12. SWIPA Synthesis: Implications of Findings

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12.1. Introduction and scope of chapter

Climate change is causing significant changes in the Arctic cryosphere, and these changes are expected to continue (Chapters 2 and 3). As reported in Chapters 4 to 9, these changes involve the timing and duration of snow and ice cover and seasonally frozen periods. They may also involve the loss or severe degradation of specific elements of the cryosphere. Observed and projected changes in the cryosphere cross the full spectrum of temporal scales (i.e., seasonal to century levels and beyond). The spatial scales involved similarly range from local to pan-Arctic and global. The changes are having, and will continue to have profound impacts on Arctic environments and human activities in the Arctic (Chapters 2, 10 and 11). Within this general context, four issues are especially important: the nature and magnitude of the changes, their timing relative to the seasonal/annual cycle, the spatial and temporal scales on which they occur, and their consequences for physical and biotic systems. This chapter provides a synthesis of the cryospheric changes documented in the preceding chapters and evaluates their combined impact on the Arctic environment and its inhabitants.

12.2. Ongoing and projected changes in the cryosphere

The increase in annual average temperature over the Arctic since 1980 is twice that over the rest of the world (with the exception of some regions of Antarctica), almost certainly due to polar amplification processes (see Chapter 1, Box 1.3). This has had considerable consequences for the cryosphere, most of which in the Northern Hemisphere is in the Arctic. It is now evident that feedbacks between the climate system and the cryosphere and between the different elements of the cryosphere are significant, and that the changes may be greater overall than projected by either the Arctic Climate Impact Assessment (ACIA) in 2005 or the Intergovernmental Panel on Climate Change (IPCC) in 2007. The current trends in cryospheric change are projected to continue within the Arctic (additional warming of 2 to 7 °C by 2100), with consequences of increasing significance expected for biological and human systems. The following sections address first-order changes (i.e., those in the cryospheric components themselves), feedbacks, and the second and higher-order changes induced by the cryospheric changes (i.e., changes in Arctic ecosystems and in the services these provide to humans).

12.2.1. Changes in the cryosphere

Substantial changes are expected throughout the Arctic cryosphere, driven by warming and in part by feedbacks among the cryospheric components and between the cryosphere and other systems.

Past/Present Climate (Chapter 2): ACIA projections of greater and more rapid warming in the Arctic than in other parts of the world are confirmed for the immediate past, particularly in autumn and spring. Sea-ice reduction is coupled with increased warming – this may represent a large shift in the Arctic climate system as evidenced by the greatest warming being over the Arctic Ocean (rather than on land as previously observed).

Model Projections (Chapter 3): General circulation model (GCM) projections based on scenarios of anthropogenic greenhouse gas (GHG) emissions indicate that the Arctic will continue to warm at a greater rate than other regions of the world over the next several decades. These projections may be regarded as 'best estimates' of future changes, but are subject to uncertainties arising from (i) natural variations in the climate system, (ii) the range of plausible trajectories of GHG concentrations, aerosols and other climate drivers over the next century, and (iii) systematic errors arising from model formulations, particularly the parameterizations of unresolved processes. The net effect of these various factors is a range of uncertainty that can be comparable to the projected change, although the use of ensembles of simulations from multiple models can help to extract the 'signal' of climate change. It must be kept in mind, however, that natural variability can result in occasional short-term trends of cooling during long-term trends of warming.

The overall average increase in surface air temperatures in the Arctic is projected to be 3 to 6 °C in autumn and winter by 2080 (6 to 7 °C in areas of sea-ice loss and 2 to 3 °C over land), relative to a 1957–2006 baseline. Precipitation is projected to increase throughout the Arctic with the greatest increases at the highest latitudes (a 5–40% increase by the end of the century for the IPCC B1 emissions scenario). The projected changes are greatest in winter (e.g., as snowfall) and autumn, and least in summer. Despite overall increased precipitation in the Arctic, some areas may experience drying of the landscapes due, in part, to increased evaporation associated with higher summer temperatures, a longer summer season, and perhaps altered drainage due to permafrost changes in some areas.

