration now drive increased Arctic Ocean primary production. Science, 369:198-202.

Liu, Q., S. Piao, I.A. Janssens, Y. Fu, S. Peng, X. Lian, P. Ciais, R.B. Myneni, J. Penuelas and T. Wang, 2018. Extension of the growing season increases vegetation exposure to frost. Nature Communications, 9:426.

López-Blanco, E., M. Lund, M. Williams, M.P. Tamstorf, A. Westergaard-Nielsen, J.-F. Exbrayat, B.U. Hansen and T.R. Christensen, 2017. Exchange of CO_2 in Arctic tundra: impacts of meteorological variations and biological disturbance. Biogeosciences, 14:4467-4483.

López-Blanco, E., M. Lund, T.R. Christensen, M.P. Tamstorf, T.L. Smallman, D. Slevin, A. Westergaard-Nielsen, B.U. Hansen, J. Abermann and M. Williams, 2018. Plant traits are key determinants in buffering the meteorological sensitivity of net carbon exchanges of Arctic tundra. Journal of Geophysical Research: Biogeosciences, 123:2675-2694.

López-Blanco, E., M. Jackowicz-Korczynski, M. Mastepanov, K. Skov, A. Westergaard-Nielsen, M. Williams and T.R. Christensen, 2020. Multi-year data-model evaluation reveals the importance of nutrient availability over climate in Arctic ecosystem C dynamics. Environmental Research Letters, 15:094007.

Loranty, M.M., B.E. Abbott, D. Blok, T.A. Douglas, H.E. Epstein, B.C. Forbes, B.M. Jones, A.L. Kholodov, H. Kropp, A. Malhotra, S.D. Mamet, I.H. Myers-Smith, S.M. Natali, J.A. O'Donnell, G.K. Phoenix, A.V. Rocha, O. Sonnentag, K.D. Tape and D.A. Walker, 2018. Reviews and syntheses: Changing ecosystem influences on soil thermal regimes in northern high-latitude permafrost regions. Biogeosciences, 15:5287-5313.

Lovejoy, C., W.F. Vincent, S. Bonilla, S. Roy, M.-J. Martineau, R. Terrado, M. Potvin, R. Massana and C. Pedrós-Alió, 2007. Distribution, phylogeny, and growth of cold-adapted picoprasinophytes in Arctic seas. Journal of Phycology, 43:78-89.

Lund, M., J.M. Falk, T. Friborg, H.N. Mbufong, C. Sigsgaard, H. Soegaard and M.P. Tamstorf, 2012. Trends in CO_2 exchange in a high Arctic tundra heath, 2000-2010. Journal of Geophysical Research: Biogeosciences, 117:G02001.

Lund, M., K. Raundrup, A. Westergaard-Nielsen, E. López-Blanco, J. Nymand and P. Aastrup, 2017. Larval outbreaks in West Greenland: Instant and subsequent effects on tundra ecosystem productivity and CO_2 exchange. Ambio, 46:26-38.

Luo, J., F. Niu, Z. Lin, M. Liu and G. Yin, 2019. Recent acceleration of thaw slumping in permafrost terrain of Qinghai-Tibet Plateau: an example from the Beiluhe region. Geomorphology, 341:79-85.

Manizza, M., D. Menemenlis, H. Zhang and C.E. Mille, 2019. Modeling the recent changes in the Arctic ocean CO_2 sink (2006–2013). Global Biochemical Cycles, 33:420-438.

Marchand, N., A. Royer, G. Krinner, A. Roy, A. Langlois and C. Vargel, 2018. Snow-covered soil temperature retrieval in Canadian Arctic permafrost areas, using a land surface scheme informed with satellite remote sensing data. Remote Sensing, 10:1703.

Marquardt, M., A. Vader, E.I. Stübner, M. Reigstad and T.M. Gabrielsen, 2016. Strong seasonality of marine microbial eukaryotes in a High-Arctic fjord (Isfjorden, in West Spitsbergen, Norway). Applied Environmental Microbiology, 82:1868-1880.

Martin, J., J.-É. Tremblay, J. Gagnon, G. Tremblay, A. Lapoussière, C. Jose, M. Poulin, M. Gosselin, Y. Gratton and C. Michel, 2010. Prevalence, structure and properties of subsurface chlorophyll maxima in Canadian Arctic waters. Marine Ecology Progress Series, 412:69-84.

Martin, L.C.P., J. Nitzbon, K.S. Aas, B. Etzelmüller. H. Kristiansen and S. Westermann, 2019. Stability conditions of peat plateaus and palsas in northern Norway. Journal of Geophysical Research: Earth Surface, 124:705-719.

Mastepanov, M., C. Sigsgaard, T. Tagesson, L. Ström, M.P. Tamstorf, M. Lund and T.R. Christensen, 2013. Revisiting factors controlling methane emissions from high-Arctic tundra. Biogeosciences, 10:5139-5158.

Mayot, N., P.A. Matrai, A. Arjona, S. Bélanger, C. Marchese, T. Jaegler, M. Ardyna and M. Steele, 2020. Springtime export of Arctic sea ice influences phytoplankton production in the Greenland Sea. Journal of Geophysical Research: Oceans, 125:e2019JC015799.

McClelland, J.W., R.M. Holmes, K.H. Dunton and R.W. Macdonald, 2012. The Arctic Ocean Estuary. Estuaries and Coasts, 35:353-368.

McGovern, M., A.K. Pavlov, A. Deininger, M.A. Granskog, E. Leu, J.E. Søreide and A.E. Poste, 2020. Terrestrial inputs drive seasonality in organic matter and nutrient biogeochemistry in a High Arctic fjord system (Isfjorden, Svalbard). Frontiers in Marine Science, 7:542563.

McGuire, A.D., T.R. Christensen, D. Hayes, A. Heroult, E. Euskirchen, J.S. Kimball, C. Koven, P. Lafleur, P.A. Miller, W. Oechel, P. Peylin, M. Williams and Y. Yi, 2012. An assessment of the carbon balance of Arctic tundra: comparisons among observations, process models, and atmospheric inversions. Biogeosciences, 9:3185-3204.

McGuire, A.D., D.M. Lawrence, C. Koven, J.S. Clein, E. Burke, G. Chen, E. Jafarov, A.H. MacDougall, S. Marchenko, D. Nicolsky, S. Peng, A. Rinke, P. Ciais, I. Gouttevin, D.J. Hayes, D. Ji, G. Krinner, J.C. Moore, V. Romanovsky, C. Schädel, K. Schaefer, E.A.G. Schuur and Q. Zhuang, 2018. Dependence of the evolution of carbon dynamics in the northern permafrost region on the trajectory of climate change. Proceedings of the National Academy of Sciences, 115:201719903.

Meire, L., J. Mortensen, P. Meire, T. Juul-Pedersen, M.K. Sejr, S. Rysgaard, R.Nygaard, P. Huybrechts and F.J.R. Meysman, 2017. Marine-terminating glaciers sustain high productivity in Greenland fjords. Global Change Biology, 23:5344-5357.

Meredith, M., M. Sommerkorn, S. Cassotta, C. Derksen, A. Ekaykin, A. Hollowed, G. Kofinas, A. Mackintosh, J. Melbourne-Thomas, M.M.C. Muelbert, G. Ottersen, H. Pritchard and E.A.G. Schuur, 2019. Polar regions. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate.

Michel, C., 2013. Marine ecosystems. In: Arctic Biodiversity Assessment. Status and trends in Arctic Biodiversity. pp. 486-526. Conservation of Arctic Flora and Fauna, Akureyri, Iceland.

Michel, C., R.G. Ingram and L. Harris, 2006. Variability of oceanographic and ecological processes in the Canadian Arctic Archipelago. Progress in Oceanography, 72:379-401.

Møller, E.F. and T.G. Nielsen, 2020. Borealization of Arctic zooplankton – smaller and less fat zooplankton species in Disko Bay, Western Greenland. Limnology and Oceanography, 65:1175-1188.

Moon, T., A. Ahlstrøm, H. Goelzer, W. Lipscomb and S. Nowicki, 2018. Rising oceans guaranteed: Arctic land ice loss and sea level rise. Current Climate Change Reports, 4:211-222.

Mortenson, E., N. Steiner, A.H. Monahan, H. Hayashida, T. Sou and A. Shao, 2020. Modeled impacts of sea ice exchange processes on Arctic Ocean carbon uptake and acidification (1980–2015). Journal of Geophysical Research: Oceans, 125:e2019JC015782.

Mosbacher, J.B., A. Michelsen, M. Stelvig, H. Hjermstad-Sollerud and N.M. Schmidt, 2019. Muskoxen modify plant abundance, phenology, and nitrogen dynamics in a High Arctic fen. Ecosystems, 22:1095-1107.

Murray, C., S. Markager, C.A. Stedmon, T. Juul-Pedersen, M.K. Sejr and A. Bruhn, 2015. The influence of glacial melt water on bio-optical properties in two contrasting Greenlandic fjords. Estuarine, Coastal and Shelf Science, 163:72-83.

Myers-Smith, I., J.T. Kerby, G.K. Phoenix, J.W. Bjerke, H.E. Epstein and 36 others, 2020. Complexity revealed in the greening of the Arctic. Nature Climate Change, 10:106-117.

Myhre, C.L., B. Ferré, S.M. Platt, A. Silyakova, O. Hermansen, G. Allen, I. Pisso, N. Schmidbauer, A. Stohl, J. Pitt, P. Jansson, J. Greinert, C. Percival, A.M. Fjaeraa, S.J. O'Shea, M. Gallagher, M. LeBreton, K.N. Bower, S.J.B. Bauguitte, S. Dalsoren, S. Vadakkepuliyambatta, R.E. Fisher, E.G. Nisbet, D. Lowry, G. Myhre, J.A. Pyle, M. Cain and J. Mienert, 2016. Extensive release of methane from Arctic seabed west of Svalbard during summer 2014 does not influence the atmosphere. Geophysical Research Letters, 43:4624-4631.

Natali, S.M., J.D. Watts, B.M. Rogers, S. Potter, S.M. Ludwig and 70 others, 2019. Large loss of CO_2 in winter observed across the northern permafrost region. Nature Climate Change, 9:852-857.

Nauta, A.L., M.M.P.D. Heijmans, D. Blok, J. Limpens, B. Elberling, A. Gallagher, B. Li, R.E. Petrov, T.C. Maximov, J. van Huissteden and F. Berendse, 2014. Permafrost collapse after shrub removal shifts tundra ecosystem to a methane source. Nature Climate Change, 5:67-70.

Neukermans, G., L. Oziel and M. Babin, 2018. Increased intrusion of warming Atlantic water leads to rapid expansion of temperate phytoplankton in the Arctic. Global Change Biology, 24:2545-2553.

Niemi, A., N. Bernadsek, C. Michel, R.A. Feely, W. Williams, K. Azetsu-Scott, W. Walkusz and J.D. Reist, 2021. Biological impact of ocean acidification in the Canadian Arctic: widespread severe pteropod shell dissolution in Amundsen Gulf. Frontiers in Marine Science, 8:600184.

Niittynen, P., R.K. Heikkinen and M. Luoto, 2018. Snow cover is a neglected driver of Arctic biodiversity loss. Nature Climate Change, 8:997-1001.

Nishino, S., Y. Kawaguchi, J. Inoue, T. Hirawake, A. Fujiwara, R. Futsuki, J. Onodera and M. Aoyama, 2015. Nutrient supply and biological response to wind-induced mixing, inertial motion, internal waves, and currents in the northern Chukchi Sea. Journal of Geophysical Research: Oceans, 120:1975-1992.

NOAA, 2019. Active and Closed Unusual Mortality Events. www.fisheries.noaa.gov/national/marine-life-distress/active-and-closed-unusual-mortality-events

Nomura, D., M.A. Granskog, A. Fransson, M. Chierici, A. Silyakova, K.I. Ohshima, L. Cohen, B. Delille, S.R. Hudson and G.S. Dieckmann, 2018. CO_2 flux over young and snow-covered Arctic pack ice in winter and spring. Biogeosciences, 15:3331-3343.

Oh, Y., Q. Zhuang, L. Liu, L.R. Welp, M.C.Y. Lau, T.C. Onstott, D. Medvigy, L. Bruhwiler, E.J. Dlugokencky, G. Hugelius, L. D'Imperio and B. Elberling, 2020. Reduced net methane emissions due to microbial methane oxidation in a warmer Arctic. Nature Climate Change, 10: 317-321.

Olefeldt, D., M.R. Turetsky, P.M. Crill and A.D. McGuire, 2013. Environmental and physical controls on northern terrestrial methane emissions across permafrost zones. Global Change Biology, 19:589-603.

Overduin, P.P., S. Liebner, C. Knoblauch, F. Günther, S. Wetterich, L. Schirrmeister, H.-W. Hubberten and M.N. Grigoriev, 2015. Methane oxidation following submarine permafrost degradation: Measurements from a central Laptev Sea shelf borehole. Journal of Geophysical Research: Biogeosciences, 120:965-978.

Oziel, L., G. Neukermans, M. Ardyna, C. Lancelot, J.-L. Tison, P. Wassmann, J. Sirven, D. Ruiz-Pino and J.-C. Gascard, 2017. Role for Atlantic inflows and sea ice loss on shifting phytoplankton blooms in the Barents Sea. Journal of Geophysical Research: Oceans, 122:5121-5139.

Oziel, L., A. Baudena, M. Ardyna, P. Massicotte, A. Randelhoff, J.-B. Sallée, R.B. Ingvaldsen, E. Devred and M. Babin, 2020. Faster Atlantic currents drive poleward expansion of temperate phytoplankton in the Arctic Ocean. Nature Communications, 11:1705.

Pan, C.G., P.B. Kirchner, J.S. Kimball and J. Du, 2020. A long-term passive microwave snowoff record for the Alaska region 1988–2016. Remote Sensing, 12:153.

Parmentier, F.-J.W., M.K. van der Molen, J. van Huissteden, S.A. Karsanaev, A.V. Kononov, D.A. Suzdalov, T.C. Maximov and A.J. Dolman, 2011. Longer growing seasons do not increase net carbon uptake in the northeastern Siberian tundra. Journal of Geophysical Research: Biogeosciences, 116:G04013.

Parmentier, F.-J.W., T.R. Christensen, L.L. Sørensen, S. Rysgaard, A.D. McGuire, P.A. Miller and D.A. Walker, 2013. The impact of lower sea-ice extent on Arctic greenhouse-gas exchange. Nature Climate Change, 3:195-202.

Parmentier, F.-J.W., D.P. Rasse, M. Lund, J.W. Bjerke, B.G. Drake, S. Weldon, H. Tømmervik and G.H. Hansen, 2018. Vulnerability and resilience of the carbon exchange of a subarctic peatland to an extreme winter event. Environmental Research Letters, 13:065009.

Pedersen, S.H., G.E. Liston, M.P. Tamstorf, J. Abermann, M. Lund and N.M. Schmidt, 2018. Quantifying snow controls on vegetation greenness. Ecosphere, 9:e02309.

Percopo, I., M.V. Ruggiero, S. Balzano, P. Gourvil, N. Lundholm, R. Siano, A. Tammilehto, D. Vaulot and D. Sarno, 2016. *Pseudo-nitzschia arctica* sp. nov., a new cold-water cryptic *Pseudo-nitzschia* species within the *P. pseudodelicatissima* complex. Journal of Phycology, 52:184-199.

Petrich, C. and H. Eicken, 2009. Growth, structure and properties of sea ice. In: Thomas, D.N. and G.S. Dieckmann (Eds.), Sea ice. pp. 23-77. Wiley-Blackwell.

Phoenix, G.K. and J.W. Bjerke, 2016. Arctic browning: extreme events and trends reversing arctic greening. Global Change Biology, 22:2960-2962.

Pirk, N., M. Mastepanov, E. López-Blanco, L.H. Christensen, H.H. Christiansen, B.U. Hansen, M. Lund, F.-J.W. Parmentier, K. Skov and T.R. Christensen, 2017. Toward a statistical description of methane emissions from Arctic wetlands. Ambio, 46:70-80.

Polyakov, I.V., A.V. Pnyushkov, M.B. Alkire, I.M. Ashik, T.M. Baumann, E.C. Carmack, I. Goszczko, J. Guthrie, V.V. Ivanov, T. Kanzow, R. Krishfield, R. Kwok, A. Sundfjord, J. Morison, R. Rember and A. Yulin, 2017. Greater role for Atlantic inflows on sea-ice loss in the Eurasian Basin of the Arctic Ocean. Science, 356:285-291.

Polyakov, I.V., M.B. Alkire, B.A. Bluhm, K.A. Brown, E.C. Carmack, M. Chierici, S.L. Danielson, I. Ellingsen, E.A. Ershova, K. Gårdfeldt, R.B. Ingvaldsen, A.V. Pnyushkov, D. Slagstad and P. Wassmann, 2020. Borealization of the Arctic Ocean in response to anomalous advection from sub-arctic seas. Frontiers in Marine Science, 7:491.

Popova, E.E., A. Yool, A.C. Coward, F. Dupont, C. Deal, S. Elliott, E. Hunke, M. Jin, M. Steele and J. Zhang, 2012. What controls primary production in the Arctic Ocean? Results from an intercomparison of five general circulation models with biogeochemistry, Journal of Geophysical Research, 117:C00D12.

Post, E., U.S. Bhatt, C.M. Bitz, J.F. Brodie, T.L. Fulton, M. Hebblewhite, J. Kerby, S.J. Kutz, I. Stirling and D.A. Walker, 2013. Ecological consequences of sea-ice decline. Science, 341:519-524.

Qi, D., L. Chen, B. Chen, A. Gao, W. Zhong, R.A. Feely, L.G. Anderson, H. Sun, J. Chen, M. Chen, L. Zhan, Y. Zhang and W.-J. Cai, 2017. Increase in acidifying water in the western Arctic Ocean. Nature Climate Change, 7:195-199.

Randelhoff, A., J. Holding, M. Janout, M.K. Sejr, M. Babin, J.-É. Tremblay and M.B. Alkire, 2020. Pan-Arctic Ocean primary production constrained by turbulent nitrate fluxes. Frontiers in Marine Science, 7:150.

Raz-Yaseef, N., M.S. Torn, Y. Wu, D.P. Billesbach, A.K. Liljedahl, T.J. Kneafsey, V.E. Romanovsky, D.R. Cook and S.D. Wullschleger, 2017. Large CO_2 and CH_4 emissions from polygonal tundra during spring thaw in northern Alaska. Geophysical Research Letters, 44:504-513.

Reigstad, M. and P. Wassmann, 2007. Does *Phaeocystis* spp. contribute significantly to vertical export of organic carbon? Biogeochemistry, 83:217-234.

Renaut, S., E. Devred and M. Babin, 2018. Northward expansion and intensification of phytoplankton growth during the early ice-free season in Arctic. Geophysical Research Letters, 45:10,590-10,598.

Rösel, A., P. Itkin, J. King, D. Divine, C. Wang, M.A. Granskog, T. Krumpen and S. Gerland, 2018. Thin sea ice, thick snow and widespread negative freeboard observed during N-ICE2015 north of Svalbard. Journal of Geophysical Research: Oceans, 123:1156-1176.

Rudy, A.C.A., S.F. Lamoureux, S.V. Kokelj, I.R. Smith and J.H. England, 2017. Accelerating thermokarst transforms ice-cored terrain triggering a downstream cascade to the ocean. Geophysical Research Letters, 44:11,080-11,087.

Rydsaa, J.H., F. Stordal, A. Bryn and L.M. Tallaksen, 2017. Effects of shrub and tree cover increase on the near-surface atmosphere in northern Fennoscandia. Biogeosciences, 14:4209-4227.

Sæmundsson, Þ., C. Morino, J.K. Helgason, S.J. Conway and H.G. Petursson, 2018. The triggering factors of the Móafellshyrna debris slide in northern Iceland: intense precipitation, earthquake activity and thawing of mountain permafrost. Science of the Total Environment, 621:1163-1175.

Sarmiento, J.L. and N. Gruber, 2006. Ocean Biogeochemical Dynamics. Princeton University Press.

Saunois, M., P. Bousquet, B. Poulter, A. Peregon, P. Ciais and 76 others, 2016. The global methane budget 2000–2012. Earth System Science Data, 8:697-751.

Sayedi, S.S., B.W. Abbott, B.F. Thornton, J.M. Frederick, J.E. Vonk and 27 others, 2020. Subsea permafrost carbon stocks and climate change sensitivity estimated by expert assessment. Environmental Research Letters, 15:124075.

Schiffrine, N., J.-É. Tremblay and M. Babin, 2020. Growth and elemental stoichiometry of the ecologically-relevant arctic diatom *Chaetoceros gelidus*: A mix of polar and temperate. Frontiers in Marine Science, 6:790.

Schuur, E.A.G., A.D. McGuire, C. Schädel, G. Grosse, J.W. Harden, D.J. Hayes, G. Hugelius, C.D. Koven, P. Kuhry, D.M. Lawrence, S.M. Natali, D. Olefeldt, V.E. Romanovsky, K. Schaefer, M.R. Turetsky, C.C. Treat and J.E. Vonk, 2015. Climate change and the permafrost carbon feedback. Nature, 520:171-179.

Semiletov, I., I. Pipko, Ö. Gustafsson, L.G. Anderson, V. Sergienko, S. Pugach, O. Dudarev, A. Charkin, A. Gukov, L. Bröder, A. Andersson, E. Spivak and N. Shakhova, 2016. Acidification of East Siberian Arctic Shelf waters through addition of freshwater and terrestrial carbon. Nature Geoscience, 9:361-365.

Shakhova, N.E., V.A. Alekseev and I.P. Semiletov, 2010. Predicted methane emission on the East Siberian shelf. Doklady Earth Sciences, 430:190-193.

Shakhova, N., I. Semiletov, I. Leifer, V. Sergienko, A. Salyuk, D. Kosmach, D. Chernykh, C. Stubbs, D. Nicolsky, V. Tumskoy and Ö. Gustafsson, 2014. Ebullition and storm-induced methane release from the East Siberian Arctic Shelf. Nature Geoscience, 7:64-70.

Smedsrud, L.H., M.H. Halvorsen, J.C. Stroeve, R. Zhang and K. Kloster, 2017. Fram Strait sea ice export variability and September Arctic sea ice extent over the last 80 years. The Cryosphere, 11:65-79.

Sørensen, H.L., B. Thamdrup, E. Jeppesen, S. Rysgaard and R.N. Glud, 2017. Nutrient availability limits biological production in Arctic sea ice melt ponds. Polar Biology, 40:1593-1606.

Sparrow, K.J., J.D. Kessler, J.R. Southon, F. Garcia-Tigreros, K.M. Schreiner, C.D. Ruppel, J.B. Miller, S.J. Lehman and X. Xu, 2018. Limited contribution of ancient methane to surface waters of the U.S. Beaufort Sea shelf. Science Advances, 4:eaao4842.

Spreen, G., L. de Steur, D. Divine, S. Gerland, E. Hansen and R. Kwok, 2020. Arctic sea ice volume export through Fram Strait from 1992 to 2014. Journal of Geophysical Research: Oceans, 125:e2019JC016039.

Stabeno, P.J. and S.W. Bell, 2019. Extreme conditions in the Bering Sea (2017–2018): Record-breaking low sea-ice extent. Geophysical Research Letters, 46:8952-8959.

Stabeno, P.J., R.L. Thoman and K. Wood, 2019. Recent warming in the Bering Sea and its impact on the ecosystem. In: Richter-Menge, J., M.L. Druckenmiller and M. Jeffries (eds.). Arctic Report Card 2019, www.arctic.noaa.gov/Report-Card

Stafford, K.M., 2019. Increasing detections of killer whales (*Orcinus orca*), in the Pacific Arctic. Marine Mammal Science, 35:696-706.

Sugie, K., A. Fujiwara, S. Nishino, S. Kameyama and N. Harada, 2020. Impacts of temperature, CO_2, and salinity on phytoplankton community composition in the western Arctic Ocean. Frontiers in Marine Science, 6:821.

Swanson, D. and M. Nolan, 2018. Growth of retrogressive thaw slumps in the Noatak Valley, Alaska, 2010–2016, measured by airborne photogrammetry. Remote Sensing, 10:983.

Tedesco, L., M. Vichi and E. Scoccimarro, 2019. Sea-ice algal phenology in a warmer Arctic. Science Advances, 5:eaav4830.

Thornton, B.F., M. Wik and P.M. Crill, 2016. Double counting challenges the accuracy of high latitude methane inventories. Geophysical Research Letters, 43:12,569-12,577.

Thornton, B.F., J. Prytherch, K. Andersson, I.M. Brooks, D. Salisbury, M. Tjernström and P.M. Crill, 2020. Shipborne eddy covariance observations of methane fluxes constrain Arctic sea emissions. Science Advances, 6:eaay7934.

Timmermans, M.-L. and C. Ladd, 2019. Sea surface temperature. In: State of the Climate in 2018. Bulletin of the American Meteorological Society, 100:S144-S146.

Timmermans, M.-L., J. Toole, R. Krishfield, 2018. Warming of the interior Arctic Ocean linked to sea ice losses at the basin margins. Science Advances, 4:eaat6773.

Tohjima, Y., J. Zeng, T. Shirai, Y. Niwa, S. Ishidoya, F. Taketani, D. Sasano, N. Kosugi, S. Kameyama, H. Takashima, H. Nara and S. Morimoto, 2021.

Estimation of CH_4 emissions from the East Siberian Arctic Shelf based on atmospheric observations aboard the R/V Mirai during fall cruises from 2012 to 2017. Polar Science, 27:100571.

Treat, C.C., A.A. Bloom and M.E. Marushchak, 2018. Nongrowing season methane emissions–a significant component of annual emissions across northern ecosystems. Global Change Biology, 44:163.

Treharne, R., J.W. Bjerke, H. Tømmervik, L. Stendardi and G.K. Phoenix, 2018. Arctic browning: Impacts of extreme climatic events on heathland ecosystem CO_2 fluxes. Global Change Biology, 25:489-503.

Turetsky, M.R., B.W. Abbott, M.C. Jones, K.W. Anthony, D. Olefeldt, E.A.G. Schuur, G. Grosse, P. Kuhry, G. Hugelius, C. Koven, D.M. Lawrence, C. Gibson, A.B.K. Sannel and A.D. McGuire, 2020. Carbon release through abrupt permafrost thaw. Nature Geoscience, 13:138-143.

Underwood, G.J.C., C. Michel, G. Meisterhans, A. Niemi, C. Belzile, M. Witt, A.J. Dumbrell and B.P. Koch, 2019. Organic matter from melting Arctic sea ice alters bacterial community structure and function. Nature Climate Change, 9:170-176.

Urbanski, J.A., L. Stempniewicz, J.M. Węsławski, K. Dragańska-Deja, A. Wochna, M. Goc and L. Iliszko, 2017. Subglacial discharges create fluctuating foraging hotspots for sea birds in tidewater glacier bays. Scientific Reports, 7:43999.

USFWS, 2019. 2019 Alaska Seabird Die-off. www.nps.gov/subjects/aknatureandscience/upload/9Sep2019-Die-Off-USFWS-Factsheet-508C-revised-29Aug.pdf

Vancoppenolle, M., L. Bopp, G. Madec, J. Dunne, T. Ilyina, P.R. Halloran and N. Steiner, 2013. Future Arctic Ocean primary productivity from CMIP5 simulations: Uncertain outcome, but consistent mechanisms. Global Biogeochemical Cycles, 27:605-619.

Wadham, J.L., J.R. Hawkings, L. Tarasov, L.J. Gregoire, R.G.M. Spencer, M. Gutjahr, A. Ridgwell and K.E. Kohfeld, 2019. Ice sheets matter for the global carbon cycle. Nature Communications, 10:3567.

Waga, H., T. Hirawake, A. Fujiwara, J.M. Grebmeier and S.-I. Saitoh, 2019. Impact of spatiotemporal variability in phytoplankton size structure on benthic macrofaunal distribution in the Pacific Arctic. Deep-Sea Research II, 162:114-126.

Watanabe, E., M. Jin, H. Hayashida, J. Zhang and N. Steiner, 2019. Multi-model intercomparison of the pan-Arctic ice-algal productivity on seasonal, interannual, and decadal timescales. Journal of Geophysical Research: Oceans, 124:9053-9084.

Wik, M., R.K. Varner, K.W. Anthony, S. MacIntyre and D. Bastviken, 2016. Climate-sensitive northern lakes and ponds are critical components of methane release. Nature Geoscience, 9:99-105.

Wild, B., A. Andersson, L. Bröder, J. Vonk, G. Hugelius, J.W. McClelland, W. Song, P.A. Raymond and Ö. Gustafsson, 2019. Rivers across the Siberian Arctic unearth the patterns of carbon release from thawing permafrost. Proceedings of the National Academy of Sciences, 116:10280-10285.

Wlodarska-Kowalczuk, M. and T.H. Pearson, 2004. Soft-bottom macrobenthic faunal associations and factors affecting species distributions in an Arctic glacial fjord (Kongsfjord, Spitsbergen). Polar Biology, 27:155-167.

Wollenburg, J.E., C. Katlein, G. Nehrke, E.-M. Nöthig, J. Matthiessen, D. A. Wolf-Gladrow, A. Nikolopoulos, F. Gázquez-Sanchez, L. Rossmann, P. Assmy, M. Babin, F. Bruyant, M. Beaulieu, C. Dybwad and I. Peeken, 2018. Ballasting by cryogenic gypsum enhances carbon export in a *Phaeocystis* under-ice bloom. Scientific Report, 8:7703.

Woodgate, R.A., 2018. Increases in the Pacific inflow to the Arctic from 1990 to 2015, and insights into seasonal trends and driving mechanisms from year-round Bering Strait mooring data. Progress in Oceanography, 160:124-154.

Woosley, R.J. and F.J. Millero, 2020. Freshening of the western Arctic negates anthropogenic carbon uptake potential. Limnology and Oceanography, 65:1834-1846.

Xiong, T., H. Zhang, J. Zhao, Z. Zhang, X. Guo, Z. Zhu and Y. Shan, 2019. Diverse responses of vegetation dynamics to snow cover phenology over the boreal region. Forests, 10:376.

Yasunaka, S., E. Siswanto, A. Olsem, M. Hoppema, E. Watanabe, A. Fransson, M. Chierici, A. Murata, S.K. Lauvset, R. Wanninkhof, T. Takahashi, N. Kosugi, A.M. Omar, S. van Heuven and J.T. Mathis, 2018. Arctic Ocean CO_2 uptake: an improved multiyear estimate of the air–sea CO_2 flux incorporating chlorophyll a concentrations. Biogeosciences, 15:1643-1661.

Yun, J., S.-J. Jeong, C.-H. Ho, C.-E. Park, H. Park and J. Kim, 2018. Influence of winter precipitation on spring phenology in boreal forests. Global Change Biology, 24:5176-5187.

Zhuang, Y., H. Jin, J. Chen, J. Ren, Y. Zhang, M. Lan, T. Zhang, J. He and J. Tian, 2020. Phytoplankton community structure at subsurface chlorophyll maxima on the western Arctic shelf: Patterns, causes, and ecological importance. Journal of Geophysical Research: Biogeosciences, 125:e2019JG005570.

Zveryaev, I.I. and A.V. Arkhipkin, 2019. Variability and changes of the growing season length and frost days number in Russian sub-Arctic. Geography, Environment, Sustainability, 12:13-22.

7. Impacts of climate change and climate extremes on Arctic livelihoods and communities

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Key findings

- *Climate change is impacting the subsistence harvest-based livelihoods of many small Arctic communities, affecting the quality or supply of traditional food and drinking water, including availability of species to be harvested, and altering transportation access.*
- *Rain-on-snow, extreme snowfall, and variable freeze-thaw cycles have resulted in severe impacts for reindeer herders. In 2020, multiple snowstorms combined with a late spring thaw resulted in high newborn calf mortality and, together with other social stresses related to Covid-19, created severe crises for reindeer herders in Fennoscandia.*
- *Commercial fisheries are expanding in Arctic shelf ecosystems with warmer oceans and less sea ice. This could benefit local economies and job creation, but may also challenge traditional livelihoods and culture and impact vulnerable Arctic ecosystems. Large uncertainties are associated with the effects of ocean acidification, which could potentially counteract increased commercial fishing opportunities. Commercial fishing is currently prohibited by international agreement in the Central Arctic Ocean.*
- *Warmer water is enabling a northward expansion of salmon farming in the ice-free European Arctic. The aquaculture industry brings employment opportunities and positive ripple effects for local economies, but also has environmental and societal costs that need to be considered in marine spatial planning and regulatory measures.*
- *Arctic cruise tourism is increasing and is attracted to the wildlife associated with the marginal ice zone. Although increased cruise tourism brings the potential for local economic development, adverse local impacts have been reported, including impacts on culture, local hunting and fishing, crowding, and revenue largely benefitting foreign-based individuals and corporations.*
- *Permafrost thaw, flooding, and coastal erosion are causing damage to buildings, roads, and other infrastructure, and pose serious financial and health risks to Arctic residents.*
- *Wildfire occurrence near populated regions in North America and Sweden, and throughout Siberia, in the past five years has resulted in significant economic loss from property damage as well as physical and mental health impacts.*
- *Fishing, cruise tourism, and increased oil and gas operations near the marginal ice zone could increase demand on search and rescue operations and may represent a considerable risk for vulnerable ecosystems. The extent of ice cover is important for determining the fate of an Arctic oil spill and research indicates longer term and more severe ecological impacts from oil spills in the Arctic than in other regions.*
- *Understanding and studying integrated socio-ecological systems, including cumulative and cascading impacts, is important not only in terms of research, but also in terms of risk mitigation, hazard response, climate adaptation, and policy response to changing climatic conditions.*

7.1 Introduction

7.1.1 Climate issues of concern to Arctic people

The focus in this chapter is on observed climate-related impacts of concern for Arctic communities and livelihoods. The previous chapters of this assessment have documented accelerating changes in the cryosphere relating to rapid warming of the Arctic. Cascades of observable impacts on infrastructure, transport, and food and water security for Arctic residents are resulting from the decline in sea ice, thawing and collapsing permafrost, and changes in snow patterns and hydrology (Chapter 2; IPCC, 2019). Indigenous hunters and fishers in these areas are reporting climate impacts on wildlife availability, reduced access, and unsafe conditions while travelling across land or on sea ice (Cold et al., 2020). Climate change also results in complex interactions that are changing both marine and terrestrial ecosystems upon which people depend. These changes are evident in sea-surface warming and increased primary production in the Arctic Ocean with implications for carbon storage and fisheries (Lewis et al., 2020), as well as in the greening of the Arctic tundra, that are together affecting wildlife and the livelihoods of subsistence Inuit hunters (Fauchald et al., 2017a). A warmer Arctic also brings new opportunities to Arctic residents, such as hunting and fishing resources, or employment in the new industries that are establishing in the wake of the growing attention to the Arctic.

Abrupt changes resulting from the interactions of multiple drivers or extreme climatic events, disease and insect outbreaks, permafrost thaw, coastal erosion, changes in hydrology and fire become more likely as the climate warms, resulting in unexpected costs and societal challenges (Myers-Smith et al., 2020). Winter abnormalities such as rain-on-snow events and extreme snowfall have serious consequences for access to fodder and for the herding of semi-domesticated reindeer. Likewise, wildfire, which is increasing in intensity and frequency in both boreal forest and Arctic tundra ecosystems, has had a significant impact on livelihoods, economy, infrastructure, and public health in North America, Sweden, and Russia (Kasischke and Turetsky, 2006; Masrur et al., 2018; Porfiriev, 2019b).

The delineation of the Arctic used here is similar to that for the Arctic Human Development Report (AHDR, 2004:17-18), and the assessment covers a broad range of impacts resulting from the decline in sea ice to the dramatic and extensive wildfires that have taken place further south in the boreal forests of the circumpolar region. This chapter is primarily a synthesis of peer-reviewed literature, with boxes illustrating climate issues of concern from a local perspective. The first step was to identify scientific literature relevant to livelihoods and extreme events impacting Arctic societies, using text mining on bibliometric data from web of science (see Appendix 7.1). Thereafter, literature specific to each subsection was compiled and analyzed for assessments of climate impacts on livelihoods and communities in the Arctic. Grey literature was examined when gaps remained for specific topics, including additional literature from Russian scientific databases. A full review of evidence from past reports or literature for each topic is not given here, but rather cases and literature are presented that provide evidence of observed societal impacts happening as a result of the climate-related changes reported in the previous chapters.