Snow (Chapter 4): Snow (structure, quantity, timing, extent, duration) is a fundamental attribute of northern environments. Snow-pack structure is changing, with winter thaws and rain-on-snow events increasing in frequency and with more ice crustings. Satellite imagery indicates that average snow cover extent decreased in summer (May–June) by 18% between 1966 and 2008. Annual snow-cover duration across the terrestrial Arctic (excluding Greenland) decreased by 3.9 days per decade, mostly due to the earlier disappearance of snow in spring (averaging 3.4 days per decade earlier for 1972 to 2009) with decreases projected to continue (by 10–20% over most of the Arctic by 2050). Some of this decline is likely to be due to albedo feedbacks (see Section 12.2.2). Projections suggest a slight increase in snow water equivalent (0–15%) over most of the Arctic by 2100 with high regional variation. In those areas with projected decreases in snow-cover duration and snow-water equivalent, the earliest and largest changes are projected to occur over coastal regions (as has been observed in the recent past).

Permafrost (Chapter 5): Permafrost temperatures have increased throughout the circumpolar area but there is high regional variation in the rates and magnitudes of warming. The thickness of the active layer (the surface layer above permafrost that thaws in summer) has progressively increased over much of Eurasia and central Alaska, but has remained relatively stable in northwestern Arctic Canada and the Alaskan North Slope. Over the past few decades, permafrost has disappeared from several lower latitude sites formerly characterized by discontinuous permafrost. Projections indicate that by 2100 the area of near-surface permafrost will be reduced by 16–20% in Canada with an additional 9–22% projected to contain taliks (i.e., areas of unfrozen ground) embedded within the permafrost. There will be widespread permafrost degradation over up to 57% of Alaska (850 000 km^2). Eastern areas of Siberia, which are particularly susceptible to climate warming, are showing similar widespread changes that are likely to continue. The consequences of these changes for landforms, ecosystems and infrastructure – such as melt water drainage, soil subsidence, slumping to lakes, and high silt loads in rivers – are likely to be profound (see Section 12.3).

River and Lake Ice (Chapter 6): The seasonal duration of river- and lake-ice cover is declining, primarily due to the earlier occurrence of spring break-ups. Some of the most profound changes have been observed on far-north lakes in recent decades. Models suggest that lake-ice duration on mid-sized lakes in the Northern Hemisphere could be 15 to 50 days shorter by around mid-century (2040–2079) compared to 1960–1999, mainly due to ice break-up occurring 10 to 30 days earlier. Maximum lake-ice thickness has also been modeled to decrease, by 10 to 50 cm. Changes in ice composition reflecting spatial patterns in ice-thickness reduction and snow-cover accumulation are also anticipated. Reduced temperature gradients along large northward-flowing rivers will favor a greater proportion of break-ups by thermal processes rather than mechanical (dynamic) processes, and thus reduced severity of ice-jam flooding. Mid-winter break-ups and associated flooding will become increasingly common in northerly areas. The nature of break-ups will also be affected by changes in the form (rain vs snow) and magnitude of precipitation.

Mountain Glaciers and Ice Caps (Chapter 7): General declines have been observed in mass (and volume) of mountain glaciers and ice caps over the past century, however, the rates of decline appear to have increased substantially since 1995. Mass losses from mountain glaciers and ice caps in the Arctic may have exceeded 150 Gt[1] per year over the past decade, similar to the mass loss from the Greenland Ice Sheet. Half of the observed loss is from glaciers in the Canadian Arctic and southern Alaska. Future projections indicate continuing losses due to warming, with the greatest losses projected for the Canadian Arctic and Alaska, followed by Svalbard and the Russian Arctic. Under the IPCC A1B emissions scenario, the total volume of Arctic glaciers is projected to decline by 13–36% by 2100, corresponding to a rise in sea level of 51–136 mm (but this estimate does not include losses by iceberg calving).