7.1.2 Indigenous and non-Indigenous peoples in the Arctic

The Arctic has a population of approximately 7 million people, of whom almost half are located within the Russian Federation. There are large social and cultural differences across populations and regions of the north, making general statements about 'Arctic societies' or 'Arctic cultures' difficult. Similarly, there are regional and cultural differences in climate change impacts and vulnerabilities. The Arctic Human Development Report identified three broad Arctic regions, acknowledging social, cultural, and economic differences within them: the Russian North, the North American North (Alaska and Canada), and northern Fennoscandia (including Greenland, Iceland, and the Faroe Islands). Further distinctions can be made between Indigenous Peoples and other local inhabitants who have lived in the Arctic for centuries, colonial residents, and more recent immigrants to the Arctic (AHDR, 2004).

Roughly 10–15% of the Arctic's inhabitants are Indigenous (Stepien et al., 2013). Different nations refer to such peoples in different ways, including Native in Alaska, and First Nations, Inuit, and Metis in Canada, or 'Indigenous' in both Alaska and Canada. Russian legislation distinguishes between 'indigenous numerically-small peoples' (less than 50,000 individuals) and other non-Russian peoples. Of the 160 peoples residing in its territory, 25% are recognized as Indigenous as per the Russian Federation's classification (IWGIA, 2012, 2018). Based on these classifications, the majority of the population in the Canadian territory of Nunavut and in Greenland is Indigenous, while Indigenous Peoples make up almost 50% of the population in Russia's Chukotka Autonomous Okrug and in Canada's Northwest Territories (Heleniak and Bogoyavlensky, 2014). In Nordic countries, no ethnic registration is allowed, but the Saami population is commonly estimated at approximately 80,000 to 100,000 individuals.

Indigenous Peoples of the Arctic encompass a heterogeneity of cultures, worldviews, traditions, ethnicities, and biophysical environments. This spectrum of identity is often underpinned by a common strong relationship and cultural commitment to the significance of ancestral lands (ADHR, 2004). In many regions, Indigenous Peoples continue to live in small remote settlements with livelihoods and cultural identities closely linked to traditional hunting, fishing, herding, and trapping activities. These livelihoods, along with a close connection to the land, might also be shared by non-Indigenous peoples, particularly in Fennoscandia and the Russian north, and create unique climate impact pathways.

It is important to keep in mind that populations in Fennoscandia and Russia have been ethnically mixed for a long period. Agro-pastoral and fishing communities have been continuously present in the ice-free coastal Arctic since the Pre-Roman Iron Age (~500 BC) (Balascio and Wickler, 2018). In Sápmi, the homeland of the Saami people in northernmost Fennoscandia and the Kola Peninsula of Russia, there are examples of agro-pastoral as well as sea Saami in both the coastal and inland areas. Populations on the Faroe Islands and Iceland descend from Norse Vikings expanding into the North Atlantic and establishing settlements in those regions in the 8th–9th centuries. The Pomor population in northwestern Russia was also of Viking origin, and traded with the communities and Indigenous reindeer herders until 1917. The vast majority of the current Russian Arctic population descends from immigrants that came to work in the expanding industry during the period of the Soviet Union. In contrast, the European colonization of the North American Arctic is more recent, roughly 400 to 500 years ago. Finally, it is important to note that most of the Arctic settlements are small (90.5% have fewer than 5000 inhabitants), whereas the majority of Arctic residents (74.3%) live in relatively few settlements and urban areas with more than 5000 inhabitants (Jungsberg et al., 2019).

Climate-related changes impact people, no matter how they are classified. It has been argued that Indigenous Peoples are disproportionately affected by climate change due to their close traditional connection to the land (Trainor et al., 2007) and coastal areas (Brattland et al., 2019). In Fennoscandia and throughout the Arctic, Indigenous Peoples also eat more traditional food (such as reindeer and moose) than non-Indigenous People, indicating a stronger subsistence culture relating to the land and sea (Petrenya et al., 2018). Nevertheless, Indigenous Peoples in the Arctic are more than the practitioners of what is often called traditional livelihoods and holders of traditional and Indigenous knowledge. They are part of modern society and participants in global processes of adaptation to changing conditions in the Arctic, for example, as reindeer herders, gas extraction workers, miners, or administrators. For this reason, the assessment of climate impacts reported in this chapter aims to reflect the concerns of both Indigenous and non-Indigenous residents.

7.2 Climate-related impacts on Arctic livelihoods and economies

This section focuses on the observed impacts of climate issues of concern on Arctic livelihoods. Livelihoods are defined in the social sciences as the capabilities, material assets, social resources, and activities required to make a living (Chambers and Conway, 1992). Societies engage in livelihood activities on individual, household, community, and regional levels and these activities involve necessary interactions between economic, social, political, and environmental features that influence wellbeing, safety, and security. While acknowledging that other forms of livelihood exist in the Arctic, this section focuses on those livelihoods that are most closely entwined with changing physical and ecological features related to climate change. This section includes discussion of observed climate impacts on wild food harvest, pastoralism, fisheries, aquaculture, tourism, and offshore hydrocarbon exploration.

7.2.1 Impacts on wild food harvest for subsistence and recreation

Subsistence-based hunting, trapping, fishing, and foraging activities (referred to herein as 'harvesting') underpin the livelihoods, food systems, and culture of many small Arctic communities (Larsen et al., 2015) (Table 7.1). For Indigenous Peoples, hunting and fishing underpin identity through the act of harvesting, preparing, and sharing traditional foods, and transferring knowledge across the generations (Pearce et al., 2015; Fauchald et al., 2017b; Dudarev et al., 2019; Ksenofontov et al., 2019; Markkula et al., 2019). While subsistence harvesting is closely associated with Indigenous customs and traditions, non-Indigenous residents also engage in subsistence food harvests. In Fennoscandia, people can generally fish for their own consumption. Harvesting is most common in rural areas, but inhabitants of urban centers also consume wild-caught fish and meat (Brown et al., 2015).

In addition to harvesting wild food for subsistence, local residents throughout the Arctic also harvest these species for recreation and/or maintaining cultural continuity (AMAP, 2018a). Recreational fisheries are important in many Arctic regions, involving "the fishing of aquatic animals that do not constitute the individual's primary resource to meet basic nutritional needs, and are not generally sold or otherwise traded on export, domestic, or black markets" (FAO, 2012) (Table 7.1). Across Fennoscandia, recreational fisheries are one of the most important outdoor leisure activities. Species harvested include salmon, perch, roach, Arctic char, and trout, in the ocean, lakes, and rivers. Although Saami people eat more traditional food such as reindeer, moose, and freshwater fish than the non-Saami (Petrenya et al., 2018), there are no statistics on harvest relating to ethnicity. In Russia, legislation on hunting and fishing ensures the traditional way of life and the traditional economy of the Indigenous Peoples of the North, alongside providing for recreational hunting and fishing. In Alaska, the majority of recreational hunters and fishers are tourists visiting Alaska from other U.S. States, spending roughly USD3.4 billion on trip-related expenses, equipment, and other goods and services in 2011 (US Fish & Wildlife Service, 2014:5). For non-Indigenous populations, there is no formal division between subsistence and recreational harvesting. Climate change can affect food security in subsistence-based livelihoods by changing the access, abundance, and/or nutritional and cultural value of wild food (Hansen et al., 2018). This is reviewed in the following sections.

7.2.1.1 Impacts on transportation for harvest

The period of open transportation access for subsistence activities on frozen rivers, lakes, ocean, and land is decreasing with warming conditions (Golovnev, 2017; Ksenofontov et al., 2017; Brown et al., 2018; Fawcett et al., 2018; Cold et al., 2020). Thinner ice, later freeze-up, earlier ice break-up, blizzards, and unpredictable weather have disrupted access on ice- and snow-based trails and have affected the safety of boats on the open sea, thereby limiting access to hunting and fishing of wild food, as well as sharing and trade with other communities (AMAP, 2018a; Hansen et al., 2018). In northwestern Greenland, hunters report that the period of travel by dogsled on firm sea ice during winter has decreased from five to three months due to changing ice dynamics, making longer journeys impossible (Nuttall, 2020), with similar observations made in eastern Greenland (Laidre et al., 2018). In northeastern Siberia, later and more erratic river-ice freeze-up is hindering winter fishing (Ksenofontov et al., 2017), although evidence for such trends in Siberia is limited (Callaghan et al., 2020). In northern Canada, less favorable snow conditions associated with windier conditions and less snow at key times of the year have reduced access to inland fishing and hunting locations (Ford et al., 2013; Cuerrier et al., 2015; AMAP, 2018a; Bush and Lemmen, 2019). In Alaska, less multiyear sea ice and thinner shorefast ice have made it harder to find ice on which to haul whales out for butchering (Huntington et al., 2016). Permafrost degradation and increased rain in summer and autumn have also reduced accessibility for all-terrain vehicles (ATVs) in Nunavut and affected road infrastructure in Chukotka (AMAP, 2017a; Bengtson and Nikitina, 2017). Remote communities and those with limited alternative transportation options have been identified to be at higher risk of compromised access due to climate change impacts (Cold et al., 2020; Pearce et al., 2020). In the Russian North, for example, many remote settlements are only connected to the outside world by ice roads in winter, and accessibility could decline by 13% in the future (Bengtson and Nikitina, 2017).

A longer period of ice-free open water is extending the times during which boats can be used for harvesting (Ford et al., 2019), although there is inconclusive evidence on the implications for transport access. There are large regional gaps in understanding, and implications vary locally depending on changes in water level, erosion and sedimentation processes on lakes and rivers (Ksenofontov et al., 2017; Cold et al., 2020; Proverbs et al., 2020), the speed at which ice decays and freezes (Cooley et al., 2020), weather conditions such as wind and

Table 7.1 Importance of subsistence harvesting and recreational fisheries in Arctic regions.

Region	Comments	Source
Alaska	75–98% of households in rural areas (legally, areas outside non-subsistence areas) harvest fish and 48–70% harvest wildlife for subsistence uses. 15,422 t of wild foods are harvested annually by residents of rural areas, and 5171 t by urban residents in all non-commercial fisheries and hunts. Annual wild food harvest is about 125 kg/y per capita for residents of rural areas. The annual rural subsistence harvest contains 176% of the protein requirements of the rural population and 25% of the caloric requirements. Urban wild food harvests contain 12% of the protein requirements and 2% of the caloric requirements.	Alaska Department of Fish and Game, 2019
Northern Canada	65% of Inuit between the ages 25 to 54 years in Inuit Nunangat hunt, fish or trap, while 48% gather wild plants. 94.7% of Inuit aged 25 to 54 years who participate in hunting, fishing, or trapping report doing so for own or family use.	Arriagada and Bleakney, 2019
	56% of Inuit aged 15 years or older participate in hunting, fishing or trapping. 47% of First Nations people living off reserve report having engaged in harvesting activities in the past 12 months, 85% either for their own or family use.	Kumar et al., 2019
	36.3% of the total population of the NWT (Indigenous and non-Indigenous) engage in traditional hunting and fishing activities. 42.7% of all Indigenous People in the NWT over 15 years of age engage in traditional hunting and fishing activities.	Government of the NWT, 2018
Greenland	67% of the population living in settlements (excluding towns) indicating wage income as the main income source engage in small-scale fishing and/or hunting activities. 80% of settlement households have members participating in hunting and/or fishing for the consumption of the household as a necessary supplement to wage incomes.	Poppel, 2015
Northern Norway (Finnmark, Troms, Nordland)	In 2017, 58% of people had fished. Coastal fisheries prevail, but are not reported, except for the sea catch of salmon and trout (121 t). In 2019, 145 t of fish were caught in recreational fisheries in rivers (68% salmon) and 48 t caught and released (90% salmon). In 2018/19, 28,200 (5.1%) of people registered as recreational hunters. Most reported hunting grouse (39%, 65,900 harvested) followed by moose (31%, 6542 felled).	Statistics Norway www.ssb.no
Northern Sweden (Västerbotten, Norrbotten)	In 2019, 131,000 (25.2%) people participated in recreational fishing at the coast and 82,000 (16%) inland. In 2017, 7.3% of the population participated in hunting. 18,729 moose were felled and 18,698 grouse were caught.	Statistics Sweden www.scb.se Swedish Environmental Protection Agency
Finnish Lapland	In 2008, 54% of households and 44% of the population participated in recreational fisheries. 2481 fish were caught, mostly perch and pike. In 2008, 34,471 (19%) people registered as recreational hunters of which 2/3 actively participated. 58% of animals hunted were fur animals and 28% deer species (including moose).	Natural Resources Institute Finland https://stat.luke.fi/en/
Russian Federation (Chukotka)	191.5 kg of annual traditional foods consumed by a native resident in three study sites; 62% from fish and marine mammals.	Dudarev et al., 2019
	In 2017, the percentage of households (Indigenous/non-Indigenous) participating in subsistence activity in a typical village was as follows: net fishery (100/83.3), seal hunting (16.7/14.3), mushroom picking (83.3/85.7), seabird egg gathering (25.0/0), angling fishery (91.7/85.7), bird hunting (41.7/42.9), berries (91.7/85.7).	Klokov, 2019
Russian Federation (Sakha Republic)	In 2008, 49.9 kg/y of traditional foods were harvested per capita, and 358 kg/y were consumed on average per household member.	Larsen et al., 2015

visibility (Huntington et al., 2017), interannual variability (Ksenofontov et al., 2017; Brown et al., 2018), and access to boating equipment (Ford et al., 2015). In Alaskan coastal communities, for example, the number of days when wind speeds exceed the 6 m/s criterion for safe boating has offset the increased boating potential afforded by more open water (Rolph et al., 2018).

Increasing rates of search and rescue incidents and accidents associated with the use of unmaintained trails have been documented in some regions with warming conditions (Fleischer et al., 2014; Durkalec et al., 2015; Clark et al., 2016a; Ksenofontov et al., 2017), although there is inconclusive evidence on how safety is being affected by climate change. In Canada's Nunavut territory, ice conditions have been shown to be predictive of the probability of a search and rescue taking place on a given day. Rates of search and rescue have increased over time as ice conditions have changed, although most incidents are related to mechanical breakdown or running out of fuel (Clark et al., 2016a).

Few studies have examined quantitative trends in search and rescue incidents or accidents, due to limited data availability resulting from a lack of research from northern Russia (Callaghan et al., 2019). Human factors related to knowledge, skills, and risk behavior have an important role in determining climate change impacts on safety (Ford et al., 2019), with younger generations identified as being at higher risk (Clark et al., 2016b, 2018; Young et al., 2016).

7.2.1.2 Impacts on the availability of species harvested

Changing sea-ice conditions are affecting species composition, production and ecosystem structure and function (Post et al., 2013, 2019; Laidre et al., 2015). Ice-dependent species identified to be at risk include walrus, various seabirds, and different species of seal (Krupnik, 2018), while ice retreat has opened new habitat for cetaceans, with more sightings of killer whales noted in some regions (Stafford, 2019; Lefort et al., 2020). In Alaska, bowhead whales have been observed to arrive earlier in spring and leave later in autumn, along with increased population numbers (Huntington et al., 2016). There is well-developed literature on polar bears and climate change, with concerns that current loss of habitat is reducing abundance and reproductive survival (Pagano et al., 2018; Laidre et al., 2020), although not all populations are equally at risk (Rode et al., 2015; Krupnik, 2018; Regehr et al., 2018), with the health of some stocks disputed between scientists and communities (Laforest et al., 2018).

In terrestrial environments, changing precipitation, snow regimes, and temperatures have been observed to alter the health, abundance, and migration timing of wildlife species (Post et al., 2013, 2019). Many caribou populations have been documented to be declining, although in some regions the body condition of caribou has improved (such as the Porcupine herd spanning Alaska and Canada; Gagnon et al., 2020), reflecting the complex interaction of climatic and ecological factors that are not well understood (Fauchald et al., 2017a; Krupnik, 2018; Parlee et al., 2018; Hansen et al., 2019). Studies of wild reindeer ecology in Taimyr (Makeev et al., 2014; Mikhailov and Kolpaschikov, 2017) and Yakutia revealed that climate warming had an adverse impact on tundra reindeer populations, leading to changes in migration routes and a significant decrease in productivity (Safronov, 2016). However, it was not possible to assess the impact of climate change on reindeer population numbers, since the relatively weak negative impact of climate change has been superseded by more powerful negative anthropogenic impacts, such as poaching and over-harvesting. Warming has had a positive effect on populations of moose and sable, which are important to Indigenous hunting and trapping in the northern taiga in Yakutia (Safronov, 2016).

Muskox are distributed across the circumpolar North, and an analysis of survey data for the 38 regions for which there were sufficient data to analyze trends indicated that populations are increasing in 23 regions (representing 36.2% of present abundance), stable in nine, and decreasing in six (Cuyler et al., 2020). Two of the declining populations were once the largest endemic populations in the world (Banks and East Victoria islands, Canada), with impacts documented on community food systems (Tomaselli et al., 2018). The role of climate change in population declines (e.g., extreme events, rain-on-snow, vegetation change, disease) is not fully understood and is compounded by other anthropogenic stressors, such as industrial development (Cuyler et al., 2020).

Greening of the tundra and higher tundra productivity are changing the wildlife species available to hunters (Wheeler et al., 2018). Range expansion for tall shrubs (>1 m) provides the necessary winter fodder for moose populations to establish on the tundra (Tape et al., 2016, 2018). Small game species of high cultural importance to hunters in Fennoscandia, such as willow grouse, are declining due to increased nest predation in the more productive vegetation (Ims et al., 2019), but also from more frequent snow-free springs and autumns (Melin et al., 2020).

Research on climate impacts on recreational fisheries is sparse, but community observations in some inland regions note declines in the amount of fish available for human consumption, linked to changing river hydrology (lower water levels) and changing spawning behavior (Baldwin et al., 2018; Ksenofontov et al., 2019). In northern Siberia, changes in river hydrology and temperature have been observed to hinder fishing because fish tend to move deeper to the bottom of a river where the water is colder, while some fishing lakes have disappeared entirely due to thawing of the underlying permafrost (Ksenofontov et al., 2017; Sohns et al., 2019a).

7.2.1.3 Impacts on food safety, security, and quality

The quality of traditional foods is sensitive to climatic conditions, with studies documenting local observations of changing food quality due to rising temperatures and changing precipitation (Hansen et al., 2018). The Inuit Circumpolar Council has put forward a framework for a holistic understanding and assessment of food security in the Arctic (ICC, 2015). Communities in Alaska (Herman-Mercer et al., 2020), northern Canada (Cuerrier et al., 2015; Bunce et al., 2016; Anderson et al., 2018), and Finland (Markkula et al., 2019) have reported changes concerning berries, including earlier ripening, reduced abundance, more year-to-year variability, and the presence of smaller, seedier berries, with variation between community and region. Decreased health of wildlife, indicated by smaller size and physical deformities, and a change in taste and other sensory qualities have been reported for populations in Nunavut (Hansen et al., 2018). Indigenous hunters and fishers have reported thinner seals and an increased prevalence of worm infestation in fish and marine mammals (Proulx et al., 2002; Ksenofontov et al., 2017; Baldwin et al., 2018; Proverbs et al., 2020).

Food security and wellbeing of local households are also under threat due to permafrost thaw and erosion (Vorontsova, 2017; AMAP, 2018a). Most families rely on food cellars cut into the permafrost to store subsistence food, thus reducing their dependence on food imported from outside the region (Agafonova et al., 2019). For example, in the villages of Alaska's North Slope, a single bowhead whale could feed a community throughout the year provided that its meat and blubber are properly stored in ice cellars. As permafrost thaws, ice cellars flood or the higher temperatures ruin food storage (Vorontsova, 2017; AMAP, 2017b). However, the monitoring of air temperature in several ice cellars from 2005 to 2015 in Utqiagvik (Barrow), Alaska, documented little difference in internal temperature over this period (Nyland et al., 2017). Food safety associated with the consumption of traditional foods has been identified as a concern in rural communities with observed climate change impacts (Berner et al., 2016; Kipp et al., 2019), which have the potential to increase the risk, incidence, and geographic spread of food- and waterborne diseases (Dobson et al., 2015; AMAP, 2018a; Waits et al., 2018; Omazic et al., 2019). Impacts on ecosystems and society from harmful algal blooms have been observed in the Arctic. As Figure 7.1 shows, paralytic shellfish poisoning is now observed in Arctic regions (Anderson et al., 2018). In Alaska,

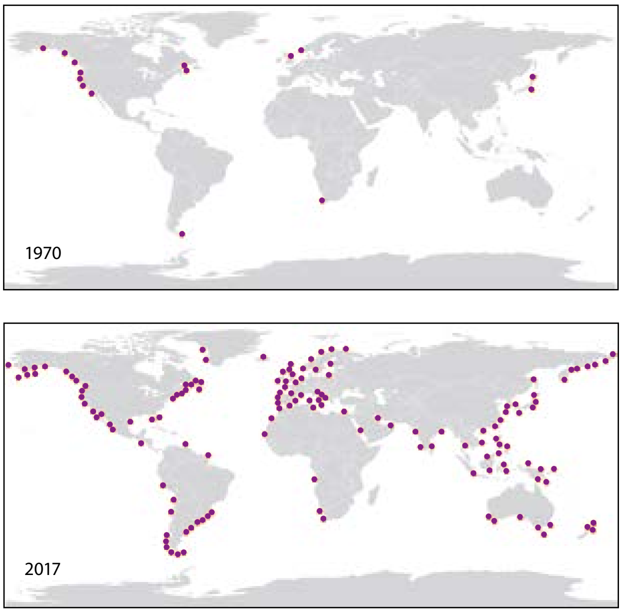

Figure 7.1 Comparison of coastal areas with paralytic shellfish poisoning (PSP) toxins in 2017 and 1970. U.S. National Office for Harmful Algal Blooms, Woods Hole Oceanographic Institution.

algal toxins have been found in marine mammals harvested for subsistence including bowhead whales, many species of seal, and walrus (Lefebvre et al., 2016).

Climate change can also influence the transport pathways of contaminants influencing food and water security. Water safety is closely linked to the safety of traditional foods, given the cultural preferences and practice of gathering untreated drinking water from streams, rivers, and lakes on harvesting trips (Sohns et al., 2019b). Many of the remote Arctic communities are dependent on surface water for their drinking supplies and have basic water treatment systems that are easily overwhelmed by extreme weather events (Harper et al., 2020). Periods of heavy rainfall and rapid snowmelt can potentially transport pathogens, contaminate drinking water resources (Harper et al., 2011), and alter the transport of contaminants (Berner et al., 2016; Dudarev et al., 2019). Snowmelt may transport mercury into freshwater ecosystems, and there is some indication of stronger bioaccumulation of contaminants in the food chain as a result of climate change (Hansen et al., 2018). Studies on food safety and security have a high level of agreement that climate change has the potential to increase risk and may already be doing so in some regions, although the quality and quantity of evidence documenting current impacts is low.

Research in non-Indigenous rural communities in Alaska suggests the potential for innovative partnerships between food pantries and local food harvest as a way to enhance food security (Burke et al., 2018). Research in Nunavut suggests local greenhouse food production may be feasible with the direct involvement of local residents (Lamalice et al., 2018). While changing climatic conditions impact wild food availability and security, other non-climatic conditions such as remoteness, high costs of fuel, hunter skill, socio-cultural factors, and political factors also affect food security and access to wild foods (Beaumier et al., 2015; Loring and Gerlach, 2015; AMAP, 2018a; Huntington et al., 2019). In Fennoscandia, food security is achieved through a high level of trade dependency (>50%) and a low level of food sovereignty (Nilsson, 2020), which makes the system less vulnerable to Arctic climate fluctuations but more vulnerable to food prices and socio-economic impacts on trade.

7.2.1.4 Summary

Impacts on wild food harvest for subsistence and recreation include that warmer winters have altered access to wild food for subsistence harvest in North America, and more search and rescue operations indicate that travelling is becoming less safe. In addition, declining availability of wildlife species and changes in migration timing have been observed across the circumpolar North, with implications for harvesting and recreational fishing. Furthermore, warmer winters, heavy rainfall, and rapid snowmelt are impacting the quality and storage of wild food in ice cellars and access to clean water.

7.2.2 Impacts on pastoralism

For food production as well as Arctic cultures, pastoralism remains a crucial livelihood in those areas where people herd domesticated reindeer. Traditionally, *Rangifer tarandus* has been a keystone animal for human subsistence in the Arctic – in its wild form known as caribou in North America, and in both wild and domestic forms as reindeer in Eurasia. Although far less is known about this, people have also kept specific Arctic breeds of cattle, horses, and sheep in a multi-species pastoral livelihood. Some of these specific Arctic pastoral species have experienced a revival, such as the Arctic Yakutian Horse and the Lapland cow. There are some remaining herds of semi-domesticated reindeer in Canada, Alaska, Iceland, and Greenland that were originally introduced by Saami reindeer herders. However, this section focuses on reindeer pastoralism in Fennoscandia and Russia as this is the major Saami livelihood in this region.

Indigenous People developed large-scale reindeer pastoralism for meat production in the 17th century (Krupnik, 1993; Golovnev, 2000), and this has continued to be an important livelihood for most Indigenous Peoples in Eurasia. The world population of domestic reindeer is roughly two million, providing a livelihood and identity-marker for 20 Indigenous groups in the Eurasian Arctic (Uboni et al., 2016). Approximately 10,000 herders depend directly on reindeer in northwestern Europe, and at least 30,000 in Russia. Most domestic reindeer in the Arctic are owned by the Nenets (one million) and Saami (600,000) people, with the former continuing to practice a nomadic form of pastoralism (Stammler, 2005; Golovnev, 2017; Stammler and Ivanova, 2020). The Saami have settled in villages and most move between seasonal pastures, but as borders have closed, migration patterns have changed (Kelman and Næss, 2019). Increasingly, Saami herders also use supplementary feeding and fences to manage their herds (Mazzullo, 2010; Riseth et al., 2016).

7.2.2.1 Observed impacts of warming, changing patterns of snowfall, and rain-on-snow events

Changing precipitation, snow regimes, and rising temperatures have been observed to alter the health, abundance, and timing of reindeer migration (Forbes et al., 2009; Bartsch et al., 2010; Golovnev, 2017; Stammler and Ivanova, 2020). The most significant adverse impact is due to ice crusts on pastures forming as a result of rain-on-snow events and heavy snowfall. While elders remember and recount such events as long as reindeer herding has existed, recently their frequency has been observed to increase on the Yamal Peninsula in northwestern Siberia. Rain-on-snow events used to happen once per generation, but happened almost every year in the period 2014–2019 (Golovnev, 2017; Stammler and Ivanova, 2020). The biggest of these events, which took place in winter 2013/2014, resulted in the death of 60,000 reindeer (Forbes et al., 2016). The impacts of warmer winters and fewer frost days in northern Finland were found to differ depending on geography. While some reindeer herders experienced reduced access to ground lichens due to deep snow and ice formation, others experienced increased access to fodder due to a thinner snow layer and shorter cold season (Rasmus et al., 2020a).

Extreme snowfall in spring, when animals are experiencing end of winter food shortages (Eidlitz, 1969; Behnke et al., 2011), has been critical for reindeer populations in all three Fennoscandian countries. Spring 2020 was extreme with an extraordinarily thick snow cover combined with a late spring. As a result, migration was disrupted and calves were born on top of the snow cover, leading to approximately 50% of calves not surviving their first days of life (Doj, 2020). Together with trade restrictions due to Covid-19, the extreme snowfall caused a critical situation for many reindeer herders (Doj, 2020). In northern Norway, some herders experienced ice crust on the pastures prior to blizzards, resulting in multiple layers of hard snow (Norwegian Agriculture Agency, 2020). The reindeer herds dispersed and the Covid-19 situation made herding and transport even more challenging by limiting the use of extra labor. The extreme snowfall also led to similar crises for the Finnish reindeer herders (Kumpula et al., 2020).

In northwestern Europe, the adverse impacts related to climate are usually mitigated by additional feeding – hay and industrially produced fodder. Due to the reorganization of reindeer grazing in Finland to occur within fenced areas (Mazzullo, 2010), supplementary feeding is becoming the norm rather than an emergency measure (Turunen and Vuojala-Magga, 2014; Horstkotte et al., 2020). In Norway, the extreme snow winter of 2020 was mitigated by crisis funds of NOK 43 million from the government for transporting fodder to the herds (Norwegian Agriculture Agency, 2020). Rain-on-snow events and deep snow have had an even greater impact in Russia, where reindeer have not been fed with supplementary fodder since the end of the Soviet era. In Yamal, Russia, herders received compensation for reindeer losses during the big rain-on-snow event in 2014. But this was a one-off measure, with no additional support given for subsequent crises. This has forced some reindeer herders to leave herding and settle in villages (Stammler and Ivanova, 2020).

Deep snow and ice crusts also impact horse and cattle pastoralism as practiced in Yakutia, although horses are heavier than reindeer and can break through thicker ice crusts with their weight, and their legs are longer. Nonetheless, increased precipitation has led to horse losses in areas such as Yakutia, where like reindeer, horses graze under the snow (Crate et al., 2008; Stammler, 2010; Takakura, 2016).

7.2.2.2 Impacts on pastoralism in snow-free seasons

A general trend towards warmer springs and earlier green-up of pastures can have a positive impact on reindeer populations (Tveraa et al., 2013; Rasmus et al., 2020a), as fresh available forage is critical for calf growth and milk-producing dams. However, some herders experience higher risk due to early springs, such as through strong flooding and increased predation (Rasmus et al., 2020a). Benefits gained from early green-up could also be counteracted by the adverse impacts of dryer summers and warmer autumns on mushrooms (Paoli et al., 2020), mold on vegetation, and the reindeer rut may be delayed or unsynchronized due to warming autumns (Rasmus et al., 2020a).

Changes in fodder quality in summer are unclear. Pasture greening, which indicates increased above-ground biomass, is one of the key findings in previous Intergovernmental Panel on Climate Change (IPCC) assessment reports (Meredith et al., 2019), but range expansion of tall shrubs into the tundra does not necessarily translate into higher fodder quality for reindeer (Fauchald et al., 2017a; Forbes et al., 2020; Myers-Smith et al., 2020). Turunen et al. (2009) examined how climate change could influence the availability and quality of reindeer forage plants. They found that a warmer climate in northern Fennoscandia would increase the height and cover of deciduous shrubs and graminoids at the expense of mosses and lichens, but whereas the quality of reindeer forage plants has been found to increase with warmer soil temperature on sites with rich bedrock and soils, the impact on the nutrient-poor soils that dominate northern Fennoscandia is not known. Plus, in some locations, complex interactions have resulted in a sudden drop in productivity due to extreme weather events, disease, herbivore outbreaks, wildfire, flooding, or erosion (Myers-Smith et al., 2020).

The higher precipitation and heavy rainfall observed by reindeer herders in Fennoscandia could be beneficial for vegetation growth and mushroom abundance, but floods and wet ground could have adverse implications for herding (Rasmus et al., 2020a). The seasonality of summer rains is particularly relevant for hay-making: summers without significant rain-free periods make hay collection harder and prevent the hay from drying, meaning that reindeer, horses, sheep, or cattle normally fed with Arctic hay must get fodder from elsewhere or starve (Takakura, 2015; Crate et al., 2017).

In the thermokarst landscapes of Yakutia, thawing permafrost means more swamps, which can lead to dying forests (Takakura, 2016; Crate et al., 2017). The hummocks featuring in changing permafrost landscapes inhibit smooth grazing and prevent hay making, because grass cannot be cut with tools or tractors in hummocky terrain (Takakura, 2016, 2018). The phenomenon of lake draining in Siberia may or may not be related to thawing permafrost, but it does affect the land/water balance in grazing areas (Forbes, 2013). Reindeer graze keenly on the fresh grass now growing in former lakes.

7.2.2.3 Impacts on access to pastures and herding

Many reindeer pastoralists report higher year-to-year variability in weather conditions (Rasmus et al., 2020a). Changes in river freeze and thaw cycles make it harder to plan seasonal migration routes, where people and reindeer cross rivers either frozen or open. Flooding due to ice jamming in spring is particularly challenging where the big rivers flow northward to the Arctic Ocean, which is the case for all major streams in Siberia. This has led to flood-induced migration (Fujiwara, 2018), and resulted in the deaths of pastoral animals (Stammler-Gossmann, 2012; Crate, 2018; Takakura, 2018; Takakura et al., 2018). However, flooding trends indicate that ice-jamming impacts will decrease, and Chapter 4 shows no documentation for increased ice-jamming events in the Arctic. In those places where slaughtering relies on natural freezing of the meat, unstable temperatures with cyclical freezing and thawing can result in lower meat quality and thus a lower annual income for herders.

7.2.2.4 Cumulative impacts affecting climate change adaptation

It is unclear whether changes related to climate or those related to industrialization of the Arctic have a greater impact on reindeer pastoralism as a livelihood (Rees et al., 2008; Forbes et al., 2009; Lavrillier, 2013; Golovnev, 2017; Krupnik, 2018; Klokov and Mikhailov 2019). Most likely, it is the cumulative impact of both that poses the greatest challenge to this livelihood (Hovelsrud et al., 2010; Stammler and Ivanova, 2020). The growing loss of land to other uses and barriers on migratory routes hindering seasonal access to different pastures is affecting the opportunities to adapt to adverse weather conditions and the presence of predators by switching pastures (Axelsson-Linkowski et al., 2020; Hausner et al., 2020). In many forested areas, the traditional alternative of feeding on tree lichens at times of deep snow is no longer possible either because the forest was clear-cut (Mazzullo, 2016; Turunen et al., 2020) or because pastures are encroached by extractive industries (Strauss and Mazzullo, 2014; Pristupa et al., 2018; Chambourg, 2019).

In boreal forests, the most significant losses in recent decades are due to predators. The number of wolves in the forests has dramatically increased, such that many reindeer holders lost all or almost all of their herds. This is a particular issue in the forests of southern Yakutia, Amur and Baikal regions (Brandišauskas, 2016, 2020; Lavrillier and Gabyshev, 2018). Whether the increased wolf population is due to the changing climate is debated in the literature (Lavrillier, 2013). The wolf population has also increased in northern Europe (Rasmus et al., 2020b; Skogen and Krange, 2020), but the scale of the problem is much less than in Russia.

7.2.2.5 Summary

The general trend of earlier green-up and warmer spring temperatures can have a positive impact on reindeer production. Contrary to these trends, reindeer herders in Fennoscandia experienced a severe crisis in 2020 when multiple snowstorms in conjunction with a late spring resulted in high calf mortality, combined with social stresses related to Covid-19. The formation of ice crusts on winter pastures has resulted in massive loss of reindeer in Russia. Summer precipitation and heavy rainfall have mixed impacts on reindeer production, with herders experiencing both positive and negative impacts. Cumulative impacts including climate impacts on wildfire, forage, and predators in conjunction with industrialization pose significant challenges to reindeer pastoralism.

7.2.3 Impacts on fisheries

7.2.3.1 Range expansion

Together with rising temperatures, a northward range extension of temperate and subarctic fish species has been observed in both the Pacific Arctic (Stevenson and Lauth, 2019) and the Atlantic Arctic (Fossheim et al., 2015; Haug et al., 2017; Andrews et al., 2019). Driven by climate change, this is already transforming the Arctic marine ecosystems (Huntington et al., 2020). In addition, reduced sea-ice cover has been accompanied by an increase in net primary production, earlier onset of the productive season (Kahru et al., 2016), and more intense spring blooms which have spread northward into the Central Arctic Ocean (Renaut et al., 2018). The subsequent reorganization of the marine ecosystems has resulted in an increase in the harvestable resources (e.g., AMAP, 2017a; Meredith et al., 2019). Combined, these observations support model projections that warmer Arctic waters will facilitate species expansions and enhance primary production, thus supporting a larger harvestable fish biomass (e.g., Cheung et al., 2016; Eide, 2017; Haug et al., 2017). Nevertheless, ocean acidification combined with complex ecosystem interactions, including changes in the flow of energy between different parts of the ecosystem and mismatch between predators and prey during critical life stages, could potentially lock the system into a less productive state (e.g., AMAP, 2018b; Hunt et al., 2011). Further connectivity between the Arctic and peripheral oceans is outlined in Chapter 6.

7.2.3.2 Ocean acidification

Ocean acidification is a process whereby increased uptake of atmospheric carbon dioxide (CO_2) by the ocean makes it more acidic (Orr et al., 2005). Acidification reduces the concentration of carbonate ions required by calcifying organisms including shell-building plankton, shellfish, and cold-water corals to produce calcium carbonate shells and skeletons. When the water becomes undersaturated with respect to calcium carbonate (either as calcite or aragonite), the water becomes 'corrosive', making it difficult for animals to form proper shells and skeletons. Because CO_2 dissolves more easily in colder water, Arctic waters are more affected by ocean acidification than waters further south. Aragonite undersaturation in Arctic surface waters is already occurring (Yamamoto-Kawai et al., 2009; Qi et al. 2017) and is projected to become widespread as atmospheric CO_2 levels continue to increase during the 21st century (Steinacher et al., 2009; AMAP, 2018b; Terhaar et al., 2020). There is strong evidence from experimental and field studies that ocean acidification can have an adverse impact on Arctic marine life, but strong ecosystem effects have not yet been observed (AMAP, 2018b). However, studies also show that effects vary between species, life stages, locations, and seasons (AMAP, 2018b), making it difficult to predict the outcome of ocean acidification for ecosystems and people. Moreover, effects on key components of the ecosystem, such as the aragonitic pteropod *Limacina helicina* (Comeau et al., 2010), are likely to propagate through the food web generating complex indirect effects.

7.2.3.3 Commercial fisheries

Models projecting ocean acidification impacts on Arctic fisheries have incorporated the impact from warming and the direct impact from ocean acidification on the life stages of target species (Lam et al., 2016a; Hänsel et al., 2020). Lam et al. (2016b) concluded that fishery revenue in the Arctic is likely to increase under global warming, but that ocean acidification has the potential to reduce this increase. Frommel et al. (2012) showed detrimental impacts from ocean acidification on the development of early life-stages of Atlantic cod (*Gadus morhua*). Hänsel et al. (2020) modeled the combined impacts of fishing, warming, and ocean acidification on the North-East Arctic cod fishery. This stock has been a cornerstone for communities in northern Norway for over 1000 years and currently supports a large commercial fishery. Hänsel et al. (2020) also found that near-term climate change is likely to benefit the fishery, but that under the likely levels of future warming and acidification, the fishery is at risk of collapse by the end of the 21st century, despite the best adaptation effort in terms of reduced fishing pressure.

In the Barents Sea, warmer waters have been associated with a northward range expansion of subarctic species and a retraction of Arctic fish communities (Fossheim et al., 2015). These include changes in the functional traits in the fish community whereby the Arctic community, dominated by small, benthic, slow-growing species such as sculpins, is replaced by a boreal community dominated by large, fast-growing species such as Atlantic cod (Frainer et al., 2017). Accordingly, the change involves a transition from a low-consumption benthic-dominated food web based on ice algae production to a high-consumption system based on pelagic phytoplankton production (Frainer et al., 2017). Although the observed changes are likely to sustain an increased fishery yield in the northern Barents Sea, an emerging fishing industry might have an adverse impact on the vulnerable High Arctic ecosystem by disturbing the benthic habitat and removing endemic Arctic species in by-catch (Christiansen et al., 2014; Jørgensen et al., 2019).

The observed changes in the Barents Sea are partly reflected by recent changes in the Pacific Arctic (Duffy-Anderson et al., 2019; Huntington et al., 2020). The inflow of nutrient-rich water to the shallow and seasonally ice-covered northern Bering and Chukchi seas supports a rich benthic-dominated food web, including abundant benthic-feeding eiders and marine mammals important for Indigenous subsistence (Grebmeier et al., 2006, 2015). In the past, ice cover and cold environments have prevented a northward migration of subarctic groundfish (e.g., Alaska or walleye pollock, Pacific cod) that dominate the rich fisheries of the southeastern Bering Sea (Stabeno et al., 2012; Stevenson and Lauth, 2019). Recent warming (2017–2019) has been accompanied by large changes in the ecosystem, suggesting that an ecosystem transformation may be under way (Huntington et al., 2020). This includes a reduction in benthic production and a range expansion of subarctic fish (Huntington et al., 2020). This could suggest a shift from a benthic-dominated food web to a pelagic food web, with a potential increase in fish biomass available for industrial fisheries (e.g., Hunt et al., 2002). However, warming is also associated with a shift in the zooplankton prey base: from large lipid-rich crustaceans to smaller lipid-poor forms, with potential negative effects on the growth and survival of juvenile fish (Hunt et al., 2011; Stabeno et al., 2012). The biomass of Pacific cod and Alaska pollock occurring in the northern Bering Sea is currently increasing, and is already being fished by midwater trawlers and longliners. An ecosystem shift would alter the basis for traditional native hunting and fishing, and coastal communities are likely to face difficult choices between increased economic opportunities from commercial fishing and traditional subsistence activities (Huntington et al., 2020).

The difference between subarctic and High Arctic ecosystems with respect to fishery yield is evident from data on fishery catch and fishing activity (Figure 7.2). Some of the world's major fisheries are found in the subarctic seas bordering the Arctic Ocean (Hollowed and Sundby, 2014; Hoel, 2018; see also Table 7.2). Among the most important stocks are Alaska pollock, Atlantic and Pacific cod, Atlantic and Pacific herring, Pacific salmon and capelin. Several of these large commercial stocks, most notably in the Atlantic, were severely overfished in periods between 1960 to 2000, resulting in stock collapses and fluctuations (Hamre, 1994; Hjermann et al., 2004; Petrie et al., 2009; Essington et al., 2015; Frank et al., 2016). Since then, improved management regimes have helped rebuild stocks, and many are currently managed within sustainable limits (Worm et al., 2009; Gullestad et al., 2014; Costello et al., 2016). Although a range of management tools is now in place, some species (e.g., Atlantic cod) are recovering very slowly, which calls for a precautionary approach and ecosystem-based management when managing fisheries (Crépin et al., 2017; Gullestad et al., 2017). Important management actions include stock assessments and implementation of total allowable catch (TAC) limits to maximize the sustainable long-term yield (AMAP, 2017a). The large Arctic fish stocks are often widely distributed and migratory, and cross the Exclusive Economic Zone (EEZ) boundaries of more than one coastal state, highlighting the importance of international cooperation to achieve sustainable stock management (Troell et al., 2017; Gullestad et al., 2020). Several bilateral or multilateral agreements have been negotiated to manage and decide TACs for transboundary and straddling stocks in the North Atlantic (Gullestad et al., 2020). Because the migration and distribution patterns of these stocks are affected by climate and fluctuations in stock size, these agreements are likely to be increasingly challenged under a warmer climate (Troell et al., 2017; Gullestad et al., 2020). In addition to TACs, Arctic fisheries and environmental management authorities utilize a suite of tools to mitigate adverse ecosystem impacts from fisheries, including gear restrictions, discard bans, time/area closures, by-catch quotas and marine protected areas (e.g., Dunn et al., 2011; Gullestad et al., 2017; Nilsson et al., 2019).

Individual transferrable quotas (ITQs) and catch shares have been introduced to distribute TACs among fishers and as a means to end the 'race to fish' (Eythórsson, 1996; Costello et al., 2008; Birkenbach et al., 2017). Although ITQs may be important to achieve environmental and economic sustainability, the privatization of the resource could entail a range of adverse societal consequences (Eythórsson, 1996; Standal and Asche, 2018). Importantly, the specific allocation of quotas among fishers and communities is important to secure local access to

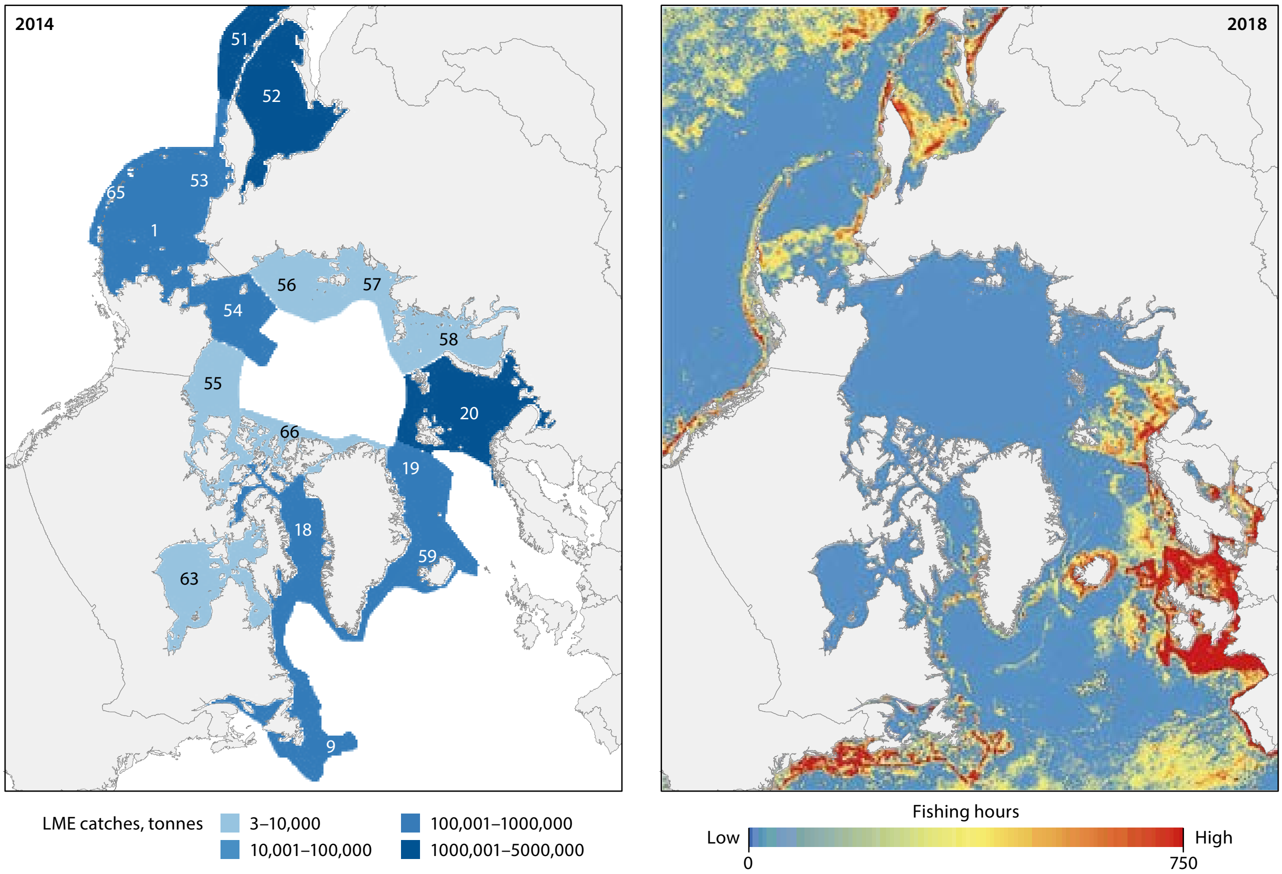

Figure 7.2 Total catches in tonnes from 17 Arctic Large Marine Ecosystems (LMEs) in 2014 (*left*). LME number is indicated, and the corresponding LME name is found in Table 7.2. The dataset was published by the Sea Around Us project (Zeller and Pauly, 2016) and downloaded from www.seaaroundus.org. Total fishing hours in 0.1×0.1 degree pixels in 2018 (*right*). Data are from Global Fishing Watch (https://globalfishingwatch.org) and hours of fishing are derived from AIS (Automatic Identification System) data. Methodology is as described by Kroodsma et al. (2018).

Table 7.2 Catch statistics for 17 Large Marine Ecosystems (LMEs) in the Arctic, grouped according to six regions. Numbers in the table relate to the area designations in Figure 7.2. Catch sizes are for 2014 and are given for the five most important fishery target species. The dataset was published by the Sea Around Us project (Zeller and Pauly, 2016) and downloaded from www.seaaroundus.org.

Region Large Marine Ecosystem	Fishery	Catch, 1000 tonnes
High Arctic	Sardine cisco	2
55-Beaufort Sea, 63-Hudson Bay Complex, 66-Canadian High Arctic - North Greenland, 58-Kara Sea, 57-Laptev Sea, 56-East Siberian Sea	Arctic char	1
	Arctic cisco	1
	Broad whitefish	1
	Whitefishes	1
	Other	3
	Total	8
Barents Sea	Atlantic cod	678
20-Barents Sea	Haddock	163
	Atlantic herring	140
	Capelin	88
	Saithe	81
	Other	149
	Total	1298
Bering Sea	Alaska pollock	1322
53-West Bering Sea, 1-East Bering Sea, 54-Northern Bering - Chukchi Seas, 65-Aleutian Islands	Pacific cod	255
	Pink salmon	197
	Yellowfin sole	124
	Pacific herring	88
	Other	886
	Total	2871
Greenland Sea and Iceland	Atlantic cod	211
19-Greenland Sea, 59-Iceland Shelf and Sea	Atlantic mackerel	148
	Capelin	140
	Golden redfish	52
	Saithe	48
	Other	488
	Total	1088
Western Arctic Atlantic	Northern prawn	192
18-Canadian Eastern Arctic - West Greenland, 9-Newfoundland - Labrador Shelf	Snow crab	70
	Atlantic herring	66
	Atlantic cod	63
	Greenland halibut	59
	Other	192
	Total	641
Sea of Okhotsk	Alaska pollock	2876
52-Sea of Okhotsk, 51-Oyashio Current	Pacific herring	545
	Pink salmon	312
	Chum salmon	216
	Squids	121
	Other	2181
	Total	6253

the resources and thus ensure that fisheries are an important and sustainable industry in the coastal Arctic communities.

The rich subarctic fisheries are largely absent in the High Arctic, and the fishing industry in these areas is negligible in terms of biomass and revenue (see Figure 7.2 and Table 7.2). The northward range expansion of the subarctic fish stocks under climate change could involve a poleward displacement of the fishing fleet. This is supported by recent analyses of automatic identification system (AIS) data showing that the industrial trawling fleet responds rapidly to reduced sea-ice concentrations, moving north as the sea ice retreats (Fauchald et al., 2021). The fishery expansion is most pronounced in Arctic shelf areas (northern Barents Sea, northern Bering Sea, Sea of Okhotsk). The rapid response of the fishing fleet to diminishing sea ice illustrates the flexibility and dynamic nature of the Arctic fishing industry (Eide, 2017; Troell et al., 2017). Historically, this industry has adapted to large interannual variation in resource availability (e.g., Eide, 2017). Northward expanding fisheries could represent an economic opportunity for small Arctic communities; however, the development would depend on the presence of local infrastructure, competent labor, and financial resources, favoring communities where commercial fisheries and fishing industry are already present. While the Arctic coastal states (Russia, USA, Canada, Greenland, Iceland, Norway) have well-developed northern commercial fisheries and fishing industries, the commercial fisheries are less developed in the High Arctic (Table 7.2), suggesting that the emerging fisheries are more likely to be developed by southern interests possessing the financial resources and large fishing vessels that can safely operate in remote Arctic waters. With this outlook, an active national and international policy is clearly needed to secure the interests of local Arctic communities.

7.2.3.4 Cascading impacts

Arctic marine ecosystems are facing cascading impacts and feedbacks from global warming and ocean acidification. This is rapidly changing the physical environment, and invasive species from the south are altering the ecological communities by introducing new predators, competitors, and pathogens. These impacts combine with an emerging fishing industry that might disturb the benthic-dominated food web by habitat disturbance from bottom trawling and removal of Arctic species in targeted fisheries and by-catch (Christiansen et al., 2014; Christiansen, 2017; Jørgensen et al., 2019). An increasing number of industrial fishing vessels will also be associated with increased noise pollution and vessel strikes with marine mammals. Industrial bottom trawling is considered especially problematic (Jørgensen et al., 2019). This is because bottom contact gears affect the seabed by resuspending and disturbing the sediments, reducing the abundance and diversity of macrobenthos, selecting communities dominated by small short-lived species, and producing carrion for scavengers (Sciberras et al., 2018). As a result, bottom trawling has been banned in Alaskan waters in the northern Bering Sea and, more recently, in an area around Svalbard in the Barents Sea (Jørgensen et al., 2020).

Indigenous People of the Arctic are closely linked to the Arctic marine ecosystem through subsistence hunting and fishing (Galappaththi et al., 2019) and the development of Arctic fisheries could disrupt this socio-ecological system by challenging the traditional culture and contributing to the erosion of the ecosystems. In light of uncertainty about the effects of trends in warming and fisheries, national and international institutions have taken a proactive role while waiting for better information to become available. As a result, the Alaska management authorities (North Pacific Fishery Management Council, National Marine Fisheries Service) banned commercial fisheries north of the Bering Strait in 2008 (Stram and Evans, 2009). Similarly, the five Arctic Ocean coastal states together with China, the European Union, Iceland, Japan, and South Korea signed the Agreement to Prevent Unregulated High Seas Fisheries in the Central Arctic Ocean in 2018. The agreement imposed a 16-year temporary moratorium on unregulated commercial fishing in the Central Arctic Ocean until the effects of climate change on fisheries are better understood and science-based management is in place (Rayfuse, 2019).

7.2.3.5 Summary

Warming waters and diminishing sea ice are allowing a northward expansion of commercial fish stocks. The long-term viability of these stocks will be affected by additional impacts from ocean acidification. A poleward shift in commercial Arctic fisheries under Arctic warming could challenge traditional livelihoods and culture and impact vulnerable ecosystems in the Arctic. The societal impacts of climate change on Arctic fisheries will depend upon cascading impacts from climate-induced changes in the marine ecosystem but also on the presence of infrastructure, labor, fishery management, and international agreements.

7.2.4 Impacts on aquaculture

Warmer water and reduced ice cover increase the potential for aquaculture in the Arctic (AMAP, 2017a). Because of physiological constraints imposed by cold water, the positive effect of warming is most pronounced in finfish farming, but could possibly also increase the yield of kelp cultivation (Froehlich et al., 2018). The effects of ocean acidification, however, are expected to limit the farming of vulnerable shell-building species (i.e., shellfish such as clams, mussels and oysters) (Froehlich et al., 2018; Stewart-Sinclair et al., 2020).

7.2.4.1 Salmon farming

Salmon farming in Norway dominates the aquaculture industry on the ice-free coasts in the Arctic, both in terms of biomass produced and economy (Troell et al., 2017). Salmon farming is present in Atlantic Russia, the Faroe Islands, Iceland, and Canada, but the production is relatively small compared to the Norwegian activity (Table 7.3). Except for Canada, there has been a considerable increase in salmon production in Arctic countries since 2008 (Table 7.3). There is currently no notable aquaculture industry present in Greenland. While certain types of aquaculture such as shellfish farming are permitted in Alaska, finfish farming was prohibited under Alaska Statutes in 1990 (Alaska Statute 16.40.210). Salmon farming except

Table 7.3 Farming of Atlantic salmon in Arctic countries in 2008 and 2018 (FAO, 2020).

	Production, tonnes	
	2008	2018
Russia	51	20,566
Norway	737,694	1,282,003
Faroe Islands	38,494	78,900
Iceland	330	13,448
Canada	104,075	123,184
Total	880,644	1,518,101

for hatcheries of local stocks is accordingly not allowed. In Alaska, farming of oysters, mussels, scallops, and kelp has been introduced, but is still operating at a relatively small scale (Troell et al., 2017). Nevertheless, hatcheries, where salmon are released as smolt, are important for the commercial wild salmon fisheries in Alaska and Russia (Zaporozhets and Zaporozhets, 2004; Ruggerone and Irvine, 2018).

A planned increase in the production of cultivated salmon is under way in northern Norway (Anon, 2015; Troell et al., 2017). The recent increase in the northernmost areas has been partly enabled by warmer water (AMAP, 2017a), and the planned increase in the north is based on the assumption that the optimal climate condition for salmon farming is expected to move north under further warming.

The increase in salmon production has made a substantial contribution to the Norwegian national economy (Johansen et al., 2019), but employment opportunities and economic ripple effects have also been important locally (Aanesen and Mikkelsen, 2020). However, there have been concerns raised related to the strong concentration of the ownership within a few large international companies (Asche et al., 2013), reducing local ownership and consequently benefits reaped by the local coastal communities (Hersoug et al., 2019; Young et al., 2019). The industry is also highly technology-intensive, yielding relatively modest local employment (Johansen et al., 2019). In addition, salmon farming competes with local fisheries, tourism, and recreation for limited space in the coastal seascape (Aanesen and Mikkelsen, 2020). On the other hand, there is evidence that consolidation among corporations could be turned into positive stewardship initiatives through collaboration with the scientific community (Österblom et al., 2017). Such collaborations can help raise the companies' awareness of their role as stewards of the biosphere and that failing to properly manage fisheries and aquaculture activities could lead to substantial challenges for their businesses (Österblom et al., 2017; Folke et al., 2019). Overall, an expanding aquaculture industry in the Arctic involves complex societal costs and benefits (Aanesen and Mikkelsen, 2020). To avoid local tensions and conflicts, it is therefore critical that increased activity is regulated by a comprehensive and locally driven marine spatial planning process (Young et al., 2019). Conflicts are also likely to be exacerbated by the lack of relevant legislation pertaining to the aquaculture industry itself and uncertainties related to user rights held by Indigenous People and local property owners (Young et al., 2019).

Salmon farming is connected to global resource systems through consumption of ingredients in the feed (Troell et al., 2017). Major ingredients include soy protein concentrate, plant oil, and fish meal and oil (Ytrestøyl et al., 2015; Aas et al., 2019). Ingredients are traded on the global market, and sustainable food production from farmed salmon depends on the feed conversion ratio and how the feed ingredients are produced locally. In addition to the global footprint associated with feed consumption, the industry has environmental impacts that might affect local ecosystem services. In Norway, local environmental concerns related to growth in the industry have been raised more frequently in recent years, and these issues have become an increasingly important part of the regulatory framework (Hersoug et al., 2019). In general, the environmental risks associated with eutrophication and local pollution from the farms are considered low (Taranger et al., 2015). However, negative impacts from cultivated Atlantic salmon on the wild salmon populations have been documented (Taranger et al., 2015; Forseth et al., 2017). Wild salmon has traditionally been an important ecosystem service for local and recreational fisheries, and negative impacts from the aquaculture industry have therefore been of special concern. Salmon louse infestation is a challenge for wild post-smolt salmon during their migration from rivers to the sea (Halttunen et al., 2018). The increased density of salmon farms along the coast increases the infestation pressure and is now threatening the survival of several wild salmon stocks (Forseth et al., 2017). Escaped farmed salmon can interbreed with wild salmon, resulting in genetic introgression of the locally adapted wild populations (Glover et al., 2017). Gene flow from domesticated to wild salmon populations has accordingly altered important life-history traits in many wild salmon populations in Norway (Bolstad et al., 2017), and introgression from escapees is now a major threat to wild populations (Forseth et al., 2017). Regulatory and mitigation actions are needed to curb impacts from louse infestation and escapees to halt the detrimental impacts on wild salmon populations.

7.4.2.2 Summary

Salmon farming is expanding northward in the ice-free North Atlantic Arctic with warmer ocean temperatures. The aquaculture industry brings employment opportunities and economic ripple effects to the local communities, but the activity competes with other industries for labor and limited space in the coastal seascape. Spreading of salmon lice and genetic introgression from farmed salmon threaten local Arctic populations of wild Atlantic salmon.

7.2.5 Impacts on cruise tourism

7.2.5.1 Trends in Arctic tourism

Although tourist numbers in the Arctic remain relatively low compared to other parts of the world, the number has risen considerably in recent years and is set to grow further (Maher, 2017). Expansion has been centered in Iceland, parts of Arctic Fennoscandia, the Faroe Islands, and Alaska, with Greenland, the Russian Arctic, and Canada likely to be emerging tourism hotspots in the coming years (Runge et al., 2020). In particular, Arctic islands, including Iceland, Greenland and Svalbard, have experienced considerable tourism growth in recent years (IPCC, 2019). Iceland has experienced a four-fold increase in visitor numbers across the period 2000–2020, with approximately 2.3 million visitors in 2018 (7.77/inh) (Icelandic Tourist Board, 2020). The Faroe Islands received 197,886 overnight guests in 2019 (3.8/inh). In Arctic Norway, Lofoten had 20.9 overnight guests per inhabitant in 2018, while Svalbard tourism increased 30% from 2015 to 2019, resulting in 166,000 overnight visitors (69.7/inh). In some locations winter tourism has increased, such as in Tromsø city (12.7/inh) and in the Santa Claus village in Rovaniemi (Runge et al., 2020).

Seaborne tourism, especially the cruise ship industry, constitutes one of the fastest-growing segments of polar tourism (Larsen and Fondahl, 2015; Bystrowska and Dawson, 2017; Dawson et al., 2018; Palma et al., 2019). Expansion in Arctic cruising coincided with the collapse of the Soviet Union in 1991, following which Russian icebreakers entered the commercial market in support of tourism operations, especially summer cruises towards the North Pole which ventured through Russian waters (Palma et al., 2019). Têtu et al. (2019) provided an overview of the expansion of cruise shipping in the Arctic between 2000 and 2017. Whereas there were only three zones that attracted cruise ships in 2000, by 2017 there were ten (Têtu et al., 2019). Newly emerging routes and destinations have been prominent (Lamers et al., 2018).

In Iceland, the number of cruise ship visitors increased from 265,935 in 2015 to 402,834 in 2017, an uplift of 66% (Icelandic Tourist Board, 2018). In 2019, 496,432 cruise passengers visited ports in northern Norway, which is a 33% increase since 2014. Today, most of the cruises organized in the High Arctic frequent the archipelago of Svalbard (Bystrowska and Dawson, 2017). The number of cruise ship visitors to Svalbard increased from 39,000 in 2008 to 63,000 in 2017, a growth of 62%. Significantly less, albeit growing, cruise ship tourism is occurring in Greenland and Canada (AMAP, 2018a). The number of cruise ship visitors to Greenland increased from 20,000 to 30,000 per year between 2008 and 2017 (Bystrowska and Dawson, 2017). Cruise ship tourism in Arctic Russia is also gradually expanding, with Arkhangelsk as a focal point (Olsen et al., 2020). Overall, cruise passenger data from the Association of Arctic Expedition Cruise Operators show a growth of visitors to the High Arctic from 67,752 in 2008 to 98,238 in 2017, an upscaling of 57% (Palma et al., 2019). The situation in 2020 was diametrically opposite, with reports of more than 50% of Arctic cruise ships being cancelled or postponed until 2021 due to the Covid-19 pandemic (Halpern, 2020).

7.2.5.2 Observed climate impacts on Arctic cruise ship tourism

There are many reasons why tourists choose to visit the Arctic, many of which can be bracketed under the motivation of 'last chance tourism' (Lemelin et al., 2013; Veijola and Strauss-Mazzullo, 2019). This is perhaps something of a misnomer, since it is not the last opportunity for tourists to see the Arctic, but rather this conception reflects the dynamic changes brought about by climate change – tourists perceive it as their last chance to see the region in its current form (IPCC, 2019). This is all the more important when ice- or wildlife-related features form the bedrock of the tourism industry, such as the outlet glaciers of the Greenland Ice Sheet (Schrot et al., 2019), or cetaceans in Skjervøy, northern Norway, whose distribution is influenced by the temperature of ocean currents and available food (Koenigstein, 2020). A 'last chance' motivation for Arctic tourists to see marine mammals in their natural ice-based habitat was found in the study by Maher and Meade (2008) on polar bears in the Canadian Arctic.

A major aspect of the Arctic marine ecosystem is that a high proportion of its wildlife is found in the marginal ice zone, which is the transition region from open ocean to pack ice where the sea-ice concentration is between 15% and 80% (Brenner et al., 2020). The cruise ship industry involves increasing interactions with the marginal ice zone, since the further tourist vessels sail into the area, the more likely they are to encounter sought-after wildlife (Palma et al., 2019). Sea ice represents a danger for shipping (Buixadé Farré et al., 2014; Jóhannsdóttir and Cook, 2015) and thus most ships operate on the outskirts of the marginal ice zone; however, an increasing number of special vessels, naval ships and cruise ships venture more deeply into these waters (Palma et al., 2019). The effects of climate change have resulted in reduced sea-ice cover and thus extended sailing seasons (Palma et al., 2019). The volume of ice in the marginal ice zone has reportedly been reduced by 70% during summer months and by 20% in the winter (Zhang et al., 2017). Future projections indicate that the Arctic Ocean could be ice-free during summer by the middle of the century (Notz and Stroeve, 2016). Bystrowska (2019) reported that more favorable sea-ice conditions were one of several factors underpinning the growth in cruise ship tourism in Svalbard, which continued for many years until the Covid-19 pandemic of 2020. In addition, destinations in the High Arctic that were once unreachable are now more accessible. In 2016, the first large cruise ship, the *Crystal Serenity*, managed to successfully navigate the once impenetrable Northwest Passage on its journey from Alaska to New York with the escort of an icebreaker ship (Nijhuis, 2017; Cajaiba-Santana et al., 2020).

In seeking wildlife, Arctic cruise ship tourism places marine ecosystems at risk (Reeves et al., 2014; Johannsdottir et al., 2021). A series of other risks pertain to the operations of the cruise ship industry in the Arctic, and these are likely to impact more seriously on this region than elsewhere on the planet due to its remoteness, lack of search and rescue facilities, limited infrastructure, and harsh climate (IPCC, 2019; Johannsdottir et al., 2021). Any cruise ship accident occurring in the Arctic will probably be more serious than one in warmer waters, in part due to the potential for contaminants to be transported by sea ice from one EEZ to another (Newton et al., 2017). Additionally, spillages of oil or other hazardous substances are likely to be difficult to remove in icy conditions where the low temperatures of the environment ensure that the processes of dissolving, decomposition, or evaporation are relatively slow (AMAP, 2010; Liu et al., 2017).

Determining the contribution of climate change to increases or decreases in tourism numbers, or effects on the quality of the visitor experience, is challenging (AMAP, 2017a). Yu et al. (2009) created a Modified Climate Index for Tourism, which sought to measure climate as a tourism resource by combining several tourism-related climate variables. The Index was applied to Alaska and Florida, providing evidence in support of more favorable tourism conditions in Alaska due to a lengthening of the warm season, and a corresponding decrease in optimal weather conditions in Florida. Naald (2020) investigated tourists' concerns about climate change and the extent to which they would prefer to avoid climate change effects on glaciers in Alaska. Using choice experiments, a common non-market valuation technique applied by environmental economists, tourists were willing to pay a mean of USD 648 per year to reduce glacier loss to 0.15 km^3 over the next 60 years (Naald, 2020).

7.2.5.3 Risks of expanded Arctic cruise ship tourism and management needs

Indirectly driven in no small part by climate change, the growth of Arctic cruise ship tourism brings important new sources of revenue to remote communities (AMAP, 2018a; Eduard, 2018). Stewart et al. (2007) labelled cruise ship tourism as "one of the few positive outcomes associated to climate change in the Arctic". Hildebrand et al. (2018), AMAP (2018a), and Trump et al. (2018) discussed the contribution that the industry makes in transitioning Indigenous communities in Greenland from subsistence to mixed economies. However, beyond the many potential environmental impacts of the industry and cruise ship tourists (Hale, 2018), several other socio-economic and socio-cultural effects of Arctic cruise ship tourism have been reported. There is the potential for small Indigenous communities to be overcrowded with large numbers of passengers entering small villages, while not providing much in terms of revenue for local businesses (Stephen, 2018; Bystrowska, 2019). Sisneros-Kidd et al. (2019) discussed the potential for 'boom and bust' to occur in tourism-dependent Arctic communities, and outlined a framework and indicators which could measure the resilience of non-extractive, resource-dependent communities. There can also be instances of negative impacts on social behavior and the undermining of traditional cultural practices undertaken by local inhabitants and small coastal communities (IPCC, 2019:260), disruption to fishing and hunting practices, and congestion at small ports (Johannsdottir et al., 2021). In addition, there have been reports that some cruise ships operate under flags of convenience, whereby they may treat their crews poorly in terms of salaries and security (Research Centre for Coastal Tourism, 2012).

Despite the systemic risks and trade-offs, the Arctic cruise ship industry has been rapidly expanding to meet demand (Johannsdottir et al., 2021). The season for cruise ship operators in the Arctic is likely to remain very short, from June to late August in most locations. This means that certain ports will become crowded, with much of the industry focused on a few core locations (Cruise Industry News, 2018). In order to maximize the economic viability of operations, there is pressure on cruise ship operators to increase the number of winter voyages, such as from Bergen to the town of Kirkenes in far northeastern Norway using a 530-passenger ship (Nilsen, 2018a).

Any tourism activities taking place in the Arctic entail considerable risks, especially those that are marine-related. Often the risks of Arctic cruise ship tourism tend to be considered in isolation, with emphasis placed on managing, through insurance mechanisms, their enterprise aspects, as opposed to systemic consequences (Johannsdottir et al., 2021). Relatively recent legal agreements, such as the International Code for Ships Operating in Polar Waters ('Polar Code', IMO, 2017), have advanced regulatory standards concerning the safety, planning and risk mitigation of shipping and cruise ship tourism in the Arctic (IMO, 2017). Although necessary, these are not enough on their own to offset the residual risks of conducting cruise ship activities in the Arctic region. There are multiple infrastructure-related issues that remain to be addressed, including enhancing satellite and monitoring programs, establishing more deep-water ports with refueling capabilities, developing more search and rescue facilities, and increasing resources for national coastguards. There is a need for all components of Arctic tourism, not just marine activities, to be evaluated with respect to their impacts on and contribution to climate change (Hillmer-Pegram, 2017).

7.2.5.4 Summary

Arctic cruise tourism is increasing and is attracted to the wildlife associated with the marginal ice zone. Although there is potential for local economic development with this increased cruise tourism, negative local impacts have been reported including impacts on culture, local hunting and fishing, crowding, and revenue largely benefitting cruise operators. Compared to other world regions, Arctic cruise tourism poses considerable risk due to the region's remoteness, lack of search and rescue facilities, limited infrastructure, and harshness of the climate.

7.2.6 Impacts on offshore oil exploration and operation

In recent years, there has been considerable expansion in the activities of extractive industries within the Arctic region. In 2008, the U.S. Geological Survey provided the first comprehensive assessment of Arctic oil and gas resources, estimating that approximately 90 billion barrels of oil, 1669 trillion cubic feet of gas, and 44 billion barrels of natural gas liquids were present in the Arctic. Of the total of 412 billion barrels of oil equivalent, approximately 84% is located offshore (Bird et al., 2008).

There has been interest in developing Arctic oil and gas resources for several decades; however, this has waned in recent years due to low resource prices, the climate change policy agenda, and the technical challenges of conducting operations in the region (Gulas et al., 2017). Thus far, five countries with Arctic Ocean coastlines have explored, extracted, or extended their exclusive rights to oil and gas resources: Canada, the USA, Russia, Norway, and Denmark (Morín and Orsini, 2015). Hydrocarbon activities have been focused on relatively shallow waters within the jurisdiction of individual Arctic nations. However, most Arctic hydrocarbon resources remain unexplored and are located on extensive Arctic continental shelves and international waters beyond continental shelves (Gulas et al., 2017). Future exploration and potential hydrocarbon production are likely to be focused on new areas, such as Russia's continental shelf (Poussenkova, 2019; Carayannis et al., 2020), Norway's Lofoten Islands (Mohn, 2019) and Alaska (Hansen and Ipalook, 2020).

7.2.6.1 Potential impacts of climate change on resource extraction

Taagholt and Brooks (2016) considered how climate change could enhance the affordability of access to rare earth minerals in Greenland, increasing the potential independence of the nation's economy from Denmark. In addition, foreign powers, such as China, are taking a deeper look at the nation, with the perspective of sourcing important metals and minerals used in electronics, solar power, and wind energy technologies (Buhmann, 2018). Doyle (2019) echoed the findings of Bendixen et al. (2019), writing that melting ice could make sand and gravel resources sufficiently accessible in Greenland to help meet a global undersupply in these resources. Other extractive industries in the Arctic may also expand as a means of diversifying resource-dependent economies, such as deep-sea gold mining in Greenland (Saintilan et al., 2020). Not only is climate change potentially enabling new industries, it is helping to weave a complex geopolitical web, where nations of the West and East seek to reduce their resource-dependency on each other, and nations that have struggled to sustain their economies are attracted to new sources of prosperity (Têtu and Lasserre, 2017; Zeuthen and Raftopoulos, 2018). According to a recent assessment of the World Economic Forum, a warming planet will create new geographic realities, like shipping lanes in the Arctic, which could stoke resource competition (WEF, 2021).

Although the climate change policy agenda, especially the Paris Agreement of 2015, is constraining moves to expand hydrocarbon activities in the Arctic, at the same time the processes of climate change are potentially increasing the accessibility of resources (Palosaari, 2019; Grigoriev, 2020). Modern technologies are increasing knowledge concerning the availability of resources, which may not be located under ice in the next two to three decades (Hwang et al., 2020). The economics of global commodity markets are currently unfavorable, a situation that is further exacerbated by the decline in oil prices during the Covid-19 pandemic (Narayan, 2020). However, it is likely that the climate change policy agenda will represent the greatest constraining force on further exploration of hydrocarbons in the Arctic region. If the world is going to keep to a 2°C temperature increase, then most unexploited fossil fuel resources will need to remain in place (Gjørv, 2017; Forbis and Hayhoe, 2018).

7.2.6.2 Risk and management

The risks of conducting Arctic hydrocarbon or offshore mining operations have often been the greatest constraining factor on further activities (Johannsdottir and Cook, 2019). Gascard et al. (2017) concluded that even allowing for the impacts of climate change, shipping routes in the Northeast Passage will still be hampered by summer sea ice until at least the year 2040. Nordam et al. (2017) explored the impacts of climate change and seasonal trends on the fate of Arctic oil spills. Based on numerical simulations using the OSCAR oil spill model, with environmental data for the period 2009–2012 and projected data for the period 2050–2053, the authors identified differences in the typical outcome of oil spills in a warmer future for the Arctic compared to the present, mainly due to a longer season of open water. Thus, the extent of ice cover is extremely important for determining the fate of an Arctic oil spill, and oil spills in a warming Arctic climate will have greater areal coverage and shoreline exposure (Nordam et al., 2017). The evidence of cases such as the *Exxon Valdez* oil spill in Prince William Sound, Alaska in 1989 suggests that oil spills in the Arctic take longer to decompose than in warmer parts of the world, leading to more severe and longer-term ecological impacts (Barron et al., 2020). The problems of biodegradation (Vergeynst et al., 2018; Lofthus et al., 2020) and dispersion of pollutants from extractive operations (Choudhury and Bandopadhyay, 2016) have been echoed elsewhere in the literature. Other ecological impacts from hydrocarbon operations that are potentially more severe in an Arctic context include negative effects on marine fish mortality (Langangen et al., 2017) and the contribution to black carbon (Shevchenko et al., 2019).

Much of the recent debate concerning risk in this context has concerned what would happen in the event of a large-scale oil spill (Johannsdottir and Cook, 2015, 2019), such as the incident in June 2020 in a nickel mine in northern Russia, which had the potential to spill some or all of 150,000 barrels of diesel oil into the Arctic Ocean (Mukherjee, 2020). Recent research shows that Arctic seabirds in the eastern Canadian Arctic are exposed to oil-related contaminants that may increase with increased traffic in the future (Provencher et al., 2020). In the light of the increased accessibility and potential economic competitiveness of Arctic hydrocarbon production in the coming years (Petrick et al., 2017), a growing body of recent research has focused on the potential risk implications of such an event in an Arctic context. Corresponding to studies about the potential risks of a hydrocarbon-related disaster in the Arctic is burgeoning literature on to how to minimize the likelihood of such an incident and the management responses necessary should an event unfold. Although space is constrained in this literature review for a more comprehensive analysis, brief mention is made of some of the topics of focus. Thorsell and Leschine (2016) reflected on how to prevent such incidents in the Arctic, Tkach (2019) articulated the challenges of adapting geotechnologies in permafrost, Ivanov et al. (2018) and Nordam et al. (2019) conducted oil spill trajectory modeling, Bubbico et al. (2020) reflected on necessary safety barrier measures, Bridges et al. (2018) considered necessary specifications for Arctic offshore structures and infrastructure, and Medvedeva (2015) debated the difficulties in assessing environmental damage in the Arctic. Wilkinson et al. (2017) considered the developments in oil response capacity in recent years in the Arctic, and the remaining limitations.

7.2.6.3 Summary

While diminishing sea ice and warming conditions make offshore oil and gas as well as other mineral extractive materials more accessible, global markets and international policy agreements play an important role in determining the trajectory of these industries. The extent of ice cover is extremely important for determining the fate of an Arctic oil spill, and research indicates longer term and more severe ecological impacts from oil spills in the Arctic than in other regions.

7.3 Cryosphere change and extreme events of relevance to Arctic communities

Extreme climate and weather events are increasing in frequency and/or intensity as climate warms in the Arctic (Chapter 4). Climate extremes can severely affect livelihoods, infrastructure, transport, buildings, health, and wellbeing of Arctic residents (AMAP, 2017b), but minimal research exists on the societal consequences of present and future extreme events. The most notable trend is the extreme warm winter temperatures that have increased on all timescales, causing a cascade of impacts with relevance to Arctic residents. In Alaska, loss of the protective coastal sea ice during the autumn storm season leaves coastal communities more vulnerable to storms, waves, and erosion (Box 7.1). Warmer winters and shorter duration of the snow season in Eurasia has co-occurred with extreme snowfall or heavy rainfall, increasing the risks of avalanches, road destruction, spring flooding, and landslides (Dyrrdal et al., 2020; Marshall et al., 2020), or increasing the impact of extreme snowfall on production and costs of reindeer herders in winter 2020.

Climate extremes occur with a range of interannual variability and are therefore difficult to predict, but impacts can be counterintuitive with respect to the average and gradual changes in temperature and precipitation seen in the Arctic. For example, wildfire events have occurred more frequently regardless of the general increase in precipitation, and cold spells have increased in some locations in Siberia, which runs counter to trends in the rest of the Arctic (Chapter 4). Climate extremes are not distributed evenly across the Arctic, and specific cases are therefore drawn on to assess the adverse impacts of extreme events. There are few studies available that assess societal impacts of climate extremes and weather events and attributing each of these cases to climate change has therefore not been the primary focus in this chapter.

Box 7.1 Coastal erosion in Port Heiden

Interview conducted May 2020. As told by Scott Anderson, Native Village of Port Heiden, Environmental Program. Transcript written by Harmony Wayner, University of Alaska, Fairbanks.

“Coastal erosion has been affecting Port Heiden at an alarming rate of approximately 30 feet per year. From 1973 to 1983 the Chistiakof barrier island moved to form a spit. Without this island as protection, we receive more wave energy hitting our shores. Sea ice provides a natural barrier in winter but has become less reliable, while storms and winds can cause large amounts of erosion over the course of a few days. The coastal land of Port Heiden was deposited from the eruption of Aniakchak volcano, so the soil is composed of pumice and ash. Pumice is lightweight and easily displaced by the wind, big tides and storms. It has been a large undertaking to adapt the village and move key infrastructure with the constant battle against the elements. The old Mesik village site has been relocated further inland and starting in 2003 family remains had to be removed from their resting places before they were washed into the Bering Sea. Many of these graves were victims of the 1919 influenza pandemic.

Erosion is a major disruption to the commercial fishing operations that many local people including myself are involved in. In 2007, the road to the protected lagoon was eroded and we moved out of the village to go further inland. Since then, commercial fishers have to launch their boats by building a ramp at the shore which is then eroded every winter. This new launch method is more exposed and is a risk for possible damage to our boats. The village is resilient in finding adaptation strategies to climate-induced changes over the past two decades, but we live with new challenges as the coastline continues to retreat.”

7.3.1 Erosion, permafrost thaw and thermokarst

7.3.1.1 Impacts of permafrost thaw

Two-thirds of all Arctic settlements are located in permafrost regions (Jungsberg et al., 2019). According to the fifth IPCC assessment report, permafrost temperatures have increased in most of these regions since the early 1980s (Larsen et al., 2014; Biskaborn et al., 2019). The speed of permafrost thaw appears to be higher than previously predicted by scientists (IPCC, 2018). If permafrost is located near the surface, then housing, buildings, roads, and infrastructure can be damaged when it thaws (Welch, 2019). In particular, deepening of the ‘active layer’ (from 0.3 to 4 m) of permafrost, namely that part of the soil profile that freezes and thaws each year, causes the ground to be less stable and even collapse in some areas, which could severely damage infrastructure and transport routes (Jorgenson et al., 2006; Zhang et al., 2008; Burn et al., 2009; Raynolds et al., 2014; Lamoureux et al., 2015; IPCC, 2019:247). In Arctic Russia, the stability of permafrost support for buildings and infrastructure has declined by about 17% from their average index value in the 1970s. In some locations the decline has been as large as 45% (Roshydromet, 2014). Numerous ‘hot spots’ of progressive permafrost degradation have been recorded by the city of Norilsk (Streletskiy et al, 2019). In some settlements, serious deformation has been observed in buildings and infrastructure: up to 50% of buildings in Pevek and Amderma have suffered permafrost-related damage, 55% in Dudinka, 60% in Igarka, and up to 100% in most of the settlements of the Taimyr Peninsula have experienced permafrost-related infrastructure damage. In Chukotka, climate change and human factors had already affected and will probably continue to affect housing, pipelines, roads, and access to remote communities via winter roads (Anisimov et al., 2010; Kokorin at al., 2013; Streletskiy and Shiklomanov, 2013). Thawing permafrost and milder winters also adversely affect winter roads, thus cutting off access to remote communities and industrial sites in the north (Stephenson et al., 2011).

The acceleration of permafrost thaw and related impacts are causing concern in Svalbard (Humlum et al., 2003), with its northernmost settlements located 1300 km above the Arctic Circle. Homes have been destabilized in the major settlement of Longyearbyen (population ~2300). About 250 homes, traditionally built on wooden beams resting on permafrost, are to be demolished due to permafrost thaw and related risks to human safety. Negative impacts on housing and service infrastructure are also observed (AMAP, 2018a). To mitigate risks, three new apartment blocks for resettlement are currently under construction following a EUR 23 million grant from the Norwegian government. The Svalbard Seed Vault that stores seeds from 4.5 million varieties of crops for future food security is also under reconstruction to protect against adverse impacts of climate change and permafrost thaw, including artificially freezing the ground around the new waterproofed entrance to reduce erosion and stabilize permafrost (Nilsen, 2018b).

Rapid permafrost thaw also directly impacts the health of Arctic residents and local communities (AMAP, 2017b). Thawing permafrost can release contaminants, such as mercury, that could be released into aquatic ecosystems (IPCC, 2019:260). The ice layers could serve as reservoirs for human viruses such as caliciviruses, influenza viruses, and enteroviruses (Smith et al., 2004). Microbes and viruses might still be infective; it is regarded as a potential threat to human health, although existing research results are still uncertain and direct spread of infection to humans from thawing permafrost has not been demonstrated. In Russia, permafrost thaw is believed to be among the reasons for the outbreaks of anthrax infection in summer 2016 in Yamal (in the area near Salekhard city) (AMAP, 2017a; Medvedkov, 2017a). The summer heatwave resulted in permafrost thaw releasing old reindeer carcasses along with dormant anthrax bacteria that had infected them (in northern Siberia, there are around 3000 burial grounds for anthrax-infected animals as a result of disease outbreaks at the start of the 20th century). Dozens of people were hospitalized, and the government authorities airlifted several families, mostly from the local reindeer breeding communities in close proximity to the grazing grounds; 2650 reindeer grazing in this area had been infected (Popova et al., 2016; Popova and Kulichenko, 2017). Reindeer burial sites can remain infectious for up to 100 years. According to Mr Maleev, the deputy director of the Central Research Institute of Epidemiology, a big challenge for public authorities in the Yamalo-Nenets Autonomous Okrug is to enhance epidemiological surveillance, undertake an inventory of former burial sites, and then restrict access to them (Maleev, 2016). By the start of the 20th century, there had been a series of anthrax outbreaks in northern Siberia, and about 3000 burial grounds for anthrax-infected animals shallowly dug in permafrost had been registered.

7.3.1.2 Impacts of thermokarst

Thermokarst occurs in inland areas where permafrost thaw is accompanied by sinking land and unstable marshy hollows, depressions, craters, basins, and small thaw lakes. Thermokarst lakes are found in Arctic and subarctic lowlands of the western Canadian Arctic, Yukon, Alaska, northern Eurasia and Siberia. Thermokarst slumping affects the traditional activities of local communities, subsistence economies, and poses risks to travel across tundra and to nomadic reindeer herding. Sediments from a thermokarst area dammed the Selawik River in northwestern Alaska which, in combination with other factors, has affected fish habitats and fishing patterns of local communities (Moerlein and Carothers, 2012; Nitze et al., 2018). This has also occurred in many remote villages in Arctic Russia, particularly in Chukotka and northern Siberia (Leksin and Porfiriev, 2017; AMAP, 2017b), where sudden collapses of permafrost and erosion have undermined river-front houses in local villages (Welch, 2019). Some villagers are faced with the need to consider changing their lifestyles and moving to towns. It has been estimated that, without adaptation measures, thawing permafrost will increase maintenance costs of public infrastructure in Alaska by 10% or USD 5.5 billion in the next decades (Larsen et al., 2008; Hong et al., 2014; Melvin et al., 2017a; AMAP, 2017b).

In May 2020, thawing permafrost at the Norilsk Nickel thermal energy power plant caused the collapse of the pilings for an oil storage tank and resulted in the discharge of about 20,000 tons of diesel fuel into the local drainage basins of the Daldyhan and Ambarnaya rivers and adjacent lakes. It was labeled by Greenpeace as the second largest Arctic oil spill in modern Russian history, with significant damage caused to the environment and the wellbeing of local communities. The ecological damage was assessed by the federal environmental service *Rosprirodnadzor* at the unprecedented level of USD 2 billion (Konopko, 2021), and Norilsk Nickel was fined. This leading non-ferrous metal company was requested to undertake regular monitoring and maintenance of its engineering facilities and constructions erected in the permafrost zone. Active layer destruction threatens the stability of waste-rock piles and tailing piles and ponds, which can lead to pollution and contaminant discharge into the environment and nearby areas (AMAP, 2017b).

7.3.1.3 Coastal erosion

Studies suggest that the rates of coastal erosion in the Arctic over the past half century have been among the highest in the world (Jorgenson and Brown, 2005). For example, in Alaska coastal erosion is increasing owing to permafrost degradation, changes in sea ice, and wave activity. Erosion rates in some regions of the Beaufort Sea east of Point Barrow (Nuvuk) have doubled over the past half century (Jones at al., 2009), significantly affecting local communities; coastal villages, property, infrastructure, and livelihoods are under threat, and the viability of some coastal villages is uncertain (Jorgenson and Brown, 2005; Larsen et al, 2008). Critical infrastructure, shoreline fuel and delivery systems such as pipelines and tanks are also threatened (AMAP, 2017b). Evidence from Canada and its northern provinces indicates that the effects of permafrost thaw coupled with increased wave activity at the coast and decreased sea ice result in more negative impacts of thermal abrasion and coastal erosion in most of the coastal Inuvialuit communities and in the Kitikmeot region (AMAP, 2017b). The erosion hazard index of the Tuktoyaktut Peninsula coastline is of a 'very high' ranking, and the coastline of the Mackenzie Delta in the Beaufort Sea is of a 'high' ranking (Solomon, 2005; Lamoureaux et al., 2015).

Few policy and socio-economic mechanisms are so far available to reduce disaster risks and ensure the combination of wellbeing, security, cost-sharing, and sustainability principles and to resolve the concerns of communities under resettlement schemes. The most widely debated pros and cons in that respect appear to have been demonstrated in the Shishmaref case from Alaska (AMAP, 2017b). Research indicates that a relocation option might often be confronted by local communities, and may not be suitable, for example, to rural tribal and reindeer herding communities of the extreme north (Marino, 2012). Similar threshold challenges might be faced in other cases of natural disaster, for example, regular floods, inundations, or droughts.

7.3.1.4 Economic costs

So far, there are no aggregated pan-Arctic assessments of the current damage and costs from permafrost thaw for local communities. Most of the existing estimates present macroeconomic mid-term and long-term perspectives, or focus either on particular regions, countries, and sectors, or infrastructure. Recent estimates by Russian scientists suggest that over the long term (up to 2100), damage from permafrost destruction due to climate change impacts might account for 1.1–1.2% of global GDP (gross domestic product). They also estimate that due to climate change by 2030, annual damage to buildings and infrastructure from permafrost thaw alone in Arctic Russia would be approximately 200 billion rubles (about USD 3 billion), or about 2.5% of GRP (gross regional product) in the Arctic Russia region (Porfiriev et al., 2017). Permafrost warming in Alaska is estimated to increase the cost of public infrastructure maintenance by a minimum of 10% (2008–2080) (Larsen et al., 2008; Hong et al., 2014) and cumulative damage assessments indicate that mitigation of greenhouse gas emissions and proactive adaptation actions (2015–2099) could reduce damage costs by USD 1.3 billion (Melvin et al., 2017a). Recent assessments of current macroeconomic costs of permafrost degradation in Arctic Russia suggest an annual level of 0.16% of GDP (Chesnokova, 2012; Porfiriev et al., 2019).

Recent research results suggest that pan-Arctic 'high hazard' zones with a specific risk of near-surface permafrost thaw by 2050 would affect a population of nearly one million and one third of existing pan-Arctic infrastructure, including over 36,000 buildings, 13,000 km of roads and 100 airports (Hjort et al., 2018). The risk to settlements and residential infrastructure, logistics of supply chains, as well as to roads and railways is especially high (Medvedkov, 2017b; Hjort et al., 2018). Significant risks also refer to pipelines, especially to the Trans-Alaska pipeline system, and to gas pipeline networks from Yamburg and the Yamalo-Nenets fields in Russia, increasing threats to human security and ecosystems in the neighboring areas (Solodovnikov et al., 2018). A third of pan-Arctic infrastructure and 45% of hydrocarbon fields in the Russian Arctic are in the 'high hazard' zone where thaw-related ground instability could cause severe damage to the built environment; critical areas include parts of the Pechora region, the northwestern parts of the Ural Mountains, and northwest and central Siberia. Areas in central and western Alaska are also within this zone.

7.3.1.5 Summary

Accelerating permafrost thaw, especially in the upper active layer, is causing damage to buildings, roads, and other infrastructure. By 2050 it is expected that 36,000 buildings, 13,000 km of roads and 100 airports in the pan-Arctic area will be affected by permafrost thaw. Relocation of settlements has been necessary due to coastal erosion in some cases. Permafrost thaw poses serious health risks to Arctic residents by releasing contaminants, viruses, microbes, and bacteria, as in the case of recent outbreaks of anthrax contagious infection in summer 2016 in Yamal.

7.3.2 Floods

7.3.2.1 Flood occurrence

As discussed in Chapter 4, extreme flooding events in the Arctic fall into two main groups – coastal floods and inland river floods. Spring snowmelt and ice jams on the rivers, as well as heavy rainfall, are the key drivers of inland river flooding, while the loss of sea ice coupled with storm surges has resulted in increased vulnerability to coastal flooding and erosion in many Arctic coastal regions. Scientific evidence suggests that Arctic flood disasters, both the spring freshet inland river floods and coastal floods, are among the most frequent and devastating hazards and have adverse societal consequences including human losses and costly damage (Buzin et al., 2014; Roshydromet, 2014; Burrell et al., 2015). River floods are caused by abnormal heat waves, earlier snowmelt, river breakup, and increased precipitation (Zheng et al., 2019). More frequent storm surges are expected under climate change (Vermaire et al., 2013). The damage and losses to local communities from flooding depend not only on the magnitude of the flood, but also on its duration and the communities' exposure and adaptive capacity. For example, it is reported that on average a flood on the northern rivers in Russia lasts five to ten days, but high-water marks have been recorded to show that floods have persisted for longer, up to 20 days or more (Semyonov and Korshunov, 2006). This significantly increases the vulnerabilities of local settlements and households already facing adaptation challenges due to permafrost thaw, floods, and other issues (Oppenheimer et al., 2019:268).

Over 80% of Alaska Native villages experience some flooding and erosion (US GAO, 2003). However, it is difficult to assess the severity of the issue because quantifiable data are scarce for remote locations. Local villages on the coast and along rivers are subject to both annual and episodic flooding and erosion (Terenzi et al., 2014). Some studies and reports indicate that coastal villages in Alaska are becoming more susceptible to flooding in part because rising temperatures cause protective shore ice to form later in the year (Fang et al., 2018) leaving the villages vulnerable to autumn storms. Villages in low-lying areas along riverbanks or in river deltas experience flooding due to ice jams, snow and glacial melts, rising sea level, and heavy rainfall (Day and Hodges, 2018; Lantz et al., 2020). For many villages, ice jams that form in the Kuskokwim and Yukon rivers during spring ice breakup cause the most frequent and severe floods by creating a buildup of water behind the jam; the resulting accumulation of water can flood entire villages (AMAP, 2017b).

In the European Arctic, scientific evidence indicates that observed changes in the period of spring flood are associated with changes in the timing of snowmelt (Kayhko et al., 2015) and ice on waterways, which is forming later in the season. Earlier break-up dates and shorter periods of ice cover have also been reported.

There has been a trend for increased annual discharge during the period 1961–2000 (AMAP, 2017a). In Siberia, most of the rural settlements and urban areas are becoming highly vulnerable to floods and their potential consequences, particularly in the basins of its three largest rivers, the Yenisey, Lena, and Ob, which contribute about 70% of the total river runoff into the Arctic Ocean. During the 1960–1990 period, their joint winter runoff increased by 165 km^3 (Savelieva et al., 2004). Almost all river basins in Arctic Russia are flood prone in spring and early summer. A combination of factors define the risk of flooding, including the level of snow storage within the river basin, the length and intensity of snowmelt, and flood mitigation actions. In a number of recent years, warmer weather contributed to an earlier start and more intensive ice drifting, ice jams, and freshet floods than their annual average for this region. At the same time, the series of recent floods on the Lena River, for example, indicated that human factors play an important role in flood disaster response and recovery (Kusatov et al., 2012). Serious gaps in disaster governance in general, and in flood mitigation, emergency response, and rehabilitation in particular, significantly impact the security and wellbeing of local communities and urban residents (Nikitina, 2006; Kontar et al., 2018a).

7.3.2.2 Flood risk and impacts

Floods in sparsely populated Arctic regions can be a threat to human safety and are associated with risks to infrastructure and public facilities. In the unpopulated areas, they are usually considered part of the natural cycle and do not call for emergency response and mitigation action. However, most remote and isolated Arctic communities are particularly vulnerable precisely because their isolation and poor infrastructure complicate search and rescue. During emergencies, local resources and capacities are extremely limited. For example, emergency services in Greenland's municipalities located far from the capital have only a few teams of sled dogs (Veselov, 2012).

In June 2017, three coastal villages in Greenland were hit by flooding caused by a massive tsunami as a result of landslides in the Nuugaatsiaq fjord; 11 houses were swept away into the water and several people died. Shortages in local resources, the remote location of the settlements, a lack of roads and difficulties in access from the sea delayed rescue operations when timing was critical. Evidence from Alaska and Canadian Northwest Territories also highlights many complications and delays during the national emergency response and disaster relief operations in the extreme north (Benoit, 2014; Kontar et al., 2018b).

Arctic settlements, and particularly urban areas, concentrate the exposure of the Northerners, their assets, activities, and wellbeing. Floods may produce significant damage in human settlements due to the higher concentrations of people and economic assets, but they also have higher capacity for recovery (Cutter et al., 2008) due to prioritization of emergency response. As in other regions, urbanization in the Arctic exacerbates the negative effects of flooding through increased runoff, high occupation of floodplains, and inadequate drainage systems undermining the security of local residents. Large cities built in delta areas are subject to coastal inundation due to sea-level rise, and more frequent and intense extreme weather events, including storms and winds; and they are becoming increasingly exposed to negative impacts, and yet are simultaneously highly dependent on construction of dams, protective barriers, and other structural measures (Birkmann and von Teichman, 2010; RF Ministry for Environment, 2016; Afanasiev and Ignatov, 2018; Hunt and Byers, 2019; Oppenheimer et al., 2019).

Recent research indicates that flood risk is especially high in rural and remote northern communities where timely flood emergency support is highly challenging and also limited (Benoit, 2014; Kravits and Gastaldo, 2017; Kontar et al., 2018b). Coastal villages and their infrastructure are especially at risk of flooding with sea-level rise and changes in coastal storm activity. Vulnerability in remote regions increases with insufficient flood-resistant infrastructure, and limited community capacity to cope, which can include lack of assets and insurance, marginal livelihoods, and less state support such as emergency public services. Floods have negative impacts and bring damage to local logistics and critical infrastructure (bridges, transportation and telecommunication, power lines, sewerage and water supply systems, coastal service facilities) which are vital for the safety and wellbeing of remote livelihoods. Human insecurity, including stress, anxiety, and mental illness, could be increased as a result of forced evacuation or displacement after flood events causing significant damage to households and property (Handmer et al., 2012).

7.3.2.3 Prevention and mitigation measures

A characteristic feature of efforts to reduce negative human impacts of flooding in all northern regions is the use of diversified structural measures that are particularly useful for flood risk reduction in local settlements (Birkmann and von Teichman, 2010). Structural measures for disaster risk reduction include a set of engineering, construction and technology tools for enhancing safety and stability of infrastructure. In flood mitigation they involve dams, flood levies, reinforcement of bridges and infrastructure, ocean wave barriers, erosion-resistant construction, and evacuation shelter. This practice has diverse applications. For instance, in Alaska, extensive engineering work has been undertaken to strengthen coastal settlements, with mixed results (Marino, 2015). Flood protection through structural measures is a key element to reduce human vulnerability in the northern parts of Finland and Sweden. Flood damage prevention plans have been developed for major river basins and include spatial planning measures, technical codes and regulations, construction permits, compliance monitoring, upgrades of hydraulic structures, and regular flood control works (Tennberg et al., 2018). Prevention of risks in areas with a relatively high population density requires additional engineering measures, including protective constructions, reinforced infrastructure, strengthening the foundations of buildings, and banning construction in the regularly flooded river valleys. Strict monitoring of land use, construction and settlement standards in flood-prone areas helps reduce damage. Recent studies indicate that a traditional set of ice-jam prevention and mitigation measures has been realized in river basins in the USA and Russian North with varying degrees of success (Belore et al., 1990; Buzin et al., 2014; Burrell et al., 2015; Kontar et al., 2018b); in some cases, loopholes in proper and regular monitoring and maintaining of hydro-technical infrastructure were among reasons for mitigation failures and resulted in recent catastrophic floods on the rivers in Siberia. Prevention of emergencies through structural measures is one of the priorities within the economic sectors and those responsible for maintaining the safety of critical infrastructure and power networks, transportation, and pipelines. According to Zurich Insurance Group, the cost of addressing the consequences of natural disasters, especially floods, is usually nine times higher than the cost of preventing them (Szoenyl, 2018).

Norway reports interesting lessons learned. Climate change factors are incorporated into the methodology for mapping and assessing local risks from floods, which in turn is a part of the dam safety manual (Norwegian Ministry of Climate and Environment, 2017). This was used in the inventory of potentially insecure dams, local decisions on land use, and urban and settlement planning and protective measures are verified against its norms and standards. It contains detailed guidelines on flood and landslide risk reduction in the basins of small mountain rivers. A system for sea-level monitoring has been established, and it provides operational data on emergency situations related to coastal flooding (Norwegian Ministry of Climate and Environment, 2017). A national warning system for extreme weather events, floods, avalanches, and landslides is being created to enhance safety in the transport sector. The Norwegian coastal administration is assessing risks to and vulnerabilities of coastal areas in order to adapt existing infrastructure projects to impacts of climate change. Arctic countries now pay much attention to developing climate services (Kuznetsov et al., 2019), which become a crucial element in enhancing human security under growing flood risk. For example, in 2013, the Norwegian Climate Service Center was established to provide services to municipalities including essential data for local flood risk reduction; it is also involved in producing disaggregated estimates and climate profiles for settlements and Arctic regions.

7.3.2.4 Complex interactions of exposure, vulnerability, and integrated approaches

Usually, flood hazard is a complex phenomenon and is caused by a combination of drivers that couple the natural and human factors (Handmer et al., 2012; Kontar et al., 2015, 2018b). Failures in engineering, in local hydro-technical facilities, drainage systems, infrastructure maintenance, irregular river-bed clean-up, and possible collapse of flood risk reduction infrastructure are among powerful contributors to flooding and local communities' vulnerability to disasters.

In most instances, vulnerability to floods is socially constructed (Lebel et al., 2010). Villages and people living in flood plains or non-resistant buildings, or facing a lack of or gaps in warning systems and awareness of augmenting flood hazard are under risk. Not all people in flood-exposed Arctic communities are equally vulnerable; low-income families and marginalized groups face higher flood risks and insecurities; and research results demonstrate differences in vulnerability and exposure of local communities in cases of flooding (Adger et al., 2005a; Adger, 2006; Kontar et al., 2018a,b). A flood is considered a disaster when a serious disruption in the functioning of a community or society occurs and causes widespread human, material, economic, or environmental losses which exceed the ability of the affected community or society to cope using its local resources (UNISDR, 2004). Declaring a state of emergency signifies recognition by a federal state (or region) of a hazardous event, and is often based on estimates of possible loss of property and investments.

There have been two main discourses on flood disasters (Dixit, 2003; Adger et al., 2005b). The dominant view is that flood disasters are inherently a characteristic of natural hazards and the impacts of climate change. Disasters arise inevitably when the magnitude of a hazard is high. This contrasts with the alternative discourse that sees flood disasters as being jointly produced by interaction of the physical hazard and social vulnerabilities. This alternative discourse brings to the front social relations, structures, technological advances, institutions, and governance in understanding flood disaster. This view posits that flooding disasters are not only the result of natural hazards, but also of socio-economic structures and political processes that make individuals, families, and communities vulnerable (Blaikie et al., 1994; Dixit, 2003; Birkmann, 2005; Kelman et al., 2020). Thus, analysis of human insecurity involves not only the incidence of flood occurrence as a result of environmental change, but is also rooted in lack of local resilience as well as failures in disaster governance, including emergency response, preparedness, and rehabilitation of flood-affected territories (Lebel et al., 2006; Pahl-Wostl et al., 2012; Nikitina, 2019).

Research applying integrated approaches to impacts of flooding is scarce in the Arctic. Statistical data on economic damage and losses from floods in the local communities of the northern regions in the Arctic States are fragmented and not compatible across territories, although estimates for particular regions are being compiled. For example, according to some estimates the cost of annual ice-jam floods in North America is about USD 280 million (Prowse et al., 2011). A variety of possible human health impacts during and after flood events was discussed and evaluated by the WHO (2017), including disaster-borne diseases, infections, food safety, fatalities, injuries, mental health, water hygiene and sanitation, evacuations and shelters, and post-flood recovery of the population, as well as how to manage each of them.

7.3.2.5 Summary

Societal impacts of flooding on livelihoods involve a combination of factors, both physical and hydrological together with human factors such as settlement patterns, hydrotechnical facility failures, irregular clean-up of river beds, and community response. Over 80% of Alaska Native villages experience some level of flooding and erosion. Sudden permafrost thaw and landslides could cause tsunamis in coastal areas, as exemplified by the Nuugaatsiaq fjord in Greenland. Floods have negative impacts and cause damage to local logistics and critical infrastructure such as bridges, transportation and telecommunications, power lines, sewerage and water supply systems, and coastal service facilities. These impacts are mediated by social factors such as government response and local resilience. Small remote villages are increasingly vulnerable to floods, as their security is highly dependent on self-reliance and community action; urban areas usually receive priority in centralized emergency response.

7.3.3 Wildfire

Wildfire is a well-known forest disturbance in the circumpolar boreal ecosystem (Chapin et al., 2006). Analysis of boreal wildfire occurrence over 10,000-year time scales indicates a shift to an era of intensifying and unprecedented wildfire activity (Kelly et al., 2013). Shorter-term trends in wildfire occurrence show extended wildfire seasons, more area burned, and extension of fire to tundra ecosystems (AMAP, 2017b; see also Figure 7.3). Of note are the Arctic wildfires in 2019, which produced radiative forcing on a scale not previously recorded since high-resolution satellite records of fires in the globe's far North began in 2003 (Figure 7.4), and the extreme extent of peatland burning in Russia in the summer of 2020 (Witze, 2020).

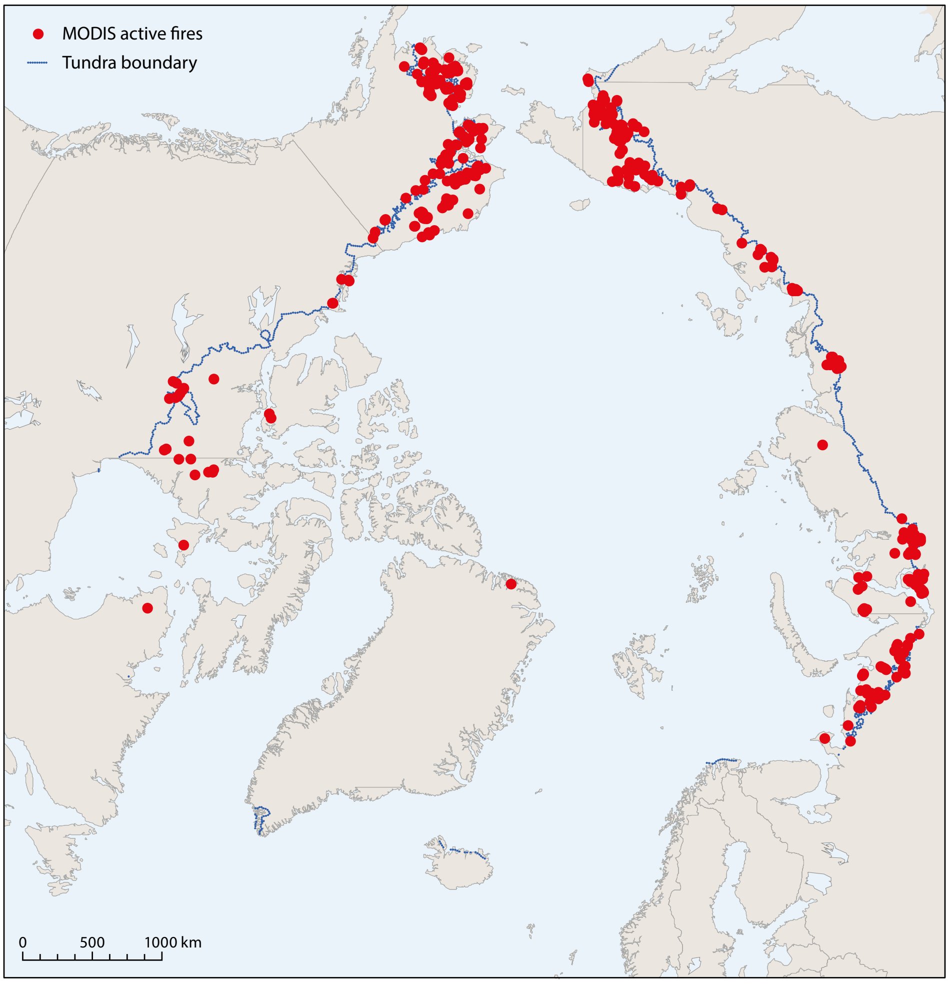

Figure 7.3 Incidence of tundra fire in the circumpolar Arctic (2001–2015). Based on Masrur et al. (2018), CAVM Team (2003) and Walker et al. (2005).

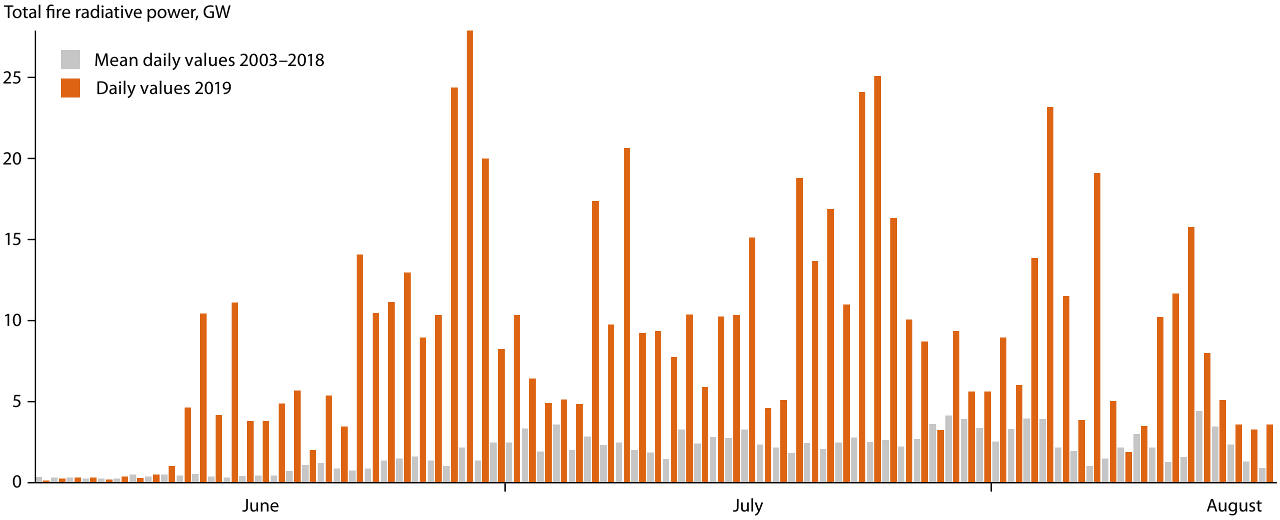

Figure 7.4 Daily total fire radiative power for June, July and August 2019 and the daily mean fire radiative power between 2003 and 2018 within the Arctic. Source: Copernicus Atmospheric Monitoring System (CAMS) Global Fire Assimilation System.

As well as the risk to life and property, societal impacts of wildfire include the costs of fire suppression, damage loss, the costs of business and transportation interruption, temporary housing costs, health consequences due to smoke and related toxins, public anxiety, and personal stress. Other implications involve ecosystem impacts that affect water quality, wild food harvest, and reindeer husbandry, especially in Chukotka and Yamal (Dodd et al., 2018; Marinaite et al., 2018). The projected future annual costs of wildfire suppression in Alaska have been estimated at USD 36 million to USD 73 million, depending on the greenhouse gas emission scenario (Melvin et al., 2017b).

7.3.3.1 Wildfire case studies

Four case studies of extreme and unprecedented wildfire activity at northern latitudes in the past five years are presented here. While many of these wildfires occurred south of the Arctic Circle, the magnitude and severity of their impacts combined with the observed increase in boreal and tundra wildfire activity merit attention (Golyatina et al., 2018). A case study of local Indigenous concern for the societal and ecological impacts of wildfire on a community level is provided in Box 7.2.

Fort McMurray, Canada 2016

In late May and early June 2016, Fort McMurray in the boreal ecoregion of Canada was engulfed by wildfire in "the most expensive natural disaster in Canadian history" (Mamuji and Rozdilsky, 2019): 88,000 people were evacuated from their homes and 2400 homes and businesses were destroyed. In the populated areas at the wildland-urban interface, structural loss experienced by some neighborhoods reached 70% of all buildings. Direct damage from the incident was estimated at about CAN 6 billion with CAN 3.6 billion in insurance loss. In the year following the fire, the Alberta Health Services received a 290% increase in mental health contacts (Mamuji and Rozdilsky, 2019). In the second year after the fire, mental health contacts remained at 150% pre-fire levels. Compared to pre-fire mental health assessments of students in Grades 7–10, post-fire assessments showed a more than doubling of the incidence of post-traumatic stress disorder, a more than tripling of rates of depression, and a doubling in the rates of anxiety (Brown et al., 2019).

Unprecedented extreme wildfire season in Sweden 2018

In July 2018, Sweden experienced an unprecedented wildfire season that outpaced its existing wildfire suppression capacity. This 2018 wildfire season followed a severe wildfire season in 2014 which cost an estimated EUR100 million and in which over 1000 people and 1700 livestock animals were evacuated, 71 buildings were damaged or destroyed, 15,000 ha were burned, and 1.4 million m^3 of timber were damaged (CAB, 2013; MSB, 2015; Lidskog et al., 2019). During the 2018 fire season, 900 of the total 8181 wildfires were caused by lightning, with 18 fires burning more than 100 ha. Of those larger fires, 15 were ignited during the four-day period 14–18 July. At the peak of the incident, over 80 distinct fires blazed at once and approximately 20,800 ha burned in total from these 15 large fires. There was one fatality. The total area burned included 21,576 ha of productive forest, 852 ha of other wooded land, 1805 ha of other open land, and 77 ha of agriculture field or pasture (San-Miguel-Ayanz et al., 2019). Suppression efforts were hampered by weather and climate conditions and required assistance from other European Union countries, which at the time was the largest coordinated EU rescue aid effort (CTIF, 2018a,b). The wildfires affected 215,000 ha of land in 31 of 51 Saami villages, wherein 81,000 ha of critical reindeer pasture was burnt. The Swedish Saami Council estimates that the wildfires cost reindeer herders at least EUR 64 million due to loss of pastures, infrastructure, and extra work hours, not taking into account the long-term effects on pastures and other indirect costs (The Sámi Parliament of Sweden, 2018).

Late-season wildfire activity in Alaska 2019

Until recently, the wildfire season in Alaska typically ended with late-July rain events. In late August 2019, wildfire in south central Alaska destroyed 50 homes, 3 businesses, and 84 outbuildings and burned through a major electric power transmission line (McGee, 2019). Nearly 400 people were evacuated (Zak, 2019). Five schools closed for a week due to related road closures. Estimated suppression costs for the 2019 wildfire season were USD 300 million (Brooks, 2019), with an estimated additional USD 10.4 million to replace the damaged electric transmission line (Brehmer, 2019).

Release of toxic smoke from Siberian wildfires 2019

Siberian wildfires during summer 2019 in the Varnava, Evenkiysky region burned between 2.5 and 4 million ha. Poor air quality associated with the smoke included carcinogenic particles exceeding allowable concentrations (Voronova et al., 2020). The major human threat was to the health of population groups at risk – children, elders, and those with lung and respiratory diseases (Chernykh, 2020). The wildfires caused

Box 7.2 2019 Wildfire season in the Bristol Bay and Lake Iliamna region, Alaska

Interview conducted May 2020. As told by Alex Anna Salmon, Igiugig Village Council President. Transcript written by Harmony Wayner, University of Alaska, Fairbanks.

"Over the past 20 years we have seen changes in our environment around the village of Igiugig. Particularly dryer, hotter, summers which make us vulnerable by affecting our subsistence way of life with the northward migration of species as well as initiating a plant community shift from a tundra bog to an alder forest. The dryness affects our tundra berry harvests, specifically the cloudberry which requires tundra lakes or bogs for their habitat. The summer of 2019 was an especially dry year. After the commercial sockeye salmon run was over in Bristol Bay, many people returned home to Igiugig in August. A wildfire was started by lightning by Naku Peak and was burning tundra grasses, eventually spreading across 30 acres. Since we are in a remote area in southwest Alaska, it took several days for firefighters to respond but the fire was eventually contained and missed the village due to the wind changing direction. The village below us, Levelock, was in imminent threat until the fire was contained. It was a scary incident all around knowing that our village and others in the area are like sitting ducks for wildfires since we have no active fire response team and no fire-fighting infrastructure installed. It highlighted the risk for remote communities like ours and the need to adapt our infrastructure to the increasing vulnerability to wildfire due to climate change."

an increase in the frequency of visits to the doctors and the number of patients with heart attacks in the hospitals doubled. Smoke from wildfires in Siberia in 2019 spread across Eurasia and affected highly populated sites in the Volga region, in the Urals, and in Mongolia and Alaska (Porfiriev, 2019a). People in Arctic settlements in the Taimyr Dolgano-Nenetsky region experienced breathing difficulties as well as generally poor health conditions and complained that "during the daytime the sun is not visible in the sky". Wildfire smoke also caused cancellation of air traffic for several days at the end of July. In some areas of western Siberia, the regime of 'black sky' had been introduced with limits or bans on allowed air emissions for industrial enterprises (Tarasenko and Simunova, 2019). During the two months of wildfire peak in 2019, the level of carbon dioxide and black carbon emissions into the air increased considerably. The Russian Federal Forestry Agency *Rosleshoz* estimated that damage from wildfires in Siberia in 2019 amounted to 7 billion rubles (Rosleshoz, 2019).

7.3.3.2 Addressing increasing wildfire risk

By 2100, the Alaskan tundra may experience twice as much total area burned and the frequency of burns may be up to four times higher compared to historical records (Hu et al., 2015; Young et al., 2017). In North American boreal forests, lightning-ignited fires more than quadrupled in average annual burned area and more than doubled in average size between 1959 and 1999 (Kasischke and Turetsky, 2006). For the same region, total area burned for the last decade of the 21st century is projected to increase 3.5–5.5 times compared to the last decade of the 20th century (Balshi et al., 2009).

Research in Alaska indicates that successful bridging of science and wildfire management through dedicated boundary spanning organizations, including international collaborations with Canada, can assist fire managers in addressing risks from increasing wildfire activity (Colavito et al., 2019; Drury, 2019; Rutherford and Schultz, 2019). Enhanced networks and other adaptive governance strategies are additional avenues for tackling wildfire management under changing conditions. Partnerships and collaborative agreements in Russia between the Yamalo-Nenets Autonomous Okrug and the Hanty-Mansy region have enhanced fire suppression capacity (YANAO, 2019). In Russia, scientists suggest that fire risk management should account for climate change, increasing human risk factors, particularly human health impacts, and the state policies in emergency fire management and in the forestry sector (Volokotina et al., 2008; Shvidenko and Schepaschenko, 2013; Ponomarev et al., 2015; Porfiriev, 2019b).

7.3.3.3 Summary

Unprecedented wildfire occurrence has been observed near populated regions in North America, Sweden, and throughout Siberia in the past five years. Associated societal impacts include significant economic loss from property damage as well as physical and mental health impacts. Enhanced international cooperation, networks, bridging science and management, and other adaptive governance strategies can facilitate fire management under changing conditions.

7.3.4 Societal impacts of compound events and extreme weather

Extreme weather events can induce a range of effects that have implications for Arctic livelihoods and communities. The IPCC refers to compound events as "(1) two or more extreme events occurring simultaneously or successively, (2) combinations of extreme events with underlying conditions that amplify the impact of the events, or (3) combinations of events that are not themselves extremes but lead to an extreme event or impact when combined" (Seneviratne et al., 2012). Compound events could be successive (temporal) in character, such as in the case of freeze-and-thaw events followed by multiple snow storms and a late spring that impacted Scandinavian reindeer populations in 2020 (see Section 7.2.2). Compound events could also be simultaneous or spatial, such as the co-occurrence of multiple wildfires putting pressure on fire, safety and health services in a region or by extreme rain- and snowfall resulting in flooding downstream.

Loss of sea ice affecting the average wave heights, coastal erosion, and change in weather patterns threaten safety and the wellbeing of coastal communities in the Bering, Chukchi and Beaufort seas (Bengtson and Nikitina, 2017). Sea-ice loss and longer ice-free seasons combined with higher storm intensity and frequency are increasing the risks for both shipping and small boat travel for subsistence. Unexpected changes in the strength and direction of winds have been reported in interviews with elders and communities. The winds are pulling dust up into the air affecting communities on land by increasing the likelihood of respiratory illnesses and reducing water quality. More frequent storms have damaged critical infrastructure such as powerlines. Airstrips and travelling have been impacted by changing patterns of snow drift. Extreme weather events such as blizzards and strong winds have consequences for the transport of fresh food to stores in remote locations (Hansen et al., 2018).

Weather extremes can cause multiple hazards, including landslides and avalanches. For example, rainfall and soil moisture are among the key factors driving permafrost thaw (Douglas et al., 2020) and together with freeze-thaw cycles are increasing the risks of landslides in hillslope terrain (Patton et al., 2019). In addition to rainfall, warm temperatures could also increase the likelihood of rockfalls. In Glacier Bay National Park, rock avalanches have been triggered by the record high temperatures in the spring and winter between 2012 and 2016 (Palmer, 2020). According to the Alaska Department of Fish and Game, compound events happening as a result of high temperature combined with glacier retreat and permafrost thaw could potentially cause a tsunami 50 km away from the rockfall, affecting 500 residents in the village Whittier as well as fishermen, recreational boaters, and campers.

Heavy snowfall and rainstorms combined with high wind speeds have also induced multiple avalanches, slush flows and landslides on the Svalbard Archipelago in the past decade (Hanssen-Bauer et al., 2017). Local residents report that changes in wind direction cause snow to accumulate in unusual locations, resulting in snow avalanches close to residential areas (Hovelsrud et al., 2020). Since 2000, nine people have died in avalanches, mostly relating to snowmobiling or tour operations, whereas two residents died as ten houses were hit by a snow avalanche on 19 December 2015. More than

140 flats have now been demolished and the residents moved to a safer area. Extreme precipitation has also resulted in flooding and mudslides threatening roads, infrastructure, and cultural heritage sites (AMAP, 2017b). Local residents report consequences for their sense of security and mental health, but also changes in their awareness about climate-related impacts and the need for climate action (Hovelsrud et al., 2020).

In the Troms region of Norway, snow avalanches have resulted in 28 fatalities over the past ten years, of which three-quarters were recreational skiers and snowboarders. Coastal residents and businesses are highly vulnerable to extreme snowfall as the avalanches cut off road access. Heavy snowfall and blizzards have increased in some of these communities, resulting in snow avalanches and lack of road access during winter (Dyrrdal et al., 2020). Risks of snow avalanches are also high in the Khibiny mountains in Russia, where mining, tourists and ski resorts, roads and infrastructure are threatened (Shnyparkov et al., 2012). Extreme weather affects safety and access to wild food harvests in Alaska and is the fourth most cited information need as expressed by communities and stakeholders (Brown et al., 2021).

Assessing societal impacts requires an understanding of complex causal chains including how physical drivers underpin multiple climate-related hazards as well as the societal drivers exacerbating the impacts (Raymond et al., 2020). There are currently few studies available on the societal consequences of compound events and extreme weather events in the Arctic.

7.4 Socio-ecological systems, cumulative impacts and multiple risks

Climate change induces a range of feedbacks and accelerating changes that can impact socio-ecological systems in the Arctic. The risk-hazard approach is most commonly used to assess climate-related impacts. This starts with a biophysical model of the key variables that indicate climate change, downscales and assesses the combination of variables resulting in compound or extreme events, and links these physical variables to hazards, exposure, and vulnerability in order to evaluate specific risks to sectors or communities (Jurgilevich et al., 2017). Consequently, most climate impact and risk assessments focus on one hazard impacting one sector at a time, and do not account for cascading effects and feedbacks such as human activities and their associated impacts on ecosystems and society. There is also a disconnect between pan-Arctic modeling of indicators of climate change and the smaller-scale studies of ecosystem changes and impacts on specific communities or regions (Landauer and Juhola, 2019). Research on coupled socio-ecological systems of Arctic tundra at a smaller scale are confined to a few cases and the low coherence of topics addressed offers few opportunities for generalizations about societal implications (Ancin-Murguzur and Hausner, 2020). To advance climate-impact research and to produce actionable research for local and regional decision makers, there is a need for more integrated modeling and assessments of societal impacts.

Falardeau and Bennett (2019) used network analysis of marine socio-ecological systems in Inuit regions based on scientific literature and found ecological science to represent 81% of all studies, while human dimensions were included in the remaining 19%. The latter tended to focus on direct climate effects on Inuit livelihoods and communities, with only a few papers linking ecological and social systems. Sea-ice decline was assessed as a major driver of socio-ecological change, affecting 58% of the network. Change in the distribution of marine mammals is particularly important and is affecting livelihoods, cultural identity, and the wellbeing of Inuit communities. Coastal erosion was also found to affect loss of areas used for travel, recreation, and social gathering (Rosales and Chapman, 2015). The literature synthesis of Falardeau and Bennett (2019) found that only 13% of articles studied how climate change interacts with other anthropogenic drivers to produce cumulative effects.

The nature of climate change impacts on wildlife, ecosystems, and people is affected by the cumulative interaction of many factors, including industrial development (Wilson et al., 2018; Ksenofontov et al., 2019), pollution (Parks et al., 2019), hydroelectric development (Baldwin et al., 2018), tourism (Rode et al., 2018; Callaghan et al., 2019; Monz et al., 2021), shipping (Dawson et al., 2020), and resource overexploitation (Safronov, 2016; Ksenofontov et al., 2019). Thus, in addition to documented environmental changes, policy, governance, economic, and social factors are key players in how communities, livelihoods, and people are impacted by climate change. For example, reindeer pastoralism faces significant challenges from changes in wildfire, forage, and predators, yet at least equally challenging to this livelihood are loss and connectivity of pastures due to land use and forestry practices. Similarly, the societal impacts of changing Arctic fisheries depend on cascading impacts from climate-induced changes in the marine ecosystem but also on the presence of infrastructure, labor, and fishery management. Commercial viability of these stocks will be influenced and potentially limited by ocean acidification and policy and regulatory frameworks.

Integrated modeling of climate change impacts on coupled socio-ecological systems are scarce, but there are a few cases where researchers have built scenarios in collaboration with managers and stakeholders that integrate climate, ecological and socio-economic factors to explore the vulnerability and resilience of socio-ecological systems. Hollowed et al. (2020) used a multi-model approach to relate downscaled climate models to the spatial distribution and abundance of fish and shellfish for different periods: current (2006–2020), mid-century (2030–2050), and end-of-century (2080–2100). These models were coupled to ecosystem-based fishery management strategies and impacts on livelihoods and the communities that depend on fisheries. The models were developed through a transdisciplinary, iterative approach based on collaboration among stakeholders, managers and scientists. Similarly, Planque et al. (2019) took a systematic and stepwise approach to assessing future socio-ecological changes in the Barents Sea by first letting a diverse set of participants related to the fishing industry, fisheries policy, non-governmental organizations, and research, develop their own single-perspective scenarios that were later synthesized into a multi-perspective scenario using storylines as a tool to integrate knowledge and perspectives.

The Arctic Resilience Assessment aimed at providing “an integrated assessment of multiple drivers of Arctic Change as a tool for Indigenous Peoples, Arctic Residents, government and industry to prepare for the future” (Carson and Peterson, 2016). It assessed 19 Arctic regime shifts that have either happened, or could potentially happen, due to climate change and other drivers. The social dynamics underlying these shifts and their implications are poorly documented in the scientific literature. Only a few could be managed by people living in the Arctic, but among those factors enhancing the capacity to adapt are diverse livelihood adaptations, use of multiple sources of knowledge, allowing for self-organization, and facilitating learning to deal with change. Resilience assessments in the Arctic have also drawn on complex adaptive systems analysis, which is a tool that can help identify systemic risks due to complex feedback loops, slowly changing trends that can reach tipping points, and increased connectivity that is changing marine food webs across the Arctic (Crépin et al., 2017; Niiranen et al., 2018).

AMAP assessed the combined impacts of ocean acidification, fisheries and sea-surface warming on socio-ecological systems in the Arctic (AMAP, 2018b). The cases reported mostly focused on bioeconomic modeling of single stocks, whereas Steiner et al. (2018) illustrated the importance of combining multiple stressors for assessing the impact on fishery income and employment. One of these studies was based on a knowledge co-production approach where modeling and Indigenous traditional knowledge was combined in multiple steps to reduce uncertainty in food web models. Steiner et al. (2018) suggested that a decline in Arctic cod biomass in its southern distribution range (Disko Bay, Greenland, eastern Greenland and Iceland, the Barents Sea and in the Inuvialuit Settlement Region) could cause cascading impacts throughout the food web, negatively impacting walrus, seals, beluga and seabirds that are important for Indigenous livelihoods and local culture. Poleward range shifts of southern species are expected to increase the total catch and value of fisheries, compensating for the loss of Arctic cod. Climate change was identified as the most influential driver of these changes, with ocean acidification playing a minor role.

A partnership approach that builds on co-design and co-production of knowledge can contribute to a more integrative understanding of the societal impacts of climate change (Falardeau et al., 2019). Indigenous knowledge has been widely used to document and understand changes taking place in the North American Arctic (Gagnon et al., 2020) and is increasingly drawn on in other Arctic regions (Ksenofontov et al., 2019; Markkula et al., 2019; Callaghan et al., 2020). However, a full partnership with Indigenous communities to bridge Indigenous knowledge and Western science approaches is not yet the norm (Knapp and Trainor, 2013). Indigenous knowledge and Western science generally concur on the nature and directionality of impacts observed or complement each other (Weatherhead et al., 2010; Savo et al., 2016; Rapinski et al., 2018; Anisimov and Orttung, 2019), but sometimes conflict when explaining why change is occurring (Krupnik, 2018; Ksenofontov et al., 2019). Community-based observatories have been established in recent years that aim at integrating Indigenous knowledge and Western science (e.g., Johnson et al., 2016; Danielsen et al., 2020), and the partnership of Indigenous and local knowledge in climate change monitoring and research could help identify how socio-ecological linkages are changing as the Arctic warms (Johnson et al., 2020).

7.5 Conclusions and recommendations

The main focus of this report has been observed climate-related impacts; specifically, what has happened as a result of climate change, as reported in the peer-reviewed literature. The implications of projections of future conditions will be assessed in a subsequent report anticipated to be published in 2025. This chapter is a novel contribution to the AMAP climate impact assessment and was initiated at a much later stage than the previous chapters, leaving less time for a comprehensive assessment of societal implications. By focusing primarily on climate-related impacts on Arctic livelihoods and extreme events, the present report thus has a narrower scope than the anticipated 2025 report. Impacts in the current report were documented through the published literature, while implications are harder to document and so require more time to assess rigorously.

To understand future changes in the Arctic it is necessary to examine the broader societal implications of climate change, including scenarios of alternative pathways of change associated with increased access to remote Arctic locations, resources, new markets, and trade routes connected to declining sea ice. A full assessment of societal implications will need to go beyond documenting evidence of observed impacts, to include multi-risk assessments, vulnerability, and the resilience of Arctic societies to impacts, as well as implications for adaptation action and Indigenous authorship. The full assessment should also examine the impacts of Covid-19 or other pandemics and their influence on community resilience and climate adaptation actions.

Among the topics that were beyond the scope of this chapter were:

- Multi-risk assessment, including projections and future risks of climate extremes.
- Potential for new economies in the Arctic. Societal implications of increased access to resources, new markets, and shipping and trade routes are important for understanding options for adaptation and transformation.
- Studies that apply integrated approaches to assess climate-related impacts, including cumulative and compound effects, on socio-ecological systems. Understanding impacts on coupled systems, as well as the combined impacts of climate change and societal stressors, is important not only in terms of research, but also in terms of risk mitigation, hazard response, climate adaptation, and policy response to changing climatic conditions.
- Costs of damage and the replacement of infrastructure such as roads, pipelines, buildings, ports, airports, and rail (see, for example, Suter et al., 2019), including targeted assessment of societal impacts in Arctic cities.
- Cascading effects of climate change on biodiversity, ecosystems, ecosystem services, and on the health and wellbeing of local communities, including Indigenous perspectives and knowledge.
- Societal implications of Arctic change for low and mid-latitudes, including increased damage from storms and hurricanes, sea-level rise, coastal erosion and flooding, and the mitigation costs of planetary feedbacks associated with the decline of terrestrial permafrost, snow, and sea ice (e.g., Yumashew et al., 2019).

Finally, and perhaps most significantly, any report on the societal impacts of climate change in the Arctic requires the holistic inclusion of the perspectives, voices, priorities, knowledge, and needs of the Indigenous Peoples who have inhabited the Arctic for millennia. This goes beyond participatory approaches and research about Indigenous People and requires what to many will be a new co-production approach (Behe et al., 2018; Wheeler et al., 2020) in which science agenda are set together with Arctic residents, and whereby Indigenous knowledge and rights are trusted and respected. The Inuit Circumpolar Council favors a shift to co-production whereby research and policy-making structures are aligned with Indigenous approaches and perspectives, and assessments welcome Indigenous knowledge holders throughout the entire process. The shift also requires recognition of the sustainable practices that Inuit have practiced for thousands of years and for the extensive community-driven work across Inuit Nunaat (i.e., Inuit homelands) that rarely gets acknowledged. In Scandinavia, for example, the Saami Council and AMAP have taken the initiative to a co-production process together with research teams in Sweden, Norway and Finland in the project Climate Impacts on Terrestrial Environments (CITE), to increase understanding of impacts and enhance the capacity of reindeer herders to adapt to climate change. Bringing together Indigenous knowledge and science needs awareness of the ethical standards and consciousness about equitable engagement of Indigenous People. Co-production processes must also be culturally sensitive to the context in which they are applied. This shift calls for the equitable and ethical engagement of Indigenous Peoples through raising the standard in Arctic research and policy to be a co-production of knowledge approach, bringing together Indigenous knowledge and science.

The 2025 AMAP report could also draw on existing initiatives for enhancing the role of community-based observation, including those represented in the Indigenous knowledge social network (SIKU, no date) or the Local Environmental Observer (LEO) network (LEO network, no date) that was initiated as a tool to help the tribal health system and local observers to share information about environmental change. The LEO network was selected as a model program under the United States Chairmanship of the Arctic Council in 2015 to communicate the impacts of climate change. Subsequently, the Arctic Council agreed to build on the success of the Alaska-based LEO network and develop the foundation for a Circumpolar Local Environmental Observer (CLEO) Network (Arctic Council, no date).

References

Aanesen, M. and E. Mikkelsen, 2020. Cost-benefit analysis of aquaculture expansion in Arctic Norway. Aquaculture Economics & Management, 24:20-42.

Aas, T.S., T. Ytrestøyl and T. Åsgård, 2019. Utilization of feed resources in the production of Atlantic salmon (*Salmo salar*) in Norway: An update for 2016. Aquaculture Reports, 15:100216.

Adger, W.N., 2006. Vulnerability. Global Environmental Change, 16:268-281.

Adger, W.N., N.W. Arnell and E.L. Tompkins, 2005a. Successful adaptation to climate change across scales. Global Environmental Change, 15:77-86.

Adger, W.N., K. Brown and E.L. Tompkins, 2005b. The political economy of cross-scale networks in resource co-management. Ecology and Society, 10:1-9.

Afanasiev, V.V. and E.I. Ignatov, 2018. Geomorphological aspects of coast protection in high latitudes. Geosystems of Transition Zones, 2:116-124. 10.30730/2541-8912.2018.2.2.116-124

Agafonova S. et al., 2019. Наводнения на реках и побережьях Арктической зоны России [Flooding on rivers and coastals of the Arctic zone of Russia]. Nizhny Novgorod, Studio F1 www.elibrary.ru/item.asp?id=41267930

AHDR, 2004. Arctic Human Development Report. Stefansson Arctic Institute, Akureyri, Iceland.

Alaska Department of Fish and Game, 2019. Subsistence in Alaska: A Year 2017 Update. www.adfg.alaska.gov/static/home/subsistence/pdfs/subsistence_update_2017.pdf

AMAP, 2010. Assessment 2007: Oil and Gas Activities in the Arctic - Effects and Potential Effects. Volume 2. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. vii + 277 pp.

AMAP, 2017a. Adaptation Actions for a Changing Arctic: Perspectives from the Barents Area. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. xiv + 267pp.

AMAP, 2017b. Adaptation Actions for a Changing Arctic: Perspectives from the Bering-Chukchi-Beaufort Region. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. xiv + 255 pp.

AMAP, 2018a. Adaptation Actions for a Changing Arctic: Perspectives from the Baffin Bay/Davis Strait Region. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. xvi + 354pp.

AMAP, 2018b. AMAP Assessment 2018: Arctic Ocean Acidification. Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway. vi+187pp.

Asmussen, C.B. and C. Møller, 2019. Smart literature review: a practical topic modelling approach to exploratory literature review. Journal of Big Data, 6: 93 doi.org/10.1186/s40537-019-0255-7

Ancin-Murguzur, F.J. and V.H. Hausner, 2020. Research gaps and trends in the Arctic tundra: a topic-modelling approach. One Ecosystem, 5:e57117.

Anderson, D., J.D. Ford and R.G. Way, 2018. The impacts of climate and social changes on cloudberry (bakeapple) picking: a case study from southeastern Labrador. Human Ecology, 46:849-863.

Andrews, A.J., J.S. Christiansen, S. Bhat, A. Lynghammar, J.I. Westgaard, C. Pampoulie and K. Præbel, 2019. Boreal marine fauna from the Barents Sea disperse to Arctic Northeast Greenland. Scientific reports, 9:1-8.

Anisimov, O. and R. Orttung, 2019. Climate change in Northern Russia through the prism of public perception. Ambio, 48:661-671.

Anisimov, O., D. Streletsky, V. Kokorev and N. Shiklomanov, 2010. Major natural and socio-economic consequences of climate change in the permafrost region: predictions based on observations and modeling. Greenpeace, Moscow, Russia, 44p. (In Russian) www.researchgate.net/publication/259762594

Anon, 2015. Meld. St. 16 (2014–2015) Forutsigbar og miljømessig bærekraftig vekst i norsk lakse- og ørretoppdrett. (Norwegian white paper on the growth in the Norwegian salmon industry; in Norwegian). www.regjeringen.no/no/dokumenter/meld.-st.-16-2014-2015/id2401865

Arctic Council, no date. Circumpolar Local Environmental Observer Network (CLEO). www.arctic-council.org/projects/circumpolar-local-environmental-observer-network-cleo

Arriagada, P. and A. Bleakney, 2019. Inuit participation in the wage and land-based economies in Inuit Nunangat. Statistics Canada.

Asche, F., K.H. Roll, H.N. Sandvold, A. Sørvig and D. Zhang, 2013. Salmon aquaculture: Larger companies and increased production. Aquaculture Economics & Management, 17:322-339.

Axelsson-Linkowski, W., A.M. Fjellström, C. Sandström, A. Westin, L. Östlund and J. Moen, 2020. Shifting strategies between generations in Sami reindeer husbandry: the challenges of maintaining traditions while adapting to a changing context. Human Ecology, 48:481-490.

Balascio, N.L. and S. Wickler, 2018. Human–environment dynamics during the Iron Age in the Lofoten Islands, Norway. Norsk Geografisk Tidsskrift-Norwegian Journal of Geography, 72:146-160.

Baldwin, C., L. Bradford, M.K. Carr, L.E. Doig, T.D. Jardine, P.D. Jones, L. Bharadwaj and K.E. Lindenschmidt, 2018. Ecological patterns of fish distribution in the Slave River Delta region, Northwest Territories, Canada, as relayed by traditional knowledge and Western science. International Journal of Water Resources Development, 34:305-324.

Balshi, M.S., A.D. McGuire, P. Duffy, M. Flannigan, J. Walsh and J. Melillo, 2009. Assessing the response of area burned to changing climate in western boreal North America using a Multivariate Adaptive Regression Splines (MARS) approach. Global Change Biology, 15:578-600.

Barron, M.G., D.N. Vivian, R.A. Heintz and U.H. Yim, 2020. Long-term ecological impacts from oil spills: comparison of Exxon Valdez, Hebei Spirit, and Deepwater Horizon. Environmental Science & Technology, 54:6456-6467.

Bartsch, A., T. Kumpula, B.C. Forbes and F. Stammler, 2010. Detection of snow surface thawing and refreezing in the Eurasian Arctic with QuikSCAT: implications for reindeer herding. Ecological Applications, 20:2346-2358.

Beaumier, M.C., J.D. Ford and S. Tagalik, 2015. The food security of Inuit women in Arviat, Nunavut: the role of socio-economic factors and climate change. Polar Record, 51:550-559.

Behe, C., R. Daniel and J. Raymond-Yakoubian, 2018. Understanding the Arctic through a co-production of knowledge - ACCAP Webinar, 2018. https://scholar.google.com/citations?view_op=view_citation&hl=no&user=NGFd_vAAAAAJ&sortby=pubdate&citation_for_view=NGFd_vAAAAAJ:ULOm3_A8WrAC

Behnke, R.H., M.E. Fernandez-Gimenez, M.D. Turner and F. Stammler, 2011. Pastoral migration. Mobile systems of livestock husbandry. In: Milner-Gulland, E.J., J. Fryxell and A.R.E Sinclair (eds.), Animal Migration–A Synthesis. pp. 144-252. Oxford University Press.

Belore, H.S., B.C. Burrell and S. Beltaos, 1990. Ice jam mitigation. Canadian Journal of Civil Engineering, 17:675-685.

Bendixen, M., I. Overeem, M.T. Rosing, A.A. Bjørk, K.H. Kjær, A. Kroon, G. Zeitz and L.L. Iversen, 2019. Promises and perils of sand exploitation in Greenland. Nature Sustainability, 2:98-104.

Bengtson, J.L. and E. Nikitina, 2017. Impacts and consequences for northern communities and society. In: Adaptation Actions for a Changing Arctic: Perspectives from the Bering-Chukchi-Beaufort Region. pp. 125-152. AMAP, Oslo.

Benoit, L., 2014. Perspectives on Emergency Response in the Canadian Arctic: Sinking of the MS Arctic Sun in Cumberland Sound, Nunavut, 22 pp. http://gordonfoundation.ca

Berner, J., M. Brubaker, B. Revitch, E. Kreummel, M. Tcheripanoff and J. Bell, 2016. Adaptation in Arctic circumpolar communities: food and water security in a changing climate. International Journal of Circumpolar Health, 75:33820.

Bird, K.J., R.R. Charpentier, D.L. Gautier, D.W. Houseknecht, T.R. Klett, J.K. Pitman, T.E. Moore, C.J. Schenk, M.E. Tennyson and C.R. Wandrey, 2008. Circum-Arctic resource appraisal: Estimates of undiscovered oil and gas north of the Arctic Circle (No. 2008-3049). U.S. Geological Survey.

Birkenbach, A.M., D.J. Kaczan and M.D. Smith, 2017. Catch shares slow the race to fish. Nature, 544:223-226.

Birkmann, J. (ed.), 2005. Measuring Vulnerability and Coping Capacity to Hazards of Natural Origin: Concepts and Methods. UNU Press, Tokyo.

Birkmann, J. and K. von Teichman, 2010. Integrating disaster risk reduction and climate change adaptation: key challenges – scales, knowledge, and norms. Sustainability Science, 5:171-184.

Biskaborn, B.K., S.L. Smith, J. Noetzli, H. Matthes, G. Vieira, D.A. Streletskiy, P. Schoeneich, V.E. Romanovsky, A.G. Lewkowicz, A. Abramov and M. Allard, 2019. Permafrost is warming at a global scale. Nature Communications, 10:264.

Blaikie, P., T. Cannon, I. Davis and B. Wisner, 1994. At Risk: Natural Hazards, People's Vulnerability, and Disaster. Routledge, London.

Bolstad, G.H., K. Hindar, G. Robertsen, B. Jonsson, H. Sægrov, O.H. Diserud, P. Fiske, A.J. Jensen, K. Urdal, T.F. Næsje and B.T. Barlaup, 2017. Gene flow from domesticated escapes alters the life history of wild Atlantic salmon. Nature Ecology & Evolution, 1:0124.

Brandišauskas, D., 2016. Leaving Footprints in the Taiga: Luck, Spirits and Ambivalence Among the Siberian Orochen Reindeer Herders and Hunters. Volume 1. Berghahn Books.

Brandišauskas, D., 2020. Living with reindeer thirty years after socialism: land use and large reindeer herding among the Evenki of Southeast Siberia. Journal of Ethnology and Folkloristics, 14:65-84.

Brattland, C., E. Eythórsson, J. Weines and K. Sunnana, 2019. Social–ecological timelines to explore human adaptation to coastal change. Ambio, 48:1516-1529.

Brehmer, E., 2019. Bradley Lake power line outage from wildfire tops $10M in cost to Alaska railbelt ratepayers. Anchorage Daily News. Retrieved from https://www.adn.com

Brenner, S., L. Rainville, J. Thomson and C. Lee, 2020. The evolution of a shallow front in the Arctic marginal ice zone. Elementa: Science of the Anthropocene, 8:17.

Bridges, R., K. Riska, L. Lu, M. du-Couedic-de-Kererant and J.M. Aubert, 2018. A study on the specification of minimum design air temperature for ships and offshore structures. Ocean Engineering, 160:478-489.

Brooks, J., 2019. Fighting Alaska's wildfires cost over $300 million this year, Anchorage Daily News. Retrieved from https://www.adn.com

Brown, C.L., K.A. Seaton, T.J. Brinkman, E.S. Euskirchen and K. Kielland, 2015. Applications of resilience theory in management of a moose–hunter system in Alaska. Ecology and Society, 20:16.

Brown, D.R., T.J. Brinkman, D.L. Verbyla, C.L. Brown, H.S. Cold and T.N. Hollingsworth, 2018. Changing river ice seasonality and impacts on interior Alaskan communities. Weather, Climate, and Society, 10:625-640.

Brown, M.R., V. Agyapong, A.J. Greenshaw, I. Cribben, P. Brett-MacLean, J. Drolet, C. McDonald-Harker, J. Omeje, M. Mankowsi, S. Noble and D.T. Kitching, 2019. Significant PTSD and other mental health effects present 18 months after the Fort Mcmurray wildfire: findings from 3,070 grades 7–12 students. Frontiers in Psychiatry, 10:623.

Brown, C., S.F. Trainor, C.N. Knapp and N. Kettle, 2021. Alaskan wild food harvester information needs and climate adaptation strategies. Ecology and Society, 26:44.

Bubbico, R., S. Lee, D. Moscati and N. Paltrinieri, 2020. Dynamic assessment of safety barriers preventing escalation in offshore Oil&Gas. Safety Science, 121:319-330.

Buhmann, K., 2018. Chinese Mineral Sourcing Interests & Greenland's Potential as a Source of 'Conflict-Free Conflict Minerals'. Arctic Yearbook 2018 : Special Section: China & the Arctic, pp. 84-101.

Buixadé Farré, A., S.R. Stephenson, L. Chen, M. Czub, Y. Dai, D. Demchev, Y. Efimov, P. Graczyk, H. Grythe, K. Keil and N. Kivekäs, 2014. Commercial Arctic shipping through the Northeast Passage: routes, resources, governance, technology, and infrastructure. Polar Geography, 37:298-324.

Bunce, A., J. Ford, S. Harper, V. Edge and IHACC Research Team, 2016. Vulnerability and adaptive capacity of Inuit women to climate change: a case study from Iqaluit, Nunavut. Natural Hazards, 83:1419-1441.

Burke, T.K., C. Durr and D. Reamer, 2018. The importance of local foods to users of food pantries in accessible rural Alaska. Journal of Agriculture, Food Systems, and Community Development, 8:53-69.

Burn, C.R., J.R. Mackay and S.V. Kokelj, 2009. The thermal regime of permafrost and its susceptibility to degradation in upland terrain near Inuvik, NWT. Permafrost and Periglacial Processes, 20:221-227.

Burrell, B.C., M. Huokuna, S. Beltaos, N. Kovachis, B. Turcotte and M. Jasek, 2015. Flood hazard and risk delineation of ice-related floods: present status and outlook. In: Proceedings of the 18th CGU-HS CRIPE Workshop on the Hydraulics of Ice Covered Rivers, Quebec City, Canada. pp. 18-21.

Bush, E. and D.S. Lemmen, 2019. Canada's Changing Climate Report. Government of Canada, Ottawa.

Buzin, V.A., N.I. Goroshkova and A.V. Strizhenok, 2014. Maximum ice-jam water levels on the northern rivers of Russia under conditions of climate change and anthropogenic impact on the ice jamming process. Russian Meteorology and Hydrology, 39:823-827.

Bystrowska, M., 2019. The impact of sea ice on cruise tourism on Svalbard. Arctic, 72:151-165.

Bystrowska, M. and J. Dawson, 2017. Making places: The role of Arctic cruise operators in 'creating' tourism destinations. Polar Geography, 40:208-226.

CAB, 2014. Skogsbranden i Västmanland 2014 [The forest fire in Västmanland 2014]. County Administrative Board of Västmanland (CAB).

Cajaiba-Santana, G., O. Faury and M. Ramadan, 2020. The emerging cruise shipping industry in the Arctic: Institutional pressures and institutional voids. Annals of Tourism Research, 80:102796.

Callaghan, T.V., O. Kulikova, L. Rakhmanova, E. Topp-Jørgensen, N. Labba, L.A. Kuhmanen, S. Kirpotin, O. Shaduyko, H. Burgess, A. Rautio, R.S. Hindshaw, L.L. Golubyatnikov, G.J. Marshall, A. Lobanov, A. Soromotin, A. Sokolov, N. Sokolova, P. Filant and M. Johansson, 2019. Improving dialogue among researchers, local and indigenous peoples and decision-makers to address issues of climate change in the North. Ambio, 49:1161-1178.

Callaghan, M.W., J.C. Minx and P.M. Forster, 2020. A topography of climate change research. Nature Climate Change, 10:118-123.

Carayannis, E., A. Ilinova and A. Chanysheva, 2020. Russian Arctic offshore oil and gas projects: methodological framework for evaluating their prospects. Journal of the Knowledge Economy, 11:1403-1429.

Carson, M. and G. Peterson (eds), 2016. Arctic Resilience Report. Stockholm Environment Institute and Stockholm Resilience Centre, Stockholm.

CAVM Team, 2003. Conservation of Arctic Flora and Fauna (CAFF) Map No 1. Circumpolar Arctic vegetation map. U.S. Fish and Wildlife Service.

Chambers, R. and G. Conway, 1992. Sustainable Rural Livelihoods: Practical Concepts for the 21st Century. Discussion Paper 296. Institute of Development Studies, University of Sussex, Brighton, UK. https://opendocs.ids.ac.uk/opendocs/handle/20.500.12413/775

Chambourg, D.S.N., 2019. "We are not dead souls": the good petroleum fairies and the spirits of the Taiga in subarctic Siberia. Sibirica, 18:109-150.

Chapin, F.S., A.L. Lovecraft, E.S. Zavaleta, J. Nelson, M.D. Robards, G.P. Kofinas, S.F. Trainor, G.D. Peterson, H.P. Huntington and R.L. Naylor, 2006. Policy strategies to address sustainability of Alaskan boreal forests in response to a directionally changing climate. Proceedings of the National Academy of Sciences, 103:16637-16643.

Chernykh, V., 2020. Лесные пожары 2019 г. - социально-экономическое бедствие Иркутской области [Forest fires of 2019 - social and economic disaster of Irkutsk region]. Baikal State University, Irkutsk. https://elibrary.ru/item.asp?id=42896583

Chesnokova, I.V., 2012. Assessment of damage from processes in cryosphere and issues for insurance and their impacts for the territory of Russia. Resources and risks for the regions with permafrost, TIPOC International Conference Proceedings, Vol 5., Tuimen.

Cheung, W.W., G. Reygondeau and T.L. Frölicher, 2016. Large benefits to marine fisheries of meeting the 1.5 C global warming target. Science, 354:1591-1594.

Choudhury, A. and S. Bandopadhyay, 2016. The effect of overall pit slope and pit geometry on the dispersion of pollutants in a hypothetical arctic open-pit mine. Natural Resources & Engineering, 1:26-34.

Christiansen, J.S., 2017. No future for Euro-Arctic ocean fishes? Marine Ecology Progress Series, 575:217-227.

Christiansen, J.S., C.W. Mecklenburg and O.V. Karamushko, 2014. Arctic marine fishes and their fisheries in light of global change. Global Change Biology, 20:352-359.

Clark, D.G., J.D. Ford, L. Berrang-Ford, T. Pearce, S. Kowal and W.A. Gough, 2016a. The role of environmental factors in search and rescue incidents in Nunavut, Canada. Public Health, 137:44-49.

Clark, D.G., J.D. Ford, T. Pearce and L. Berrang-Ford, 2016b. Vulnerability to unintentional injuries associated with land-use activities and search and rescue in Nunavut, Canada. Social Science & Medicine, 169:18-26.

Clark, D.G., J.D. Ford and T. Tabish, 2018. What role can unmanned aerial vehicles play in emergency response in the Arctic: A case study from Canada. PLoS ONE, 13:e0205299.

Colavito, M.M., S.F. Trainor, N.P. Kettle and A. York, 2019. Making the transition from science delivery to knowledge coproduction in boundary spanning: a case study of the Alaska Fire Science Consortium. Weather, Climate, and Society, 11:917-934.

Cold, H.S., T.J. Brinkman, C.L. Brown, T.N. Hollingsworth, D.R.N. Brown and K.M. Heeringa, 2020. Assessing vulnerability of subsistence travel to effects of environmental change in Interior Alaska. Ecology and Society, 25:20.

Comeau, S., R. Jeffree, J.L. Teyssie and J.P. Gattuso, 2010. Response of the arctic pteropod *Limacina helicina* to projected future environmental conditions. PLoS ONE, 5:e11362.

Cooley, S.W., J.C. Ryan, L.C. Smith, C. Horvat, B. Pearson, B. Dale and A.H. Lynch, 2020. Coldest Canadian Arctic communities face greatest reductions in shorefast sea ice. Nature Climate Change, 10:533-538.

Costello, C., S.D. Gaines and J. Lynham, 2008. Can catch shares prevent fisheries collapse? Science, 321:1678-1681.

Costello, C., D. Ovando, T. Clavelle, C.K. Strauss, R. Hilborn, M.C. Melnychuk, T.A. Branch, S.D. Gaines, C.S. Szuwalski, R.B. Cabral, D.N. Rader and A. Leland, 2016. Global fishery prospects under contrasting management regimes. Proceedings of the National Academy of Sciences, 113:5125-5129.

Crate, S.A., 2018. Water, water everywhere: perceptions of chaotic water regimes in Northeastern Siberia, Russia. In: Hiyama, T. and H. Takakura (eds.), Global Warming and Human-Nature Dimension in Northern Eurasia. pp. 1-10. Springer.

Crate, B.S.A., N. Einarsson, J.D. Ford, M. Lahsen, M. Paolisso, G. Schlee and S.A. Crate, 2008. Gone the bull of winter? Grappling with the cultural implications of and anthropology's role(s) in global climate change. Current Anthropology, 49:569-595.

Crate, S., M. Ulrich, J.O. Habeck, A.R. Desyatkin, R.V. Desyatkin, A.N. Fedorov, T. Hiyama, Y. Iijima, S. Ksenofontov, C. Mészáros and H. Takakura, 2017. Permafrost livelihoods: A transdisciplinary review and analysis of thermokarst-based systems of indigenous land use. Anthropocene, 18:89-104.

Crépin, A.S., Å. Gren, G. Engström and D. Ospina, 2017. Operationalising a social–ecological system perspective on the Arctic Ocean. Ambio, 46:475-485.

Cruise Industry News, 2018. 2018 Expedition Market Report. www.cruiseindustrynews.com/store/product/digital-reports/2018-expedition-report

CTIF, 2018a. Sweden is burning – the EU rushes to aid in multiple unstoppable forest fires during hottest summer in 260 years. International Association of Fire and Rescue Services (CTIF). www.ctif.org/news/sweden-burning-eu-rushes-aid-multiple-unstoppable-forest-fires-during-hottest-summer-260-years

CTIF, 2018b. Investigation claims "Swedish authorities are severely lacking in emergency planning for wildfire disasters". International Association of Fire and Rescue Services (CTIF). www.ctif.org/news/investigation-claims-swedish-authorities-are-severely-lacking-emergency-planning-wildfire

Cuerrier, A., N.D. Brunet, J. Gérin-Lajoie, A. Downing and E. Lévesque, 2015. The study of Inuit knowledge of climate change in Nunavik, Quebec: a mixed methods approach. Human Ecology, 43:379-394.

Cutter, S.L., L. Barnes, M. Berry, C. Burton, E. Evans, E. Tate and J. Webb, 2008. A place-based model for understanding community resilience to natural disasters. Global Environmental Change, 18:598-606.

Cuyler, C., J. Rowell, J. Adamczewski, M. Anderson, J. Blake, T. Bretten, V. Brodeur, M. Campbell, S.L. Checkley, H.D. Cluff, S.D. Côté, T. Davison, M. Dumond, B. Ford, A. Gruzdev, A. Gunn, P. Jones, S. Kutz, L.M. Leclerc, C. Mallory, F. Mavrot, J.B. Mosbacher, I.M. Okhlopkov, P. Reynolds, N.M. Schmidt, T. Sipko, M. Suitor, M. Tomaselli and B. Ytrehus, 2020. Muskox status, recent variation, and uncertain future. Ambio, 49:805-819.

Danielsen, F., N. Johnson, O. Lee, M. Fidel, L. Iversen, M.K. Poulsen … M. Enghoff, 2020. Voices from the Arctic: Community-based monitoring in the Arctic. University Alaska Press.

Dawson, J., L. Pizzolato, S.E. Howell, L. Copland and M.E. Johnston, 2018. Temporal and spatial patterns of ship traffic in the Canadian Arctic from 1990 to 2015. Arctic, 71:15-26.

Dawson, J., N. Carter, N. van Luijk, C. Parker, M. Weber, A. Cook, K. Grey and J. Provencher, 2020. Infusing Inuit and local knowledge into the Low Impact Shipping Corridors: An adaptation to increased shipping activity and climate change in Arctic Canada. Environmental Science & Policy, 105:19-36.

Day, J.J. and K.I. Hodges, 2018. Growing land-sea temperature contrast and the intensification of Arctic cyclones. Geophysical Research Letters, 45:3673-3681.

Dixit, A., 2003. Floods and vulnerability: need to rethink flood management. In: Flood Problem and Management in South Asia. pp. 155-179. Springer.

Dobson, A., P.K. Molnár and S. Kutz, 2015. Climate change and Arctic parasites. Trends in Parasitology, 31:181-188.

Dodd, W., P. Scott, C. Howard, C. Scott, C. Rose, A. Cunsolo and J. Orbinski, 2018. Lived experience of a record wildfire season in the Northwest Territories, Canada. Canadian Journal of Public Health, 109:327-337.

Doj, R., 2020. Analys av Renköttsbranschen säsongen 2020/21 utifrån situationer runt COVID-19 [Analysis of the reindeer meat business season 2020/21 based on the Covid-19 situation]. Sametinget [The Swedish Sami Parliament], Kiruna. www.sametinget.se/150169

Douglas, T.A., M.R. Turetsky and C.D. Koven, 2020. Increased rainfall stimulates permafrost thaw across a variety of Interior Alaskan boreal ecosystems. npj Climate and Atmospheric Science, 3:28.

Doyle, A., 2019. As ice melts, Greenland could become big sand exporter - study. Australia's Paydirt, 1:269.

Drury, S.A., 2019. Observed versus predicted fire behavior in an Alaskan black spruce forest ecosystem: an experimental fire case study. Fire Ecology, 15:35.

Dudarev, A.A., S. Yamin-Pasternak, I. Pasternak and V.S. Chupakhin, 2019. Traditional diet and environmental contaminants in coastal Chukotka I: Study design and dietary patterns. International Journal of Environmental Research and Public Health, 16:702.

Duffy-Anderson, J.T., P. Stabeno, A.G. Andrews III, K. Cieciel, A. Deary, E. Farley, C. Fugate, C. Harpold, R. Heintz, D. Kimmel, K. Kuletz, J. Lamb, M. Paquin, S. Porter, L. Rogers, A. Spear and E. Yasumiishi, 2019. Responses of the northern Bering Sea and southeastern Bering

Sea pelagic ecosystems following record-breaking low winter sea ice. Geophysical Research Letters, 46:9833-9842.

Dunn, D.C., A.M. Boustany and P.N. Halpin, 2011. Spatio-temporal management of fisheries to reduce by-catch and increase fishing selectivity. Fish and Fisheries, 12:110-119.

Durkalec, A., C. Furgal, M.W. Skinner and T. Sheldon, 2015. Climate change influences on environment as a determinant of Indigenous health: Relationships to place, sea ice, and health in an Inuit community. Social Science & Medicine, 136:17-26.

Dyrrdal, A.V., K. Isaksen, J.K.S. Jacobsen and I.B. Nilsen, 2020. Present and future changes in winter climate indices relevant for access disruptions in Troms, northern Norway. Natural Hazards and Earth System Sciences, 20:1847-1865.

Eduard, B.G., 2018. Ecological tourism as a factor of sustainable development of the Western Arctic. Social and Economic Development, 32:15-24.

Eide, A., 2017. Climate change, fisheries management and fishing aptitude affecting spatial and temporal distributions of the Barents Sea cod fishery. Ambio, 46:387-399.

Eidlitz, K., 1969. Food and Emergency Food in the Circumpolar Area. Almqvist & Wiksells, Uppsala.

Essington, T.E., P.E. Moriarty, H.E. Froehlich, E.E. Hodgson, L.E. Koehn, K.L. Oken, M.C. Siple and C.C. Stawitz, 2015. Fishing amplifies forage fish population collapses. Proceedings of the National Academy of Sciences, 112:6648-6652.

Eythórsson, E., 1996. Coastal communities and ITQ management. The case of Icelandic fisheries. Sociologia Ruralis, 36:212-223.

Falardeau, M. and E.M. Bennett, 2019. Towards integrated knowledge of climate change in Arctic marine systems: a systematic literature review of multidisciplinary research. Arctic Science, 6:1-23.

Falardeau, M., C. Raudsepp-Hearne and E.M. Bennett, 2019. A novel approach for co-producing positive scenarios that explore agency: case study from the Canadian Arctic. Sustainability Science, 14:205-220.

Fang, Z., P.T. Freeman, C.B. Field and K.J. Mach, 2018. Reduced sea ice protection period increases storm exposure in Kivalina, Alaska. Arctic Science, 4:525-537.

FAO, 2012. Technical Guidelines for Responsible Fisheries. No. 13. United Nations Food and Agriculture Organization (FAO), Rome.

FAO, 2020. Fishery Statistical Collections. Global Aquaculture Production. United Nations Food and Agriculture Organization (FAO), Rome. www.fao.org/fishery/statistics/global-aquaculture-production/en

Fauchald, P., T. Park, H. Tømmervik, R. Myneni and V.H. Hausner, 2017a. Arctic greening from warming promotes declines in caribou populations. Science Advances, 3:e1601365.

Fauchald, P., V. Hausner, J. Schmidt and D. Clark, 2017b. Transitions of social-ecological subsistence systems in the Arctic. International Journal of the Commons, 11:275-329.

Fauchald, P., P. Arneberg, J.B. Debernard, S. Lind, E. Olsen and V.H. Hausner, 2021. Poleward shifts in marine fisheries under Arctic warming. Environmental Research Letters, 16:074057.

Fawcett, D., T. Pearce, R. Notaina, J.D. Ford and P. Collings, 2018. Inuit adaptability to changing environmental conditions over an 11-year period in Ulukhaktok, Northwest Territories. Polar Record, 54:119-132.

Fleischer, N.L., P. Melstrom, E. Yard, M. Brubaker and T. Thomas, 2014. The epidemiology of falling-through-the-ice in Alaska, 1990–2010. Journal of Public Health, 36:235-242.

Folke, C., H. Österblom, J.B. Jouffray, E.F. Lambin, W.N. Adger, M. Scheffer, B.I. Crona, M. Nyström, S.A. Levin, S.R. Carpenter, J.M. Anderies, S. Chapin, A.S. Crépin, A. Dauriach, V. Galaz, L.J. Gordon, N. Kautsky, B.H. Walker, J.R. Watson, J. Wilen and A. de Zeeuw, 2019. Transnational corporations and the challenge of biosphere stewardship. Nature Ecology and Evolution, 3:1396-1403.

Forbes, B.C., 2013. Cultural resilience of social-ecological systems in the Nenets and Yamal-Nenets Autonomous Okrugs, Russia: a focus on reindeer nomads of the tundra. Ecology and Society, 18:36.

Forbes, B.C., F. Stammler, T. Kumpula, N. Meschtyb, A. Pajunen and E. Kaarlejärvi, 2009. High resilience in the Yamal-Nenets social–ecological system, west Siberian Arctic, Russia. Proceedings of the National Academy of Sciences, 106:22041-22048.

Forbes, B.C., T. Kumpula, N. Meschtyb, R. Laptander, M. Macias-Fauria, P. Zetterberg, M. Verdonen, A. Skarin, K.Y. Kim, L.N. Boisvert and J.C. Stroeve, 2016. Sea ice, rain-on-snow and tundra reindeer nomadism in Arctic Russia. Biology Letters, 12:20160466.

Forbes, B.C., M.T. Turunen, P. Soppela, S. Rasmus, T. Vuojala-Magga and H. Kitti, 2020. Changes in mountain birch forests and reindeer management: Comparing different knowledge systems in Sápmi, northern Fennoscandia. Polar Record, 55:507-521.

Forbis, Jr, R. and K. Hayhoe, 2018. Does Arctic governance hold the key to achieving climate policy targets? Environmental Research Letters, 13:020201.

Ford, J.D., G. McDowell, J. Shirley, M. Pitre, R. Siewierski, W. Gough, F. Duerden, T. Pearce, P. Adams and S. Statham, 2013. The dynamic multiscale nature of climate change vulnerability: an Inuit harvesting example. Annals of the Association of American Geographers, 103:1193-1211.

Ford, J.D., G. McDowell and T. Pearce, 2015. The adaptation challenge in the Arctic. Nature Climate Change, 5:1046-1053.

Ford, J.D., D. Clark, T. Pearce, L. Berrang-Ford, L. Copland, J. Dawson, M. New and S.L. Harper, 2019. Changing access to ice, land and water in Arctic communities. Nature Climate Change, 9:335-339.

Forseth, T., B.T. Barlaup, B. Finstad, P. Fiske, H. Gjøsæter, M. Falkegård, A. Hindar, T.A. Mo, A.H. Rikardsen, E.B. Thorstad and L.A. Vøllestad, 2017. The major threats to Atlantic salmon in Norway. ICES Journal of Marine Science, 74:1496-1513.

Fossheim, M., R. Primicerio, E. Johannesen, R.B. Ingvaldsen, M.M. Aschan and A.V. Dolgov, 2015. Recent warming leads to a rapid borealization of fish communities in the Arctic. Nature Climate Change, 5:673-677.

Frainer, A., R. Primicerio, S. Kortsch, M. Aune, A.V. Dolgov, M. Fossheim and M.M. Aschan, 2017. Climate-driven changes in functional biogeography of Arctic marine fish communities. Proceedings of the National Academy of Sciences, 114:12202-12207.

Frank, K.T., B. Petrie, W.C. Leggett and D.G. Boyce, 2016. Large-scale, synchronous variability of marine fish populations driven by commercial exploitation. Proceedings of the National Academy of Sciences, 113:8248-8253.

Froehlich, H.E., R.R. Gentry and B.S. Halpern, 2018. Global change in marine aquaculture production potential under climate change. Nature Ecology & Evolution, 2:1745-1750.

Frommel, A.Y., R. Maneja, D. Lowe, A.M. Malzahn, A.J. Geffen, A. Folkvord, U. Piatkowski, T.B.H. Reusch and C. Clemmesen, 2012. Severe tissue damage in Atlantic cod larvae under increasing ocean acidification. Nature Climate Change, 2:42-46.

Fujiwara, J., 2018. Flood risk and migration in the Sakha Republic (Yakutia). In: Hiyama, T. and H. Takakura (eds.), Global Warming and Human-Nature Dimension in Northern Eurasia. pp. 125-143. Global Environmental Studies.

Gagnon, C.A., S. Hamel, D.E. Russell, T. Powell, J. Andre, M.Y. Svoboda and D. Berteaux, 2020. Merging indigenous and scientific knowledge links climate with the growth of a large migratory caribou population. Journal of Applied Ecology, 57:1644-1655.

Galappaththi, E.K., J.D. Ford, E.M. Bennett and F. Berkes, 2019. Climate change and community fisheries in the arctic: a case study from Pangnirtung, Canada. Journal of Environmental Management, 250:109534.

Gascard, J.C., K. Riemann-Campe, R. Gerdes, H. Schyberg, R. Randriamampianina, M. Karcher, J. Zhang and M. Rafizadeh, 2017. Future sea ice conditions and weather forecasts in the Arctic: Implications for Arctic shipping. Ambio, 46:355-367.

Gjørv, G.H., 2017. Tensions between environmental, economic and energy security in the Arctic. In: Northern Sustainabilities: Understanding and Addressing Change in the Circumpolar World. pp. 35-46. Springer.

Glover, K.A., M.F. Solberg, P. McGinnity, K. Hindar, E. Verspoor, M.W. Coulson, M.M. Hansen, H. Araki, Ø. Skaala and T. Svåsand, 2017. Half a century of genetic interaction between farmed and wild Atlantic salmon: Status of knowledge and unanswered questions. Fish and Fisheries, 18:890-927.

Golovnev, A.V., 2017. Challenges to Arctic nomadism: Yamal Nenets facing climate change era calamities. Arctic Anthropology, 54:40-51.

Golovnev, A., 2000. 'Put' k Semi Chumam'. In: Golovnev, A. (ed.), Drevnosti Yamala, pp. 208-236. Ural Branch of the Russian Academy of Sciences.

Golyatina, M., I. Vahnina and E. Noskova, 2018. Estimation of the dynamics of areas passed by fire in the territory of Zabaikalsky region under conditions of climate change according to DSP data Perm, Perm State National Research University. https://elibrary.ru/item.asp?id=35723291

Government of the NWT, 2018. Traditional Activities. Government of the Northwest Territories (NWT) Bureau of Statistics. [Online]. www.statsnwt.ca/Traditional%20Activities

Grebmeier, J.M., L.W. Cooper, H.M. Feder and B.I, Sirenko, 2006. Ecosystem dynamics of the Pacific-influenced northern Bering and

Chukchi Seas in the Amerasian Arctic. Progress in Oceanography, 71:331-361.

Grebmeier, J.M., B.A. Bluhm, L.W. Cooper, S.L. Danielson, K.R. Arrigo, A.L. Blanchard, J.T. Clarke, R.H. Day, K.E. Frey, R.R. Gradinger and M. Kędra, 2015. Ecosystem characteristics and processes facilitating persistent macrobenthic biomass hotspots and associated benthivory in the Pacific Arctic. Progress in Oceanography, 136:92-114.

Grigoriev, M.N., 2020. Development of maritime transportation of the Arctic oil and gas condensate. Burenye i Neft, 9:16-25. (In Russian)

Gulas, S., M. Downton, K. D'Souza, K. Hayden and T.R. Walker, 2017. Declining Arctic Ocean oil and gas developments: Opportunities to improve governance and environmental pollution control. Marine Policy, 75:53-61.

Gullestad, P., A. Aglen, Å. Bjordal, G. Blom, S. Johansen, J. Krog, O.A. Misund and I. Røttingen, 2014. Changing attitudes 1970–2012: evolution of the Norwegian management framework to prevent overfishing and to secure long-term sustainability. ICES Journal of Marine Science, 71:173-182.

Gullestad, P., A.M. Abotnes, G. Bakke, M. Skern-Mauritzen, K. Nedreaas and G. Søvik, 2017. Towards ecosystem-based fisheries management in Norway – practical tools for keeping track of relevant issues and prioritising management efforts. Marine Policy, 77:104-110.

Gullestad, P., S. Sundby and O.S. Kjesbu, 2020. Management of transboundary and straddling fish stocks in the Northeast Atlantic in view of climate-induced shifts in spatial distribution. Fish and Fisheries, 21:1008-1026.

Hale, B.W., 2018. Mapping potential environmental impacts from tourists using data from social media: a case study in the Westfjords of Iceland. Environmental Management, 62:446-457.

Halpern, A., 2020. What the Future of Polar Travel Looks Like? www.cntraveler.com/story/how-the-coronavirus-could-impact-polar-travel?verso=true

Halttunen, E., K.Ø. Gjelland, K.A. Glover, I.A. Johnsen, R.M. Serra-Llinares, Ø. Skaala, R. Nilsen, P.A. Bjørn, Ø. Karlsen, B. Finstad and O.T. Skilbrei, 2018. Migration of Atlantic salmon post-smolts in a fjord with high infestation pressure of salmon lice. Marine Ecology Progress Series, 592:243-256.

Hamre, J., 1994. Biodiversity and exploitation of the main fish stocks in the Norwegian-Barents Sea ecosystem. Biodiversity & Conservation, 3:473-492.

Handmer, J., Y. Honda, Z.W. Kundzewicz, N. Arnell, G. Benito, J. Hatfield, I.F. Mohamed, P. Peduzzi, S. Wu, B. Sherstyukov,K. Takahashi and Z. Yan, 2012. Changes in impacts of climate extremes: human systems and ecosystems. In: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). pp. 231-290. Cambridge University Press.

Hänsel, M.C., J.P. Schmidt, M.H. Stiasny, M.T. Stöven, R. Voss and M.F. Quaas, 2020. Ocean warming and acidification may drag down the commercial Arctic cod fishery by 2100. PLoS ONE, 15:e0231589.

Hansen, A.M. and P. Ipalook, 2020. Local views on oil development in a village on the North Slope of Alaska. In: Johnstone, R.L. and A.M. Hansen (eds), Regulation of Extractive Industries: Community Engagement in the Arctic. Chapter 8. Routledge.

Hansen, A.M., L. Ingebrigtson and S. Edmunds-Potvin, 2018. Health and well-being. In: Adaptation Actions for a Changing Arctic: Perspectives from the Baffin Bay/Davis Strait Region. pp. 101-120. Arctic Monitoring and Assessment Programme, Oslo, Norway.

Hansen, B.B., Å.Ø. Pedersen, B. Peeters, M. Le Moullec, S.D. Albon, I. Herfindal, B.E. Sæther, V. Grøtan and R. Aanes, 2019. Spatial heterogeneity in climate change effects decouples the long-term dynamics of wild reindeer populations in the high Arctic. Global Change Biology, 25:3656-3668.

Hanssen-Bauer, I., E.J. Førland, H. Hisdal, S. Mayer, A.B. Sandø and A. Sorteberg (eds), 2019. Climate in Svalbard 2100 - a knowledge base for climate adaptation. Norwegian Centre of Climate Services (NCCS) for Norwegian Environment Agency (Miljødirektoratet). NCCS report 1/2019.

Harper, S.L., V.L. Edge, C.J. Schuster-Wallace, O. Berke and S.A. McEwen, 2011. Weather, water quality and infectious gastrointestinal illness in two Inuit communities in Nunatsiavut, Canada: potential implications for climate change. EcoHealth, 8:93-108.

Harper, S.L., C. Wright, S. Masina and S. Coggins, 2020. Climate change, water, and human health research in the Arctic. Water Security, 10:100062.

Haug, T., B. Bogstad, M. Chierici, H. Gjøsæter, E.H. Hallfredsson, Å.S. Høines, A.H. Hoel, R.B. Ingvaldsen, L.L. Jørgensen, T. Knutsen and H. Loeng, 2017. Future harvest of living resources in the Arctic Ocean north of the Nordic and Barents Seas: a review of possibilities and constraints. Fisheries Research, 188:38-57.

Hausner, V.H., S. Engen, C. Brattland and P. Fauchald, 2020. Sámi knowledge and ecosystem-based adaptation strategies for managing pastures under threat from multiple land uses. Journal of Applied Ecology, 57:1656-1665.

Heleniak, T. and D. Bogoyavlensky, 2014. Arctic populations and migration. In: Arctic Human Development Report: Regional Processes and Global Linkages, pp. 53-104.

Herman-Mercer, N.M., R.A. Loehman, R.C. Toohey and C. Paniyak, 2020. Climate- and disturbance-driven changes in subsistence berries in coastal Alaska: Indigenous Knowledge to inform ecological inference. Human Ecology, 48:85-99.

Hersoug, B., E. Mikkelsen and K.M. Karlsen, 2019. "Great expectations" – Allocating licenses with special requirements in Norwegian salmon farming. Marine Policy, 100:152-162.

Hildebrand, L.P., L.W. Brigham and T.M. Johansson (eds.), 2018. Sustainable Shipping in a Changing Arctic. Springer.

Hillmer-Pegram, K., 2017. Within the changing system of Arctic tourism, what should be made resilient to what, and for whom? In: Lew, A.A. and J.M. Cheer (eds), Tourism Resilience and Adaptation to Environmental Change: Definitions and Frameworks. Chapter 16. Routledge.

Hjermann, D.Ø., G. Ottersen and N.C. Stenseth, 2004. Competition among fishermen and fish causes the collapse of Barents Sea capelin. Proceedings of the National Academy of Sciences, 101:11679-11684.

Hjort, J., O. Karjalainen, J. Aalto, S. Westermann, V.E. Romanovsky, F.F. Nelson, B. Etzelmüller and M. Luoto, 2018. Degrading permafrost puts Arctic infrastructure at risk by mid-century. Nature Communications, 9:5147.

Hoel, A.H., 2018. Northern fisheries. In: Nuttall, M., T.R. Christensen and M. Siegert (eds.), The Routledge Handbook of the Polar Regions. Routledge.

Hollowed, A.B. and S. Sundby, 2014. Change is coming to the northern oceans. Science, 344:1084-1085.

Hollowed, A.B., K.K. Holsman, A.C. Haynie, A.J. Hermann, A.E. Punt, K. Aydin, J.N. Ianelli, S. Kasperski, W. Cheng, A. Faig and A. Kearney, 2020. Integrated modeling to evaluate climate change impacts on coupled social-ecological systems in Alaska. Frontiers in Marine Science, 6:775.

Hong, E., R. Perkins and S. Trainor, 2014. Thaw settlement hazard of permafrost related to climate warming in Alaska. Arctic, 67:93-103.

Horstkotte, T., É. Lépy and C. Risvoll (eds.), 2020. Supplementary feeding in reindeer husbandry – Results from a workshop with reindeer herders and researchers from Norway, Sweden and Finland. Umeå University. www.rexsac.org/wp-content/uploads/2020/12/25166_Rapporten_eng.pdf

Hovelsrud, G.K., J.L. White, M. Andrachuk and B. Smit, 2010. Community adaptation and vulnerability integrated. In: Hovelsrud, G.K. and B. Smit (eds.), Community Adaptation and Vulnerability in Arctic Regions. pp. 335-348. Springer.

Hovelsrud, G.K., B.P. Kaltenborn and J. Olsen, 2020. Svalbard in transition: adaptation to cross-scale changes in Longyearbyen. The Polar Journal, 10:420-442.

Hu, F.S., P.E. Higuera, P. Duffy, M.L. Chipman, A.V. Rocha, A.M. Young, R. Kelly and M.C. Dietze, 2015. Arctic tundra fires: natural variability and responses to climate change. Frontiers in Ecology and the Environment, 13:369-377.

Humlum, O., A. Instanes and J.L. Sollid, 2003. Permafrost in Svalbard: a review of research history, climatic background and engineering challenges. Polar Research, 22:191-215.

Hunt, J.D. and E. Byers, 2019. Reducing sea level rise with submerged barriers and dams in Greenland. Mitigation and Adaptation Strategies for Global Change, 24:779-794.

Hunt, Jr, G.L., P. Stabeno, G. Walters, E. Sinclair, R.D. Brodeur, J.M. Napp and N.A. Bond, 2002. Climate change and control of the southeastern Bering Sea pelagic ecosystem. Deep Sea Research II, 49:5821-5853.

Hunt, Jr, G.L., K.O. Coyle, L.B. Eisner, E.V. Farley, R.A. Heintz, F. Mueter, J.M. Napp, J.E. Overland, P.H. Ressler, S. Salo and P.J. Stabeno, 2011. Climate impacts on eastern Bering Sea foodwebs: a synthesis of new data and an assessment of the Oscillating Control Hypothesis. ICES Journal of Marine Science, 68:1230-1243.

Huntington, H.P., L.T. Quakenbush and M. Nelson, 2016. Effects of changing sea ice on marine mammals and subsistence hunters in northern Alaska from traditional knowledge interviews. Biology Letters, 12:20160198.

Huntington, H.P., L.T. Quakenbush and M. Nelson, 2017. Evaluating the effects of climate change on indigenous marine mammal hunting in northern and western Alaska using traditional knowledge. Frontiers in Marine Science, 4:319.

Huntington, H.P., M. Carey, C. Apok, B.C. Forbes, S. Fox, L.K. Holm, A. Ivanova, J. Jaypoody, G. Noongwook and F. Stammler, 2019. Climate change in context: putting people first in the Arctic. Regional Environmental Change, 19:1217-1223.

Huntington, H.P., S.L. Danielson, F.K. Wiese, M. Baker, P. Boveng, J.J. Citta, A. De Robertis, D.M. Dickson, E. Farley, J.C. George and K. Iken, 2020. Evidence suggests potential transformation of the Pacific Arctic ecosystem is underway. Nature Climate Change, 10:342-348.

Hwang, B., Y. Aksenov, E. Blockley, M. Tsamados, T. Brown, J. Landy, D. Stevens and J. Wilkinson, 2020. Impacts of climate change on Arctic sea ice. MCCIP Science Review, 2020:208-227.

ICC, 2015. Alaskan Inuit Food Security Conceptual Framework: How to Assess the Arctic from an Inuit Perspective. Inuit Circumpolar Council (ICC). https://iccalaska.org/wp-icc/wp-content/uploads/2016/05/Food-Security-Full-Technical-Report.pdf

Icelandic Tourist Board, 2018. Tourism in Iceland in Figures. May 2018. www.ferdamalastofa.is/static/files/ferdamalastofa/talnaefni/ferdatjonusta-i-tolum/tourism-in-iceland-2018_en_skjal.pdf

Icelandic Tourist Board, 2020. Number of foreign visitors. www.ferdamalastofa.is/en/recearch-and-statistics/numbers-of-foreign-visitors Accessed 18 June 2020.

IMO, 2017. International Code for Ships Operating in Polar Waters (Polar Code). International Maritime Organization (IMO).

Ims, R.A., J.A. Henden, M.A. Strømeng, A.V. Thingnes, M.J. Garmo and J.U. Jepsen, 2019. Arctic greening and bird nest predation risk across tundra ecotones. Nature Climate Change, 9:607-610.

IPCC, 2018. Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Intergovernmental Panel on Climate Change (IPCC).

IPCC, 2019. Technical Summary. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Intergovernmental Panel on Climate Change (IPCC).

Ivanov, A.Y., N.A. Filimonova, A.Y. Kucheiko, N.V. Evtushenko and N.V. Terleeva, 2018. Oil spills in the Barents Sea based on satellite monitoring using SAR: spatial distribution and main sources. International Journal of Remote Sensing, 39:4484-4498.

IWGIA, 2012. Briefing Note: Indigenous Peoples of the Russian Federation. International Work Group for Indigenous Affairs (IWGIA). Copenhagen, Denmark. www.iwgia.org/images/publications/0573_THE_INDIGENOUS_ORLD-2012_eb.pdf

IWGIA, 2018. The Indigenous World 2018. International Work Group for Indigenous Affairs (IWGIA). Copenhagen, Denmark. www.iwgia.org/images/documents/indigenous-world/indigenous-world-2018.pdf

Jóhannsdóttir, L. and D. Cook, 2015. An insurance perspective on Arctic opportunities and risks: Hydrocarbon exploration and shipping. Institute of International Affairs. Centre for Arctic Policy Studies, University of Iceland.

Johannsdottir, L. and D. Cook, 2019. Systemic risk of maritime-related oil spills viewed from an Arctic and insurance perspective. Ocean & Coastal Management, 179:104853.

Johannsdottir, L., D. Cook and G.M. Arruda, 2021. Systemic risk of cruise ship incidents from an Arctic and insurance perspective. Elementa: Science of the Anthropocene, 9:00009.

Johansen, U., H. Bull-Berg, L.H. Vik, A.M. Stokka, R. Richardsen and U. Winther, 2019. The Norwegian seafood industry–Importance for the national economy. Marine Policy, 110:103561.

Johnson, N., C. Behe, F. Danielsen, E.M. Krümmel, S. Nickels and P.L. Pulsifer, 2016. Community-based monitoring and indigenous knowledge in a changing arctic: a review for the sustaining Arctic observing networks. Sustaining Arctic Observing Networks Task, Final report to Sustaining Arctic Observing Networks. Ottawa, Canada : Inuit Circumpolar Council, 65pp. http://dx.doi.org/10.25607/OBP-822

Johnson, N., T. Pearce, K. Breton-Honeyman, D.N. Etiendem and L.L. Loseto, 2020. Knowledge mobilization on co-management, co-production of knowledge, and community-based monitoring to support effective wildlife resource decision making and Inuit self-determination. Arctic Science, 6:1240126.

Jones, B.M., C.D. Arp, M.T. Jorgenson, K.M. Hinkel, J.A. Schmutz and P.L. Flint, 2009. Increase in the rate and uniformity of coastline erosion in Arctic Alaska. Geophysical Research Letters, 36:10.1029/2008GL036205

Jorgenson, M.T. and J. Brown, 2005. Classification of the Alaskan Beaufort Sea Coast and estimation of carbon and sediment inputs from coastal erosion. Geo-Marine Letters, 25:69-80.

Jorgenson, M.T., Y.L. Shur and E.R. Pullman, 2006. Abrupt increase in permafrost degradation in Arctic Alaska. Geophysical Research Letters, 33: 10.1029/2005GL024960

Jørgensen, L.L., R. Primicerio, R. Ingvaldsen, M. Fossheim, N. Strelkova, T. Thangstad, I. Manushin and D. Zakharov, 2019. Impact of multiple stressors on sea bed fauna in a warming Arctic. Marine Ecology Progress Series, 608:1-12.

Jørgensen, L.L., G. Bakke and A.H. Hoel, 2020. Responding to global warming: New fisheries management measures in the Arctic. Progress in Oceanography, 188:102423.

Jungsberg, L., E. Turunen, T. Heleniak, S. Wang, J. Ramage and J. Roto, 2019. Atlas of Population. Society and Economy in the Arctic. doi.org/10.30689/WP2019:3.1403-2511

Jurgilevich, A., A. Räsänen, F. Groundstroem and S. Juhola, 2017. A systematic review of dynamics in climate risk and vulnerability assessments. Environmental Research Letters, 12:013002.

Kahru, M., Z. Lee, B.G. Mitchell and C.D. Nevison, 2016. Effects of sea ice cover on satellite-detected primary production in the Arctic Ocean. Biology Letters, 12:20160223.

Kasischke, E.S. and M.R. Turetsky, 2006. Recent changes in the fire regime across the North American boreal region – Spatial and temporal patterns of burning across Canada and Alaska. Geophysical Research Letters, 33(9).

Kayhko, J., E. Apsite, A. Bolek, N. Filatov, S. Kondratyev, J. Korhonen, J. Kriaučiūnienė, G. Lindstrom, L. Nazarova, A. Pyrh and M. Sztobryn, 2015. Recent change: river run-off and ice cover. In: Second Assessment of Climate Change for the Baltic Sea Basin. pp. 99-116.

Kelly, R., M.L. Chipman, P.E. Higuera, I. Stefanova, L.B. Brubaker and F.S. Hu, 2013. Recent burning of boreal forests exceeds fire regime limits of the past 10,000 years. Proceedings of the National Academy of Sciences, 110:13055-13060.

Kelman, I. and M.W. Næss, 2019. Climate change and migration for Scandinavian Saami: A review of possible impacts. Climate, 7:47 10.3390/cli7040047

Kelman, I., A.K. Sydnes, P.I. Duda, E. Nikitina and C. Webersik, 2020. Norway-Russia disaster diplomacy for Svalbard. Safety Science, 130:104896.

Kipp, A., A. Cunsolo, K. Vodden, N. King, S. Manners and S.L. Harper, 2019. At-a-glance climate change impacts on health and wellbeing in rural and remote regions across Canada: a synthesis of the literature. Health Promotion and Chronic Disease Prevention in Canada: Research, Policy and Practice, 39:122-126.

Klokov, K.B., 2019. Evolution of the subsistence pattern of indigenous population of the coast of southern Chukotka: energy and resources aspects. In: IOP Conference Series: Earth and Environmental Science. 10.1088/1755-1315/302/1/012077

Klokov, K.B. and V.V. Mikhailov, 2019. Assessment of climatic conditions for Siberian reindeer herding on the basis of heat balance modelling. Arctic, 72:28-42.

Knapp, C.N. and S.F. Trainor, 2013. Adapting science to a warming world. Global Environmental Change, 23:1296-1306.

Koenigstein, S., 2020. Arctic marine ecosystems, climate change impacts, and governance responses: an integrated perspective from the Barents Sea. In: Arctic Marine Sustainability. pp. 45-71. Springer.

Kokorin, A., E. Smirnova and D. Zamolodchikov, 2013. Climate Change. Volume 2, Regions of the Far East. WWF, Russia, Moscow, www.wwf.ru/resources/publ/book/809 (In Russian)

Konopko, A., 2021. Fuel Spill in Norilsk. Vesti, 05.02.2021. http://www.vesti.ru/article

Kontar, Y.Y., U.S. Bhatt, S.D. Lindsey, E.W. Plumb and R.L. Thoman, 2015. Interdisciplinary approach to hydrological hazard mitigation and disaster response and effects of climate change on the occurrence of flood severity in central Alaska. Proceedings of the International Association of Hydrological Sciences, 369:13-17.

Kontar, Y.Y., J.C. Eichelberger, T.N. Gavrilyeva, V.V. Filippova, A.N. Savvinova, N.I. Tananaev and S.F. Trainor, 2018a. Springtime flood risk reduction in rural Arctic: a comparative study of interior Alaska, United States and Central Yakutia, Russia. Geosciences, 8:90. doi:10.3390/geosciences8030090

Kontar, Y., S. Trainor, T. Gavrilyeva, J. Eichelberger and N. Tananaev, 2018b. Advancing Spring Flood Risk Reduction in the Arctic through Interdisciplinary Research and Stakeholder Collaborations. In: Beer, T., J. Li and K. Alverson (eds.), Global Change and Future Earth: The Geoscience Perspective. Special Publications of the International Union of Geodesy and Geophysics, pp. 341-348. Cambridge University Press.

Kravits, M. and V. Gastaldo, 2017. Emergency management in the Arctic: The context explained. In: Lackenbauer, W. and H. Nicol (eds.), Whole of Government through Arctic Lens. pp. 269-294. Mulreney Institute of Government, Nova Scotia, Canada.

Kroodsma, D.A., J. Mayorga, T. Hochberg, N.A. Miller, K. Boerder, F. Ferretti, A. Wilson, B. Bergman, T.D. White, B.A. Block and P. Woods, 2018. Tracking the global footprint of fisheries. Science, 359:904-908.

Krupnik, I., 1993. Native Whalers and Reindeer Herders of Northern Eurasia. Arctic Visions Series. University Press of New England.

Krupnik, I., 2018. 'Arctic crashes:' revisiting the human-animal disequilibrium model in a time of rapid change. Human Ecology, 46:685-700.

Ksenofontov, S., N. Backhaus and G. Schaepman-Strub, 2017. 'To fish or not to fish?': fishing communities of Arctic Yakutia in the face of environmental change and political transformations. Polar Record, 53:289-303.

Ksenofontov, S., N. Backhaus and G. Schaepman-Strub, 2019. 'There are new species': indigenous knowledge of biodiversity change in Arctic Yakutia. Polar Geography, 42:34-57.

Kumar, M.B., C. Furgal, P. Hutchinson, W. Roseborough and S. Kootoo-Chiarello, 2019. Harvesting activities among First Nations people living off reserve, Métis and Inuit: Time trends, barriers and associated factors. Edited by Statistics Canada.

Kumpula, J., M. Jokinen, J. Siitari and S. Siitari, 2020. Talven 2019–2020 sää-, lumi- ja luonnonolosuhteiden poikkeuksellisuus ja vaikutukset poronhoitoon [Exceptional weather, snow and natural conditions in winter 2019–2020 and effects on reindeer husbandry]. Luonnonvara- ja biotalouden tutkimus 58/2020. https://jukuri.luke.fi/handle/10024/546154

Kusatov, K.I., A.P. Ammosov, Z.G. Kornilova and R.N. Shpakova, 2012. Anthropogenic factor of ice jamming and spring breakup flooding on the Lena River. Russian Meteorology and Hydrology, 37:392-396.

Kuznetsov, A., E. Nikitina and J. Baronona, 2019. The changing Arctic: vision for prospects of sustainable development on northern areas. World Economy & International Relations, 63:64-69.

Laforest, B.J., J.S. Hébert, M.E. Obbard and G.W. Thiemann, 2018. Traditional ecological knowledge of polar bears in the northern Eeyou marine region, Québec, Canada. Arctic, 71:40-58.

Laidre, K.L., H. Stern, K.M. Kovacs, L. Lowry, S.E. Moore, E.V. Regehr, S.H. Ferguson, Ø. Wiig, P. Boveng, R.P. Angliss, E.W. Born, D. Litovka, L. Quakenbush, C. Lydersen, D. Vongraven and F. Ugarte, 2015. Arctic marine mammal population status, sea ice habitat loss, and conservation recommendations for the 21st century. Conservation Biology, 29:724-737.

Laidre, K.L., A.D. Northey and F. Ugarte, 2018. Traditional knowledge about polar bears (*Ursus maritimus*) in East Greenland: changes in the catch and climate over two decades. Frontiers in Marine Science, 5.

Laidre, K.L., S. Atkinson, E.V. Regehr, H.L. Stern, E.W. Born, Ø. Wiig, N.J. Lunn and M. Dyck, 2020. Interrelated ecological impacts of climate change on an apex predator. Ecological Applications, 30:e02071.

Lam, V.W., W.W. Cheung and U.R. Sumaila, 2016a. Marine capture fisheries in the Arctic: winners or losers under climate change and ocean acidification? Fish and Fisheries, 17:335-357.

Lam, V.W., W.W. Cheung, G. Reygondeau and U.R. Sumaila, 2016b. Projected change in global fisheries revenues under climate change. Scientific Reports, 6:32607.

Lamalice, A., D. Haillot, M.A. Lamontagne, T.M. Herrmann, S. Gibout, S. Blangy, J.L. Martin, V. Coxam, J. Arsenault, L. Munro and F. Courchesne, 2018. Building food security in the Canadian Arctic through the development of sustainable community greenhouses and gardening. Écoscience, 25:325-341.

Lamers, M., P. Duske and L. van Bets, 2018. Understanding user needs: A practice-based approach to exploring the role of weather and sea ice services in European Arctic expedition cruising. Polar Geography, 41:262-278.

Lamoureux, S., D.L. Forbes, T. Bell, G.K. Manson, A.C.A. Rudy, J. Lalonde, M. Brown, I.R. Smith, T.S. James, N.J. Couture and D.J.R. Whalen, 2015. The impact of climate change on infrastructure in the Western and Central Canadian Arctic. In: Stern, G.A. and A. Gaden (eds.), From Science to Policy in the Western and Central Canadian Arctic: an Integrated Regional Impact Study (IRIS) of Climate Change and Modernization. pp. 300-341. ArcticNet.

Landauer, M. and S. Juhola, 2019. Loss and damage in the rapidly changing arctic. In: Loss and Damage from Climate Change. pp. 425-447. Springer.

Langangen, Ø., J. Ohlberger, L.C. Stige, J.M. Durant, E. Ravagnan, N.C. Stenseth and D.Ø. Hjermann, 2017. Cascading effects of mass mortality events in Arctic marine communities. Global Change Biology, 23:283-292.

Lantz, T.C., N.D. Moffat, B.M. Jones, Q. Chen and C.E. Tweedie, 2020. Mapping exposure to flooding in three coastal communities on the North Slope of Alaska using Airborne LiDAR. Coastal Management, 48:96-117.

Larsen, J.N. and G. Fondahl (eds.), 2015. Arctic Human Development Report: Regional processes and global linkages. Nordic Council of Ministers, Copenhagen, Denmark. 10.6027/TN2014-567

Larsen, P.H., S. Goldsmith, O. Smith, M.L. Wilson, K. Strzepek, P. Chinowsky and B. Saylor, 2008. Estimating future costs for Alaska public infrastructure at risk from climate change. Global Environmental Change, 18:442-457.

Larsen, J.N., O.A. Anisimov, A. Constable, A.B. Hollowed, N. Maynard, P. Prestrud, T.D. Prowse and J.M.R. Stone, 2014. Polar regions. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. pp. 1567-1612. Cambridge University Press.

Larsen, J.N., P. Schweitzer and A. Petrov, 2015. Arctic Social Indicators: ASI II: Implementation. Nordic Council of Ministers.

Lavrillier, A., 2013. Climate change among nomadic and settled Tungus of Siberia: continuity and changes in economic and ritual relationships with the natural environment. Polar Record, 49:260-271.

Lavrillier, A. and S. Gabyshev, 2018. An emic science of climate: a reindeer Evenki environmental knowledge and the notion of an extreme process of change. Études Mongoles et Sibériennes, 49.

Lebel, L., E. Nikitina and J. Manuta, 2006. Flood disaster risk management in Asia: An institutional and political perspective. Science and Culture, 71:2-9.

Lebel, L., B.T. Sinh and E. Nikitina, 2010. Adaptive governance of risks: climate, water, and disasters. In: Climate Change Adaptation and Disaster Risk Reduction: Issues and Challenges. Emerald Group Publishing.

Lefebvre, K.A., L. Quakenbush, E. Frame, K.B. Huntington, G. Sheffield, R. Stimmelmayr, A. Bryan, P. Kendrick, H. Ziel, T. Goldstein, J.A. Snyder, F. Gulland, B. Dickerson and B. Gill, 2016. Prevalence of algal toxins in Alaskan marine mammals foraging in a changing arctic and subarctic environment. Harmful Algae, 55:13-24.

Lefort, K.J., C.J. Matthews, J.W. Higdon, S.D. Petersen, K.H. Westdal, C.J. Garroway and S.H. Ferguson, 2020. A review of Canadian Arctic killer whale (*Orcinus orca*) ecology. Canadian Journal of Zoology, 98:245-253.

Leksin V. and B. Porfiriev, 2017 Специфика трансформации пространственной системы и стратегии переосвоения Российской Арктики в условиях изменений климата [Specificities of spatial system transformation and strategies of the Russian Arctic redevelopment under the conditions of climate changes]. Yekaterinburg, Institute of Economics, Ural Branch of the Russian Academy of Sciences www.elibrary.ru/item.asp?id=30047972

Lemelin, R.H., E. Stewart and J. Dawson, 2013. An introduction to last chance tourism. In: Last Chance Tourism. pp. 21-27. Routledge.

LEO network, no date. About LEO Network: The eyes, ears, and voice of our changing environment www.leonetwork.org/en/docs/about/about

Lewis, K.M., G.L. van Dijken and K.R. Arrigo, 2020. Changes in phytoplankton concentration now drive increased Arctic Ocean primary production. Science, 369:198-202.

Lidskog, R., J. Johansson and D. Sjödin, 2019. Wildfires, responsibility and trust: public understanding of Sweden's largest wildfire. Scandinavian Journal of Forest Research, 34:319-328.

Liu, N., E.A. Kirk and T. Henriksen (eds.), 2017. The European Union and the Arctic. Brill.

Lofthus, S., I. Bakke, J. Tremblay, C.W. Greer and O.G. Brakstad, 2020. Biodegradation of weathered crude oil in seawater with frazil ice. Marine Pollution Bulletin, 154:111090.

Loring, P.A. and S.C. Gerlach, 2015. Searching for progress on food security in the North American North: a research synthesis and meta-analysis of the peer-reviewed literature. Arctic, 68:380-392.

Maher, P.T., 2017. Tourism futures in the Arctic. In: The Interconnected Arctic – UArctic Congress 2016. pp. 213-220. Springer.

Maher, P.T. and D. Meade, 2008. Cruise Tourism in Auyuittuq, Sirmilik and Quttinirpaaq National Parks. Technical Report-ORTM Publication Series 2008-02. UNBC ORTM Program, Prince George.

Makeev, V.M., K.B. Klokov, L.A. Kolpashchikov and V.V. Mikhailov, 2014. Reindeer in Conditions of Changing Climate. Lemma, Saint-Petersburg.

Maleev, V., 2016. Anthrax Outbreak in Yamal: Warming wakes up the bacteria. Interview with BBC News, Russian Service, 2 August 2016. www.bbc.com/russian/features-36954908

Mamuji, A.A. and J.L. Rozdilsky, 2019. Wildfire as an increasingly common natural disaster facing Canada: understanding the 2016 Fort McMurray wildfire. Natural Hazards, 98:163-180.

Marinaite, I.I., E.V. Molozhnikova and T.V. Khodzher, 2018. PAHs transfer and intake to the water area of Lake Baikal during the summer forest fires in 2016. In: 24th International Symposium on Atmospheric and Ocean Optics: Atmospheric Physics, 10833:1083374.

Marino, E., 2012. The long history of environmental migration: Assessing vulnerability construction and obstacles to successful relocation in Shishmaref, Alaska. Global Environmental Change, 22:374-381.

Marino, E., 2015. Fierce Climate, Sacred Ground: An Ethnography of Shishmaref, Alaska. University of Alaska Press.

Markkula, I., M. Turunen and S. Rasmus, 2019. A review of climate change impacts on the ecosystem services in the Saami Homeland in Finland. Science of the Total Environment, 692:1070-1085.

Marshall, G.J., K. Jylhä, S. Kivinen, M. Laapas and A.V. Dyrrdal, 2020. The role of atmospheric circulation patterns in driving recent changes in indices of extreme seasonal precipitation across Arctic Fennoscandia. Climatic Change, 162:741-759.

Masrur, A., A.N. Petrov and J. DeGroote, 2018. Circumpolar spatio-temporal patterns and contributing climatic factors of wildfire activity in the Arctic tundra from 2001–2015. Environmental Research Letters, 13:014019.

Mazzullo, N., 2010. More than meat on the hoof. In: Stammler, F. and H. Takakura (eds.), Good to Eat, Good to Live with: Nomads and Animals in Northern Eurasia and Africa, 11:101-119. Northeast Asian Study Series. Center for Northeast Asian studies, Tohoku University.

Mazzullo, N., 2016. The Nellim Forest conflict in Finnish Lapland: between state forest mapping and local forest living. In: Nomadic and Indigenous Spaces. pp. 107-128. Routledge.

McGee, M., 2019. Governor's disaster declaration over Mat-Su, Kenai Peninsula wildfires opens up aid for residents. Anchorage Daily News. www.adn.com

Medvedeva, O.E., 2015. Zadachi otsenki ekologicheskogo ushcherba v Arkticheskoi zone [The tasks of the assessment of environmental damage in the Arctic]. Arktika i Sever, 18:131-147.

Medvedkov, A., 2017a Арктическая зона Российской Федерации: геоэкологические риски в условиях глобальных изменений климата [The Arctic zone of the Russian Federation: geoecological risks in the context of global climate change]. Moscow State Regional University www.elibrary.ru/item.asp?id=32238802

Medvedkov, A., 2017b. Арктическая зона России: экологические угрозы в условиях климатических изменений [Russian Arctic zone: environmental threats under climatic change]. All-Russian Research Institute for Civil Defense and Emergencies EMERCOM of Russia www.elibrary.ru/item.asp?id=30642644

Melin, M., L. Mehtätalo, P. Helle, K. Ikonen and T. Packalen, 2020. Decline of the boreal willow grouse (*Lagopus lagopus*) has been accelerated by more frequent snow-free springs. Scientific Reports, 10:6987.

Melvin, A.M., P. Larsen, B. Boehlert, J.E. Neumann, P. Chinowsky, X. Espinet, J. Martinich, M.S. Baumann, L. Rennels, A. Bothner and D.J. Nicolsky, 2017a. Climate change damages to Alaska public infrastructure and the economics of proactive adaptation. Proceedings of the National Academy of Sciences, 114:E122-E131.

Melvin, A.M., J. Murray, B. Boehlert, J.A. Martinich, L. Rennels and T.S. Rupp, 2017b. Estimating wildfire response costs in Alaska's changing climate. Climatic Change, 141:783-795.

Meredith, M., M. Sommerkorn, S. Cassotta, C. Derksen, A. Ekaykin, A. Hollowed, G. Kofinas, A. Mackintosh, J. Melbourne-Thomas, M.M.C. Muelbert, G. Ottersen, H. Pritchard and E.A.G. Schuur, 2019. Polar regions. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate.

Mikhailov, V. and L. Kolpaschikov, 2017. Population dynamics of the Taimyr wild reindeer herd. International Journal of Environmental Studies, 74:862-883.

Moerlein, K.J. and C. Carothers, 2012. Total environment of change: impacts of climate change and social transitions on subsistence fisheries in northwest Alaska. Ecology and Society, 17:10.

Mohn, K., 2019. Arctic Oil and Public Finance: Norway's Lofoten Region and Beyond. The Energy Journal, 40:3.

Monz, C.A., K.J. Gutzwiller, V.H. Hausner, M.W. Brunson, R. Buckley and C.M. Pickering, 2021. Understanding and managing the interactions of impacts from nature-based recreation and climate change. Ambio, 50:631-643.

Morin, J.F. and A. Orsini (eds.), 2015. Essential Concepts of Global Environmental Governance. Routledge.

MSB, 2015. Observatörsrapport. Skogsbranden i Västmanland 2014. [Observer report. The forest fire in Västmanland 2014]. Swedish Civil Contingencies Agency publication No. 798.

Mukherjee, A., 2020. Arctic oil leak 2020: Not a recent phenomenon - reveals satellite imagery. International Strategic and Security Studies, National Institute of Advanced Studies, Bangalore, India.

Myers-Smith, I.H., J.T. Kerby, G.K. Phoenix, J.W. Bjerke, H.E. Epstein, J.J. Assmann, C. John, L. Andreu-Hayles, S. Angers-Blondin, P.S. Beck, L.T. Berner et al., 2020. Complexity revealed in the greening of the Arctic. Nature Climate Change, 10:106-117.

Naald, V.B., 2020. Examining tourist preferences to slow glacier loss: evidence from Alaska. Tourism Recreation Research, 45:107-117.

Narayan, P.K., 2020. Oil price news and COVID-19 – Is there any connection? Energy Research Letters, 1:13176.

Newton, R., S. Pfirman, B. Tremblay and P. DeRepentigny, 2017. Increasing transnational sea-ice exchange in a changing Arctic Ocean. Earth's Future, 5:633-647.

Niiranen, S., A. Richter, T. Blenckner, L.C. Stige, M. Valman and A.-M. Eikeset, 2018. Global connectivity and cross-scale interactions create uncertainty for Blue Growth of Arctic fisheries. Marine Policy, 87:321-330.

Nijhuis, M., 2017. Cruel North: On violence and the Arctic. Virginia Quarterly Review, 93:192-195.

Nikitina, E.N., 2006. Success and failures in flood risk reduction programs across Asia: some lessons learned. Science and Culture, 72:72-84.

Nikitina, E.N., 2019. Climate change in the Arctic: Adaptation to new challenges. Outlines of Global Transformations: Politics, Economics, Law, 12:177-200 (In Russian).

Nilsen, T., 2018a. Arctic cruise ship boom: 28 (and counting) new expedition ships capable of sailing Arctic waters are coming to the market over the next four years. The Independent Barents Observer, 22 May 2018.

Nilsen, T., 2018b. Thawing permafrost melts ground under homes and around Global Seed Vault in Svalbard. The Independent Barents Observer, 12 October 2018.

Nilsson, J.A., C.R. Johnson, E.A. Fulton and M. Haward, 2019. Fisheries sustainability relies on biological understanding, evidence-based management, and conducive industry conditions. ICES Journal of Marine Science, 76:1436-1452.

Nilsson, L.M., 2021. Some reflections on Swedish food strategies from a Sami and an Arctic perspective. In: Hossain, K., L.M. Nilsson and T.M. Herrmann (eds.), Food Security in the High North: contemporary challenges across the circumpolar region. pp. 203-218. Routledge

Nitze, I., G. Grosse, B.M. Jones, V.E. Romanovsky and J. Boike, 2018. Remote sensing quantifies widespread abundance of permafrost region disturbances across the Arctic and Subarctic. Nature Communications, 9:5423.

Nordam, T., D.A. Dunnebier, C.J. Beegle-Krause, M. Reed and D. Slagstad, 2017. Impact of climate change and seasonal trends on the fate of Arctic oil spills. Ambio, 46:442-452.

Nordam, T., R. Nepstad, E. Litzler and J. Röhrs, 2019. On the use of random walk schemes in oil spill modelling. Marine Pollution Bulletin, 146:631-638.

Norwegian Agriculture Agency, 2020. Beitekrisen 2020. Reindriftsnytt [News of Reindeer Husbandry in Norway) 1:2020.

Norwegian Ministry of Climate and Environment, 2017. Norway's Seventh National Communication under the UN Framework Convention on Climate Change. Norwegian Ministry of Climate and Environment, Oslo, Norway.

Notz, D. and J. Stroeve, 2016. Observed Arctic sea-ice loss directly follows anthropogenic CO_2 emissions. Science, 354:747-750.

Nuttall, M., 2020. Water, Ice, and Climate Change in Northwest Greenland. Wiley Interdisciplinary Reviews-Water, 7.

Nyland, K.E., A.E. Klene, J. Brown, N.I. Shiklomanov, F.E. Nelson, D.A. Streletskiy and K. Yoshikawa, 2017. Traditional Iñupiat ice cellars (SIĠḶUAQ) in Barrow, Alaska: characteristics, temperature monitoring, and distribution. Geographical Review, 107:143-158.

Olsen, J., M. Nenasheva, K.A. Wigger, A. Pashkevich, S.H. Bickford and T. Maksimova, 2020. Marine tourism development in the Arkhangelsk Region, Russian Arctic: stakeholder's perspectives. In: Arctic Marine Sustainability. pp. 365-389. Springer.

Omazic, A., H. Bylund, S. Boqvist, A. Högberg, C. Björkman, M. Tryland, B. Evengård, A. Koch, C. Berggren, A. Malogolovkin, D. Kolbasov, N. Pavelko, T. Thierfelder and A. Albihn, 2019. Identifying climate-sensitive infectious diseases in animals and humans in Northern regions. Acta Veterinaria Scandinavica, 61:53.

Oppenheimer, M., B.C. Glavovic, J. Hinkel, R. van de Wal, A.K. Magnan, A. Abd-Elgawad, R. Cai, M. Cifuentes-Jara, R.M. DeConto, T. Ghosh, J. Hay, F. Isla, B. Marzeion, B. Meyssignac and Z. Sebesvari, 2019. Sea level rise and implications for low-lying islands, coasts and communities. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate.

Orr, J.C., V.J. Fabry, O. Aumont, L. Bopp, S.C. Doney, R.A. Feely, A. Gnanadesikan, N. Gruber, A. Ishida, F. Joos, R.M. Key, K. Lindsay, E. Maier-Reimer, R. Matear, P. Monfray, A. Mouchet, R.G. Najjar, G.K. Plattner, K.B. Rodgers, C.L. Sabine, J.L. Sarmiento, R. Schlitzer, R.D. Slater, I.J. Totterdell, M.F. Weirig, Y. Yamanaka and A. Yool, 2005. Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. Nature, 437:681-686.

Österblom, H., J.B. Jouffray, C. Folke and J. Rockström, 2017. Emergence of a global science–business initiative for ocean stewardship. Proceedings of the National Academy of Sciences, 114:9038-9043.

Pagano, A.M., G.M. Durner, K.D. Rode, T.C. Atwood, S.N. Atkinson, E. Peacock, D.P. Costa, M.A. Owen and T.M. Williams, 2018. High-energy, high-fat lifestyle challenges an Arctic apex predator, the polar bear. Science, 359:568-572.

Pahl-Wostl, C., L. Lebel, C. Knieper and E. Nikitina, 2012. From applying panaceas to mastering complexity: toward adaptive water governance in river basins. Environmental Science & Policy, 23:24-34.

Palma, D., A. Varnajot, K. Dalen, I.K. Basaran, C. Brunette, M. Bystrowska, A.D. Korablina, R.C. Nowicki and T.A. Ronge, 2019. Cruising the marginal ice zone: climate change and Arctic tourism. Polar Geography, 42:215-235.

Palmer, J., 2020. A slippery slope: Could climate change lead to more landslides? Eos, 101.

Palosaari, T., 2019. The Arctic paradox (and how to solve it). Oil, gas and climate ethics in the Arctic. In: The Global Arctic Handbook. pp. 141-152. Springer.

Paoli, A., R.B. Weladji, Ø. Holand and J. Kumpula, 2020. The onset in spring and the end in autumn of the thermal and vegetative growing season affect calving time and reproductive success in reindeer. Current Zoology, 66:123-134.

Parks, M., A. Ahmasuk, B. Compagnoni, A. Norris and R. Rufe, 2019. Quantifying and mitigating three major vessel waste streams in the northern Bering Sea. Marine Policy, 106:103530.

Parlee, B.L., J. Sandlos and D.C. Natcher, 2018. Undermining subsistence: Barren-ground caribou in a "tragedy of open access". Science Advances, 4:e1701611.

Patton, A.I., S.L. Rathburn and D.M. Capps, 2019. Landslide response to climate change in permafrost regions. Geomorphology, 340:116-128.

Pearce, T., J. Ford, A.C. Willox and B. Smit, 2015. Inuit traditional ecological knowledge in adaptation to climate change in the Canadian Arctic. Arctic, 68:233-245.

Pearce, T., D. Fawcett and J. Ford. 2020. Climate Change and the proposed Canadian Northern Corridor. The School of Public Policy Publications, University of Calgary.

Petrenya, N., G. Skeie, M. Melhus and M. Brustad, 2018. Food in rural northern Norway in relation to Sami ethnicity: the SAMINOR 2 Clinical Survey. Public Health Nutrition, 21:2665-2677.

Petrick, S., K. Riemann-Campe, S. Hoog, C. Growitsch, H. Schwind, R. Gerdes and K. Rehdanz, 2017. Climate change, future Arctic sea ice, and the competitiveness of European Arctic offshore oil and gas production on world markets. Ambio, 46:410-422.

Petrie, B., K.T. Frank, N.L. Shackell and W.C. Leggett, 2009. Structure and stability in exploited marine fish communities: quantifying critical transitions. Fisheries Oceanography, 18:83-101.

Planque, B., C. Mullon, P. Arneberg, A. Eide, J.M. Fromentin, J.J. Heymans, A.H. Hoel, S. Niiranen, G. Ottersen, A.B. Sandø and M. Sommerkorn, 2019. A participatory scenario method to explore the future of marine social-ecological systems. Fish and Fisheries, 20:434-451.

Ponomarev, E.I., V. Ivanov and N. Korshunov, 2015. System of wildfires monitoring in Russia. In: Wildfire Hazards, Risks and Disasters. pp. 187-205. Elsevier.

Popova, A. and A. Kulichenko (eds.), 2017. Опыт ликвидации вспышки сибирской язвы на Ямале в 2016 г. [The experience of elimination of anthrax outbreak in the Yamal in 2016]). Izhevsk, (in Russian).

Popova, A.Y., Y.V. Demina, E.B. Ezhlova, A.N. Kulichenko, A.G. Ryazanova and V.V. Maleev, 2016. Outbreak of anthrax in the Yamalo-Nenets autonomous district in 2016, epidemiological peculiarities. Problems of Particularly Dangerous Infections, 4:42-46.

Poppel, B. (ed.), 2015. SLiCA: Arctic Living Conditions: Living conditions and quality of life among Inuit, Saami and Indigenous peoples of Chukotka and the Kola Peninsula. Nordic Council of Ministers. Copenhagen, Denmark.

Porfiriev, B., 2019a. The Order for Wildfire. Expert, No 34(1130), https://expert.ru/dossier/author/boris-porfiriev

Porfiriev, B., 2019b. О мнимой и реальной экономической эффективности борьбы с лесными пожарами. ЭКО, No 11, с. 8-26 [Alleged and actual economic effectiveness of fighting wildfires in Siberia. ECO Journal, No 11 (545), pp. 8-26] http://dx.doi.org/10.30680/ECO0131-7652-2019-11-8-26

Porfiriev, B.N., S.A. Voronina, V.V. Semikashev, N.E. Terentiev, D.O. Eliseev and Y.V. Naumova, 2017. Climate change impact on economic growth and specific sectors' development of the Russian Arctic. Arctic Ecology and Economy, 4:4-17.

Porfiriev, B.N., D.O. Elisseev and D.A. Streletskiy, 2019. Economic assessment of the impact of permafrost degradation induced by climate change the road infrastructure resilience in the Russian Arctic. Вестник Российской академии наук, 89:1228-1239.

Post, E., U.S. Bhatt, C.M. Bitz, J.F. Brodie, T.L. Fulton, M. Hebblewhite, J. Kerby, S.J. Kutz, I. Stirling and D.A. Walker, 2013. Ecological consequences of sea-ice decline. Science, 341:519-524.

Post, E., R.B. Alley, T.R. Christensen, M. Macias-Fauria, B.C. Forbes, M.N. Gooseff, A. Iler, J.T. Kerby, K.L. Laidre, M.E. Mann, J. Olofsson, J.C. Stroeve, F. Ulmer, R.A. Virginia and M.Y. Wang, 2019. The polar regions in a 2°C warmer world. Science Advances, 5:eaaw9883.

Poussenkova, N.N., 2019. Arctic offshore oil in Russia: optimism, pessimism, realism. Outlines of Global Transformations: Politics, Economics, Law, 12:86-108.

Pristupa, A.O., M. Tysiachniouk, A.P. Mol, R. Leemans, T. Minayeva and A. Markina, 2018. Can zoning resolve nature use conflicts? The case of the Numto Nature Park in the Russian Arctic. Journal of Environmental Planning and Management, 61:1674-1700.

Proulx, J.F., J.D. MacLean, T.W. Gyorkos, D. Leclair, A.K. Richter, B. Serhir, L. Forbes and A.A. Gajadhar, 2002. Novel prevention program for trichinellosis in Inuit communities. Clinical Infectious Diseases, 34:1508-1514.

Provencher, J.F., P.J. Thomas, B. Pauli, B.M. Braune, R.P. Franckowiak, M. Gendron, G. Savard, S.N. Sarma, D. Crump, Y. Zahaby and J. O'Brien, 2020. Polycyclic aromatic compounds (PACs) and trace elements in four marine bird species from northern Canada in a region of natural marine oil and gas seeps. Science of the Total Environment, 744:140959.

Proverbs, T.A., T.C. Lantz, S.I. Lord, A. Amos and N.C. Ban, 2020. Social-ecological determinants of access to fish and well-being in four Gwich'in communities in Canada's Northwest Territories. Human Ecology, 48:155-171.

Prowse, T.D., K. Alfredsen, S. Beltaos, S. Bonsal, C. Duguay, A. Korhola and F. Wrona, 2011. Changing lake and river ice regimes: Trends, effects and implications. In: Snow, Water, Ice and Permafrost in the Arctic (SWIPA): Climate Change and the Cryosphere. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway.

Qi, D., L. Chen, B. Chen, Z. Gao, W. Zhong, R.A. Feely, L.G. Anderson, H. Sun, J. Chen, M. Chen, L. Zhan, Y. Zhang and W.J. Cai, 2017. Increase in acidifying water in the western Arctic Ocean. Nature Climate Change, 7:195-199.

Rapinski, M., F. Payette, O. Sonnentag, T.M. Herrmann, M.J.S. Royer, A. Cuerrier, L.S. Collier, L. Hermanutz and G. Guanish, 2018. Listening to Inuit and Naskapi peoples in the eastern Canadian Subarctic: a quantitative comparison of local observations with gridded climate data. Regional Environmental Change, 18:189-203.

Rasmus, S., M. Turunen, A. Luomaranta, S. Kivinen, K. Jylhä and J. Räihä, 2020a. Climate change and reindeer management in Finland: Co-analysis of practitioner knowledge and meteorological data for better adaptation. Science of the Total Environment, 710:136229.

Rasmus, S., I. Kojola, M. Turunen, H. Norberg, J. Kumpula and T. Ollila, 2020b. Mission impossible? Pursuing the co-existence of viable predator populations and sustainable reindeer husbandry in Finland. Journal of Rural Studies, 80:135-148.

Rayfuse, R., 2019. The role of law in the regulation of fishing activities in the Central Arctic Ocean. Marine Policy, 110:103562.

Raymond, C., R.M. Horton, J. Zscheischler, O. Martius, A. AghaKouchak, J. Balch, S.G. Bowen, S.J. Camargo, J. Hess, K. Kornhuber and M. Oppenheimer, 2020. Understanding and managing connected extreme events. Nature Climate Change, 10:611-621.

Raynolds, M.K., D.A. Walker, K.J. Ambrosius, J. Brown, K.R. Everett, M. Kanevskiy, G.P. Kofinas, V.E. Romanovsky, Y. Shur and P.J. Webber, 2014. Cumulative geoecological effects of 62 years of infrastructure and climate change in ice-rich permafrost landscapes, Prudhoe Bay Oilfield, Alaska. Global Change Biology, 20:1211-1224.

Rees, W.G., F.M. Stammler, F.S. Danks and P. Vitebsky, 2008. Vulnerability of European reindeer husbandry to global change. Climatic Change, 87:199-217.

Reeves, R.R., P.J. Ewins, S. Agbayani, M.P. Heide-Jørgensen, K.M. Kovacs, C. Lydersen, R. Suydam, W. Elliott, G. Polet, Y. van Dijk and R. Blijleven, 2014. Distribution of endemic cetaceans in relation to hydrocarbon development and commercial shipping in a warming Arctic. Marine Policy, 44:375-389.

Regehr, E.V., N.J. Hostetter, R.R. Wilson, K.D. Rode, M.S. Martin and S.J. Converse, 2018. Integrated population modeling provides the first empirical estimates of vital rates and abundance for polar bears in the Chukchi Sea. Scientific Reports, 8:16780.

Renaut, S., E. Devred and M. Babin, 2018. Northward expansion and intensification of phytoplankton growth during the early ice-free season in Arctic. Geophysical Research Letters, 45:10,590-10,598.

Research Centre for Coastal Tourism, 2012. Cruise Tourism: From a broad perspective to a focus on Zeeland. www.academia.edu/32086736/Cruise_Tourism_From_a_broad_perspective_to_a_focus_on_Zeeland

RF Ministry for Environment, 2016. State Report, 2016. On the state and use of water resources in the Russian Federation in 2015. NIA Priroda, Moscow.

Riseth, J.Å., H. Tømmervik and J.W. Bjerke, 2016. 175 years of adaptation: North Scandinavian Sámi reindeer herding between government policies and winter climate variability (1835–2010). Journal of Forest Economics, 24:186-204.

Rode, K.D., R.R. Wilson, E.V. Regehr, M. St. Martin, D.C. Douglas and J. Olson, 2015. Increased land use by Chukchi Sea polar bears in relation to changing sea ice conditions. PLoS ONE, 10:e0142213.

Rode, K.D., J.K. Fortin-Noreus, D. Garshelis, M. Dyck, V. Sahanatien, T. Atwood, S. Belikov, K.L. Laidre, S. Miller, M.E. Obbard and D. Vongraven, 2018. Survey-based assessment of the frequency and potential impacts of recreation on polar bears. Biological Conservation, 227:121-132.

Rolph, R.J., A.R. Mahoney, J. Walsh and P.A. Loring, 2018. Impacts of a lengthening open water season on Alaskan coastal communities: deriving locally relevant indices from large-scale datasets and community observations. Cryosphere, 12:1779-1790.

Rosales, J. and J.L. Chapman, 2015. Perceptions of obvious and disruptive climate change: community-based risk assessment for two native villages in Alaska. Climate, 3:812-832.

Roshydromet, 2014. Second Roshydromet Assessment Report on Climate Change and its Consequences in Russian Federation. Roshydromet, St. Petersburg, Russia. https://cc.voeikovmgo.ru/ru/publifatsii/2016-03-21-16-23-52 (In Russian)

Rosleshoz, 2019. Rosleshoz assessed the area of forest burnt in 2019. TASS, 25 September, 2019. https://tass.ru/obschestvo/6924964

Ruggerone, G.T. and J.R. Irvine, 2018. Numbers and biomass of natural-and hatchery-origin pink salmon, chum salmon, and sockeye salmon in the north Pacific Ocean, 1925–2015. Marine and Coastal Fisheries, 10:152-168.

Runge, C.A., R.M. Daigle and V.H. Hausner, 2020. Quantifying tourism booms and the increasing footprint in the Arctic with social media data. PLoS ONE, 15:e0227189.

Rutherford, T.K. and C.A. Schultz, 2019. Adapting wildland fire governance to climate change in Alaska. Ecology and Society, 24:27.

Safronov, V.M., 2016. Climate change and mammals of Yakutia. Biology Bulletin, 43:1256-1270.

Saintilan, N.J., D. Selby, J.W. Hughes, D.M. Schlatter, J. Kolb and A. Boyce, 2020. Source of gold in Neoarchean orogenic-type deposits in the North Atlantic Craton, Greenland: Insights for a proto-source of gold in sub-seafloor hydrothermal arsenopyrite in the Mesoarchean. Precambrian Research, 343:105717.

San-Miguel-Ayanz, J., T. Durrant, R. Boca, G. Libertà, A. Branco, D. de Rigo, D. Ferrari, P. Maianti, T. Artes, D. Oom, H. Pfeiffer, D. Nuijten, T. Leray, A. Benchikha, F. Humer, H. Vacik, M. Müller, V. Konstantinov, J. Villa and J. Dan, 2019. Forest fires in Europe, Middle East and North Africa 2018. EUR 29856 EN, Publications Office of the European Union, Luxembourg. doi:10.2760/561734

Savelieva, N.I., I.P. Semiletov, G.E. Weller and L.N. Vasilevskaya, 2004. Climate change in the northern Asia in the second half of the 20th century. Pacific Oceanography, 2:74-84.

Savo, V., D. Lepofsky, J.P. Benner, K.E. Kohfeld, J. Bailey and K. Lertzman, 2016. Observations of climate change among subsistence-oriented communities around the world. Nature Climate Change, 6:462-473.

Schrot, O.G., J.H. Christensen and H. Formayer, 2019. Greenland winter tourism in a changing climate. Journal of Outdoor Recreation and Tourism, 27:100224.

Sciberras, M., J.G. Hiddink, S. Jennings, C.L. Szostek, K.M. Hughes, B. Kneafsey, L.J. Clarke, N. Ellis, A.D. Rijnsdorp, R.A. McConnaughey, R. Hilborn, J.S. Collie, C.R. Pitcher, R.O. Amoroso, A.M. Parma, P. Suuronen and M.J. Kaiser, 2018. Response of benthic fauna to experimental bottom fishing: A global meta-analysis. Fish and Fisheries, 19:698-715.

Semyonov, V.A. and A.A. Korshunov, 2006. Floods on the Russian rivers in the late 20th century and the early 21st century. Issues of Geography and Geo-ecology, 5:6-12.

Seneviratne, S.I., N. Nicholls, D. Easterling, C.M. Goodess, S. Kanae, J. Kossin, Y. Luo, J. Marengo, K. McInnes, M. Rahimi, M. Reichstein, A. Sorteberg, C. Vera and X. Zhang, 2012. Changes in climate extremes and their impacts on the natural physical environment. In: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). pp. 109-230. Cambridge University Press.

Shevchenko, V.P., V.M. Kopeikin, A.N. Novigatsky and G.V. Malafeev, 2019. Black carbon in the atmospheric boundary layer over the North Atlantic and the Russian Arctic seas in June–September 2017. Oceanology, 59:692-696.

SIKU, no date. The Indigenous Knowledge Social Network: Facilitating self-determination in research, education and stewardship for Indigenous communities. https://siku.org

Shnyparkov, A., S. Fuchs, S. Sokratov, P. Koltermann, Y. Seliverstov and M. Vikulina, 2012. Theory and practice of individual snow avalanche risk assessment in the Russian Arctic. Geography, Environment, Sustainability, 5:64-81.

Shvidenko, A.Z. and D.G. Schepaschenko, 2013. Climate change and wildfires in Russia. Contemporary Problems of Ecology, 6:683-692.

Sisneros-Kidd, A.M., C. Monz, V. Hausner, J. Schmidt and D. Clark, 2019. Nature-based tourism, resource dependence, and resilience of Arctic communities: Framing complex issues in a changing environment. Journal of Sustainable Tourism, 27:1259-1276.

Skogen, K. and O. Krange, 2020. The political dimensions of illegal wolf hunting: anti-elitism, lack of trust in institutions and acceptance of illegal wolf killing among Norwegian hunters. Sociologia Ruralis, 60:551-573.

Smith, A.W., D.E. Skilling, J.D. Castello and S.O. Rogers, 2004. Ice as a reservoir for pathogenic human viruses: specifically, caliciviruses, influenza viruses, and enteroviruses. Medical Hypotheses, 63:560-566.

Sohns, A., J.D. Ford, M. Riva, B. Robinson and J. Adamowski, 2019a. Water vulnerability in Arctic households: a literature-based analysis. Arctic, 72:300-316.

Sohns, A., J. Ford, B.E. Robinson and J. Adamowski, 2019b. What conditions are associated with household water vulnerability in the Arctic? Environmental Science & Policy, 97:95-105.

Solodovnikov A. et al., 2018. Научный вестник Ямало-Ненецкого автономного округа [Scientific bulletin of Yamalo-Nenets autonomous district]. Scientific Center for Arctic Studies, Salekhard. www.elibrary.ru/title_about_new.asp?id=32895

Solomon, S.M., 2005. Spatial and temporal variability of shoreline change in the Beaufort-Mackenzie region, Northwest Territories, Canada. Geo-Marine Letters, 25:127-137.

Stabeno, P.J., N.B. Kachel, S.E. Moore, J.M. Napp, M. Sigler, A. Yamaguchi and A.N. Zerbini, 2012. Comparison of warm and cold years on the southeastern Bering Sea shelf and some implications for the ecosystem. Deep Sea Research II, 65:31-45.

Stafford, K.M., 2019. Increasing detections of killer whales (*Orcinus orca*), in the Pacific Arctic. Marine Mammal Science, 35:696-706.

Stammler, F., 2005. Reindeer Nomads Meet the Market: Culture, Property and Globalisation at the End of the Land. Halle Studies in the Anthropology of Eurasia.

Stammler, F., 2010. Animal diversity and its social significance among Arctic pastoralists. In: Stammler, F. and H. Takakura (eds.), Good to Eat, Good to Live With: Nomads and Animals in Northern Eurasia and Africa. Northeast Asia Studies Series, 11:215-243. Center for Northeast Asian studies, Tohoku University.

Stammler, F.M. and A. Ivanova, 2020. From spirits to conspiracy? Nomadic perceptions of climate change, pandemics and disease. Anthropology Today, 36:8-12.

Stammler-Gossmann, A., 2012. The big water of a small river: flood experiences and a community agenda for change. In: Tennberg, M. (ed.), Governing the Uncertain: Adaptation and Climate in Russia and Finland. pp. 55-82. Springer.

Standal, D. and F. Asche, 2018. Hesitant reforms: the Norwegian approach towards ITQs. Marine Policy, 88:58-63.

Steinacher, M., F. Joos, T.L. Frölicher, G.K. Plattner and S.C. Doney, 2009. Imminent ocean acidification in the Arctic projected with the NCAR global coupled carbon cycle-climate model. Biogeosciences, 6:515-533.

Steiner, N.S., W.W.L. Cheung, H. Drost, C. Hoover, J. Lam, L. Miller, A. Cisneros-Montemayor, T. Sou, U.R. Sumaila, P. Suprenand, T. Tai and D.L. VanderZwaag, 2018. Changing ocean impacts on the key forage fish species Arctic cod in the Western Canadian Arctic – Linking climate model projections to subsistence fisheries. In: AMAP Assessment 2018: Arctic Ocean Acidification. Annex 6. Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway.

Stephen, K., 2018. Societal impacts of a rapidly changing Arctic. Current Climate Change Reports, 4:223-237.

Stephenson, S.R., L.C. Smith and J.A. Agnew, 2011. Divergent long-term trajectories of human access to the Arctic. Nature Climate Change, 1:156-160.

Stepien, A., T. Koivurova, A. Gremsperger and H. Niemi, 2013. Arctic indigenous peoples and the challenge of climate change. In: Arctic Marine Governance. pp. 71-99. Springer.

Stevenson, D.E. and R.R. Lauth, 2019. Bottom trawl surveys in the northern Bering Sea indicate recent shifts in the distribution of marine species. Polar Biology, 42:407-421.

Stewart, E.J., S.E. Howell, D. Draper, J. Yackel and A. Tivy, 2007. Sea ice in Canada's Arctic: Implications for cruise tourism. Arctic, 60:370-380.

Stewart-Sinclair, P.J., K.S. Last, B.L. Payne and T.A. Wilding, 2020. A global assessment of the vulnerability of shellfish aquaculture to climate change and ocean acidification. Ecology and Evolution, 10:3518-3534.

Stram, D.L. and D.C. Evans, 2009. Fishery management responses to climate change in the North Pacific. ICES Journal of Marine Science, 66:1633-1639.

Strauss, H. and N. Mazzullo, 2014. Narratives, bureaucracies and indigenous legal orders: resource governance in Finnish Lapland. In: Powell, R. and K. Dodds (eds.), Polar Geopolitics? Knowledge, Resources and Legal Regimes, pp. 295-312. Social And Political Science. Edward Elgar Publishing.

Streletskiy, D. and N. Shiklomanov, 2013. Arctic Urban Sustainability and Permafrost. In: Arctic Urban Sustainability Conference, Washington, DC, USA.

Streletskiy, D.A., L.J. Suter, N.I. Shiklomanov, B.N. Porfiriev and D.O. Eliseev, 2019. Assessment of climate change impacts on buildings, structures and infrastructure in the Russian regions on permafrost. Environmental Research Letters, 14:025003.

Suter, L., D. Streletskiy and N. Shiklomanov, 2019. Assessment of the cost of climate change impacts on critical infrastructure in the circumpolar Arctic. Polar Geography, 42:267-286.

Szoenyl, M., 2018. Flood Resilience Alliance 2.0: A Look at Five Years of Supporting Communities Building Resilience against Floods. Zurich Insurance Company. www.zurich.com/en/knowledge/articles/2018/07/flood-resilience-alliance-2

Taagholt, J. and K. Brooks, 2016. Mineral riches: a route to Greenland's independence? Polar Record, 52:360-371.

Takakura, H., 2015. Arctic Pastoralist Sakha: Ethnography of Evolution and Microadaptation in Siberia. Trans Pacific Press, Balwyn North, Australia.

Takakura, H., 2016. Limits of pastoral adaptation to permafrost regions caused by climate change among the Sakha people in the middle basin of Lena River. Polar Science, 10:395-403.

Takakura, H., 2018. Local perception of river thaw and spring flooding of the Lena River. In: Hiyama, T. and H. Takakura (eds.), Global Warming and Human-Nature Dimension in Northern Eurasia. pp. 29-51. Global Environmental Studies. Springer.

Takakura, H., Y. Yoshikawa, M. Watanabe, T. Sakai and T. Hiyama, 2018. Ice movement in the Lena River and effects of spring flooding on human society: an interpretation of local sources integrated with satellite imagery in a multidisciplinary approach. In: Hiyama, T. and H. Takakura (eds.), Global Warming and Human-Nature Dimension in Northern Eurasia. pp. 101-123. Global Environmental Studies. Springer.

Tape, K.D., D.D. Gustine, R.W. Ruess, L.G. Adams and J.A. Clark, 2016. Correction: range expansion of moose in Arctic Alaska linked to warming and increased shrub habitat. PLoS ONE, 11:e0160049.

Tape, K.D., B.M. Jones, C.D. Arp, I. Nitze and G. Grosse, 2018. Tundra be dammed: Beaver colonization of the Arctic. Global Change Biology, 24:4478-4488.

Taranger, G.L., Ø. Karlsen, R.J. Bannister, K.A. Glover, V. Husa, E. Karlsbakk, B.O. Kvamme, K.K. Boxaspen, P.A. Bjørn, B. Finstad and A.S. Madhun, 2015. Risk assessment of the environmental impact of Norwegian Atlantic salmon farming. ICES Journal of Marine Science, 72:997-1021.

Tarasenko, O. and P. Simunova, 2019. Проблема Сибирских пожаров в России в июле 2019 года [The problem of Siberian fires in Russia in July 2019]. Scientific Information Publishing Center, Moscow. https://elibrary.ru/item.asp?id=41512996

Tennberg, M., T. Vuojala-Magga, J. Vola, H. Sinevaara-Niskanen and M. Turunen, 2018. Negotiating risk and responsibility: Political economy of flood protection management in northern Finland. In: Global Warming and Human-Nature Dimension in Northern Eurasia. pp. 207-221. Springer, Singapore.

Terenzi, J., M.T. Jorgenson and C.R. Ely, 2014. Storm-surge flooding on the Yukon-Kuskokwim delta, Alaska. Arctic, 67:360-374.

Terhaar, J., L. Kwiatkowski and L. Bopp, 2020. Emergent constraint on Arctic Ocean acidification in the twenty-first century. Nature 582:379–383

Têtu, P.L. and F. Lasserre, 2017. Chinese investment in Greenland's mining industry: Toward a new framework for foreign direct investment. The Extractive Industries and Society, 4:661-671.

Têtu, P.L., J. Dawson and F. Lasserre, 2019. The evolution and relative competitiveness of global Arctic cruise tourism destinations. In: Arctic Shipping: Climate Change, Commercial Traffic and Port Development. Chapter 6. Routledge.

The Sámi Parliament of Sweden, 2018. Application to the Ministry of Enterprise and Innovation for compensation of loss for droughts and wildfires dnr 6.2.6-2018-1036. www.sametinget.se/126951

Thorsell, D.E. and T.M. Leschine, 2016. An evaluation of oil pollution prevention strategies in the Arctic: A comparison of Canadian and US approaches. Marine Policy, 72:255-262.

Tkach, S.M., 2019. Adaptation of geotechnologies to mineral mining conditions in permafrost: Challenges. In: IOP Conference Series: Earth and Environmental Science. Vol. 262, No. 1, p. 012076. IOP Publishing.

Tomaselli, M., S.C. Gerlach, S.J. Kutz, S.L. Checkley and Community of Iqaluktutiaq, 2018. Iqaluktutiaq voices: Local perspectives about the importance of muskoxen, contemporary and traditional use and practices. Arctic, 71:1-14.

Trainor, S.F, F.S Chapin III, H.P. Huntington, G. Kofinas and D.C. Natcher, 2007. Arctic climate impacts: environmental injustice in Canada and the United States. Local Environment, 12:627-643.

Troell, M., A. Eide, J. Isaksen, Ø. Hermansen and A.S. Crépin, 2017. Seafood from a changing Arctic. Ambio, 46:368-386.

Trump, B.D., M. Kadenic and I. Linkov, 2018. A sustainable Arctic: Making hard decisions. Arctic, Antarctic, and Alpine Research, 50:e1438345.

Turunen, M. and T. Vuojala-Magga, 2014. Past and present winter feeding of reindeer in Finland: herders adaptive learning of feeding practices. Arctic, 67:173-188.

Turunen, M., P. Soppela, H. Kinnunen, M.-L. Sutinen and F. Martz, 2009. Does climate change influence the availability and quality of reindeer forage plants? A review. Polar Biology, 32:813-832.

Turunen, M., S. Rasmus, J. Järvenpää and S. Kivinen, 2020. Relations between forestry and reindeer husbandry in northern Finland: Perspectives of science and practice. Forest Ecology and Management, 457:117677.

Tveraa, T., A. Stien, B.J. Bårdsen and P. Fauchald, 2013. Population densities, vegetation green-up, and plant productivity: impacts on reproductive success and juvenile body mass in reindeer. PloS ONE, 8:e56450.

Uboni, A., T. Horstkotte, E. Kaarlejärvi, A. Sévêque, F. Stammler, J. Olofsson, B.C. Forbes and J. Moen, 2016. Long-term trends and role of climate in the population dynamics of Eurasian reindeer. PLoS ONE, 11:e0158359.

UNISDR, 2004. Living with Risk: A global review of disaster reduction initiatives. UN Inter-Agency Secretariat of the International Strategy for Disaster Reduction, Geneva.

US Fish & Wildlife Service, 2014. 2011 National Survey of Fishing, Hunting, and Wildlife-Associated Recreation: Alaska. https://digitalmedia.fws.gov/digital/collection/document/id/1538

US GAO, 2003. Alaska Native villages: Most are affected by flooding and erosion, but few qualify for federal assistance. GAO -04 -142. United States Senate. U.S. General Accounting Office (US GAO). www.gao.gov/assets/gao-04-142.pdf

Veijola, S. and H. Strauss-Mazzullo, 2019. Tourism at the crossroads of contesting paradigms of Arctic development. In: The GlobalArctic Handbook. pp. 63-81. Springer.

Vergeynst, L., S. Wegeberg, J. Aamand, P. Lassen, U. Gosewinkel, J. Fritt-Rasmussen, K. Gustavson and A. Mosbech, 2018. Biodegradation of marine oil spills in the Arctic with a Greenland perspective. Science of the Total Environment, 626:1243-1258.

Vermaire, J.C., M.F. Pisaric, J.R. Thienpont, C.J. Courtney Mustaphi, S.V. Kokelj and J.P. Smol, 2013. Arctic climate warming and sea ice declines lead to increased storm surge activity. Geophysical Research Letters, 40:1386-1390.

Veselov, I.A., 2012. The First Pan-Arctic Legally Binding Agreement. The Arctic Herald. No. 1. https://issuu.com/arctic-herald/docs/arctic-herald-1-full

Volokitina, A., M. Sofronov and T. Sofronova, 2008. Topical scientific and practical issues of wildland fire problem. Mitigation and Adaptation Strategies for Global Change, 13:661-674.

Voronova, O., A. Zima, V. Kladov and E. Cherepanova, 2020. Аномальные пожары на территории Сибири летом 2019 г. [Anomalous wildfires in Siberia in summer 2019]. Russian Academy of Sciences, Moscow. https://elibrary.ru/item.asp?id=42474335

Vorontsova, S., 2017. Влияние климатических изменений на транспортную инфраструктуру в Арктической зоне и на территориях распространения вечной мерзлоты [Influence of climate change on functioning of transport infrastructure objects in Russian Federation's Arctic zone and in the territories affected by permafrost]. T-PRESS, Saint-Petersburg. www.elibrary.ru/item.asp?id=29899117

Waits, A., A. Emelyanova, A. Oksanen, K. Abass and A. Rautio, 2018. Human infectious diseases and the changing climate in the Arctic. Environment International, 121:703-713.

Walker, D.A., M.K. Raynolds, F.J.A. Daniëls, E. Einarsson, A. Elvebakk, W.A. Gould, A.E. Katenin, S.S. Kholod, C.J. Markon, E.S. Melnikov, N.G. Moskalenko, S.S. Talbot, B.A. Yurtsev and The other members of the CAVM Team, 2005 The circumpolar Arctic vegetation map. Journal of Vegetation Science, 16:267-282.

Weatherhead, E., S. Gearheard and R.G. Barry, 2010. Changes in weather persistence: Insight from Inuit knowledge. Global Environmental Change, 20:523-528.

WEF, 2021. The Global Risks Report 2021. 16th Edition, Switzerland. World Economic Forum (WEF). http://wef.ch/risks2021

Welch, C., 2019. Arctic permafrost is thawing fast. That affects us all. National Geographic, September, 2019.

Wheeler, H.C., T.T. Høye and C. Svenning, 2018. Wildlife species benefitting from a greener Arctic are most sensitive to shrub cover at leading range edges. Global Change Biology, 24:212-223.

Wheeler, H.C., F. Danielsen, M. Fidel, V. Hausner, T. Horstkotte, N. Johnson … N. Vronski, 2020. The need for transformative changes in the use of Indigenous knowledge along with science of environmental decision-making in the Arctic. People and Nature, 2:544-556.

WHO, 2017. Flooding: Managing Health Risks in the WHO European Region. World Health Organization (WHO).

Wilkinson, J., C.J. Beegle-Krause, K.U. Evers, N. Hughes, A. Lewis, M. Reed and P. Wadhams, 2017. Oil spill response capabilities and technologies for ice-covered Arctic marine waters: A review of recent developments and established practices. Ambio, 46:423-441.

Wilson, R.R., C. Perham, D.P. French-McCay and R. Balouskus, 2018. Potential impacts of offshore oil spills on polar bears in the Chukchi Sea. Environmental Pollution, 235:652-659.

Witze, A., 2020. The Arctic is burning like never before – and that's bad news for climate change. Nature, 585:336-337.

Worm, B., R. Hilborn, J.K. Baum, T.A. Branch, J.S. Collie, C. Costello, M.J. Fogarty, E.A. Fulton, J.S. Hutchings, S. Jennings and O.P. Jensen, 2009. Rebuilding global fisheries. Science, 325:578-585.

Wulder, M.A., C. Campbell, J.C. White, M. Flannigan and I.D. Campbell, 2007. National circumstances in the international circumboreal community. The Forestry Chronicle, 83:539-556.

Yamamoto-Kawai, M., F.A. McLaughlin, E.C. Carmack, S. Nishino and K. Shimada, 2009. Aragonite undersaturation in the Arctic Ocean: effects of ocean acidification and sea ice. Science, 326:1098-1100.

YANAO, 20209. On amendments to YANAO forestry programme. YANAO Governor Office. http://docs.cntd.ru

Young, S.K., T.B. Tabish, N.J. Pollock and T.K. Young, 2016. Backcountry travel emergencies in arctic Canada: a pilot study in public health surveillance. International Journal of Environmental Research and Public Health, 13:276.

Young, A.M., P.E. Higuera, P.A. Duffy and F.S. Hu, 2017. Climatic thresholds shape northern high-latitude fire regimes and imply vulnerability to future climate change. Ecography, 40:606-617.

Young, N., C. Brattland, C. Digiovanni, B. Hersoug, J.P. Johnsen, K.M. Karlsen, I. Kvalvik, E. Olofsson, K. Simonsen, A.M. Solås and H. Thorarensen, 2019. Limitations to growth: social-ecological challenges to aquaculture development in five wealthy nations. Marine Policy, 104:216-224.

Ytrestøyl, T., T.S. Aas and T. Åsgård, 2015. Utilisation of feed resources in production of Atlantic salmon (*Salmo salar*) in Norway. Aquaculture, 448:365-374.

Yu, G., Z. Schwartz and J.E. Walsh, 2009. Effects of climate change on the seasonality of weather for tourism in Alaska. Arctic, 62:443-457.

Yumashev, D., C. Hope, K. Schaefer, K. Riemann-Campe, F. Iglesias-Suarez, E. Jafarov, E.J. Burke, P.J. Young, Y. Elshorbany and G. Whiteman, 2019. Climate policy implications of nonlinear decline of Arctic land permafrost and other cryosphere elements. Nature Communications, 10:1900.

Zak, A., 2019. Wildfire Updates: All Residents near McKinley Fire Accounted for, Mat-Su Official Says. Anchorage Daily News. www.adn.com/alaska-news/2019/08/21/wildfire-updates-3-southcentral-alaska-blazes-were-human-caused-report-says/

Zaporozhets, O.M. and G.V. Zaporozhets, 2004. Interaction between hatchery and wild Pacific salmon in the Far East of Russia: a review. Reviews in Fish Biology and Fisheries, 14:305-319.

Zeller, D. and D. Pauly, 2016. Reconstructing marine fisheries catch data. Catch reconstruction: concepts, methods and data sources. Online Publication. Sea Around Us (www.seaaroundus.org). University of British Columbia.

Zeuthen, J.W. and M. Raftopoulos, 2018. Promises of hope or threats of domination: Chinese mining in Greenland. The Extractive Industries and Society, 5:122-130.

Zhang, Y., W. Chen and D.W. Riseborough, 2008. Transient projections of permafrost distribution in Canada during the 21st century under scenarios of climate change. Global and Planetary Change, 60:443-456.

Zhang, J., D.A. Rothrock and M. Steele, 2017. Projections of an ice-diminished Arctic Ocean – retrospection and future projection. http://psc.apl.uw.edu/research/projects/projections-of-an-ice-diminished-arctic-ocean/

Zheng, L., I. Overeem, K. Wang and G.D. Clow, 2019. Changing arctic river dynamics cause localized permafrost thaw. Journal of Geophysical Research: Earth Surface, 124:2324-2344.

Appendix 7.1 Methodology for assessing peer-reviewed literature

A quantitative assessment of peer-reviewed literature was undertaken using topic modeling.

Collection of articles from web of science. Here we updated a literature search that was done previously from 1990 to 2016 using search terms relating to names of regions, places, rivers, oceans/seas and Indigenous groups and combined these with all web of science categories relating to social sciences as well as environmental science, ecology, environmental studies and multidisciplinary sciences. The dataset we worked on is from 2015–2020. We checked that we retrieved the same papers by comparing a random selection of articles from 2015 in the old dataset (1990–2016) with the new one (2015–2020).

Topic modeling using Latent Dirichlet Allocation to select 125 topics (i.e., sentences with a similar combination of words in a text). 125 was chosen since it was the optimal number for the 1990–2016 dataset. For a practical guide to exploratory literature review using topic modeling see Asmundsen and Möller (2019).

Identifying papers about climate change and societal implications. We selected all economic and social issues and climate-related topics and set as a criteria that at least 10% of the title, abstract, keywords, and keyword plus should refer to social/economic issues and 10% should refer to climate-related topics. We assumed this would reduce the number of peer-reviewed papers to those relevant for societal implications of climate change.

Screening the papers for relevance. The place names used resulted in the inclusion of many non-Arctic papers (e.g., there is a Tana river in Arctic Norway and in Kenya). Furthermore, using such broad search strings brings many papers that are not relevant to our topic. We manually screened all 1233 abstracts that we retrieved and removed non-Arctic and non-relevant papers, resulting in 684 abstracts.

Extra search to retrieve more papers on Indigenous livelihoods and climate extremes. There were very few abstracts about climate change and Indigenous livelihoods or climate extremes so we conducted an extra search using the Indigenous names from the UArctic task force and combined them with search for "climate change". We also searched on specific words relating to climate extremes (e.g., wildfires combined with names of regions, Indigenous groups, rivers, oceans and seas and places).

Abstracts were allocated to contributing experts in Chapter 7 for further examination. Abstracts were allocated based on the tasks each expert were leading in Chapter 7. The task leaders examined the abstracts and selected the papers that were based on empirical data. Conceptual papers could be used to provide some context to the topics that are assessed, but our assessment is primarily based on empirical studies.

Searching past AMAP and IPCC assessments, grey literature and Russian databases. We can search Google Scholar for topics that are poorly covered by peer-reviewed literature. Russian databases were also examined for additional data from Russia. Comparing with results from previous AMAP and IPCC reports.

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Acronyms and Abbreviations

ALT	Active layer thickness
AMAP	Arctic Monitoring and Assessment Programme
AMO	Atlantic Multidecadal Oscillation
AOGCM	Atmosphere-Ocean General Circulation Model
AR5	IPCC Fifth Assessment Report
ATV	All-terrain vehicle
CanESM2	Canadian Earth System Model version 2
CH_4	Methane
CMIP	Coupled Model Intercomparison Project
CMIP5	The Coupled Model Intercomparison Project phase 5
CMIP6	The Coupled Model Intercomparison Project phase 6
CO_2	Carbon dioxide
ECS	Effective climate sensitivity
ERA5	EU Copernicus monthly reanalysis air temperature record
ESM	Earth system model
EUR	Euro
GCM	Global climate model
GrIS	Greenland Ice Sheet
HighResMIP	High Resolution Model Intercomparison Project
IMBIE	Ice sheet Mass Balance Inter-comparison Exercise.
inh	Inhabitants
IPCC	Intergovernmental Panel on Climate Change
LDLE	Large daily loss event
MIP	Model Intercomparison Project
NAO	North Atlantic Oscillation
NDVI	Normalized differential vegetation index
NSIDC	National Snow and Ice Data Center
P-E	Precipitation minus evapotranspiration
RCP	Representative Concentration Pathway
RILE	Rapid ice loss event
SCF	Snow-cover fraction
SSP	Shared Socioeconomic Pathway
SWIPA	Snow, Water, Ice and Permafrost in the Arctic (assessment)
USD	US dollar
WCRP	World Climate Research Programme
WHO	World Health Organization

Arctic Monitoring and Assessment Programme

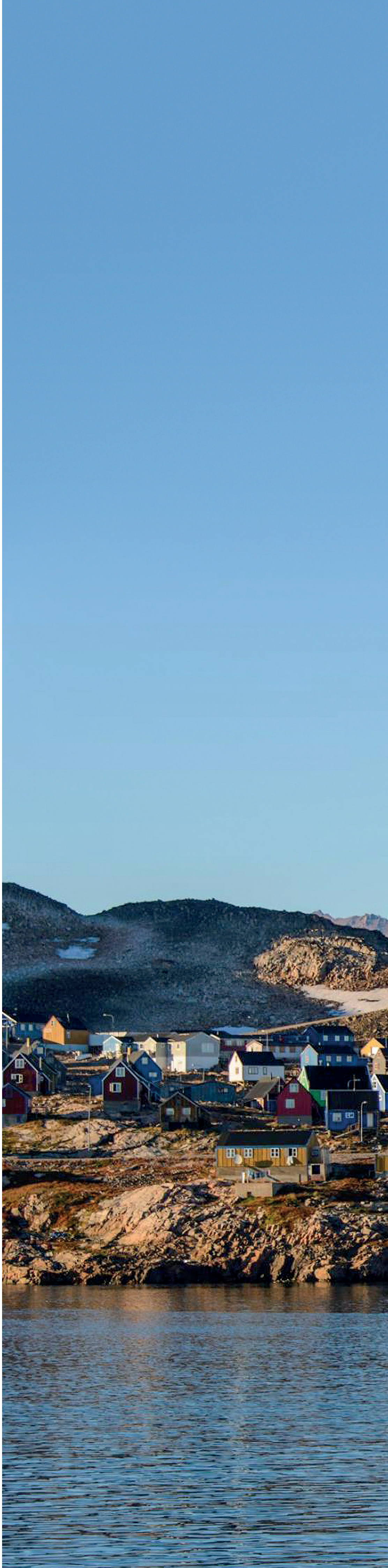
The Arctic Monitoring and Assessment Programme (AMAP) was established in June 1991 by the eight Arctic countries (Canada, Denmark, Finland, Iceland, Norway, Russia, Sweden and the United States) to implement parts of the Arctic Environmental Protection Strategy (AEPS). AMAP is now one of six working groups of the Arctic Council, members of which include the eight Arctic countries, the six Arctic Council Permanent Participants (Indigenous Peoples' organizations), together with observing countries and organizations.

AMAP's objective is to provide 'reliable and sufficient information on the status of, and threats to, the Arctic environment, and to provide scientific advice on actions to be taken in order to support Arctic governments in their efforts to take remedial and preventive actions to reduce adverse effects of contaminants and climate change'.

AMAP produces, at regular intervals, assessment reports that address a range of Arctic pollution and climate change issues, including effects on health of Arctic human populations. These are presented to Arctic Council Ministers in 'State of the Arctic Environment' reports that form a basis for necessary steps to be taken to protect the Arctic and its inhabitants.

This report has been subject to a formal and comprehensive peer review process. The results and any views expressed in this series are the responsibility of those scientists and experts engaged in the preparation of the reports.

The AMAP Secretariat is located in Tromsø, Norway. For further information regarding AMAP or ordering of reports, please contact the AMAP Secretariat (The Fram Centre, P.O. Box 6606 Stakkevollan, N-9296 Tromsø, Norway) or visit the AMAP website at www.amap.no.



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