Greenland Ice Sheet (Chapter 8): Up until 1990, the total amount of ice added to and lost each year from the Greenland Ice Sheet was roughly in balance. Mass loss by both meltwater and ice discharge have increased since 1990 and the inputs and losses are no longer in balance. The estimated rate of net mass loss from the Greenland Ice Sheet over the recent past is four times that of earlier estimates (i.e., 205 ± 50 Gt per year for 2005–2006 compared to 50 ± 50 Gt per year for 1995–2000, of which roughly half is due to melting and half due to discharge). Increased ice discharge is primarily due to accelerated flow in many of the fast-flowing glaciers that terminate on ocean water in the fjords. This speeding up of the ocean-terminating glaciers, a phenomenon that has spread northward along the west coast of Greenland over the past 10 to 15 years, appears to have been triggered by contact with warmer ocean water.

Sea ice (Chapter 9): The average extent of the summer (September) minimum sea-ice cover has declined by 25–30% since estimates based on satellite information began in 1979. The rate of decline increased over the past ten years and is now greater than reported by ACIA. Complete summer sea-ice loss is projected as likely to occur by mid-century. Variability in summer sea-ice extent is projected to increase initially, but then to decrease as ice-free summers are approached. Sea ice is generally thinning and older ice types (5+ years old) are being lost with increasing frequency; first-year ice is projected to dominate in the future. Shifts in the proportion and areal extent of multi-year ice versus first-year ice have immediate physical consequences including a larger area of open ocean during summer and autumn and greater heat absorption. Loss of summer sea ice and increased heat storage in the upper ocean are modifying regional wind patterns with increasing potential for impacts in mid-latitudes as sea ice retreats further in the coming decades. However, trends toward increased cloudiness have suppressed surface warming of the Arctic Ocean to some degree. Projections of annual maximum extent and duration of seasonal sea-ice cover are uncertain and regionally variable (and affected by local bathymetry and weather conditions), but maximum extent and duration are very likely to be less than at present (i.e., with a more northerly distribution, smaller area, shorter duration). Corroboration of local changes, especially for land-fast ice through traditional knowledge and local observations, support these findings (i.e., later freeze-up, earlier break-up, longer ice-free summer, shifted ice dynamics and types). The extent and location of summer/autumn polar pack (i.e., multi-year sea-ice remnants) will be uncertain in future years as the summer ice decline continues, but most models project that pack-ice remnants are very likely to occur along the northwestern margin of the Canadian Archipelago and the north coast of Greenland at least until complete loss.

12.2.2. Feedbacks

Arctic climate change results from complex interactions between the atmosphere, ocean, and individual components of the cryosphere. Many aspects of Arctic climate change are simple responses to a driving force, for example, higher (or lower) air temperatures will alter the ice balance in a particular area. Other changes may involve a feedback whereby a change in one component of the system drives a change in another, which ultimately induces additional change in the original component (see Chapter 11, Section 11.1). Such feedbacks can be positive (i.e., induced change reinforces and exacerbates the original change), whereas others can be negative (i.e., induced change dampens, cancels or reverses the original change)[2]. Feedbacks are important because they may alter rates of change, magnitudes of change, or even directions of change. Owing to

[1] 1 Gt = 1 gigatonne = 1 billion tonnes, which is slightly greater than 1.1 cubic kilometres of water.

[2] Note – positive and negative here refer to the feedback itself and not the warming or cooling effects in the cryosphere context.

their unpredictable effects and their variable scales (spatial and temporal) of operation, feedbacks also add to the uncertainties of outcomes especially for higher-order consequences of climate and cryospheric change. Appropriate parameterization of processes and their interactions, and thus feedback processes, may be inadequately represented in climate models. This affects projections of future states of the climate system.

Two aspects of feedback are important in the present context: feedbacks between the cryosphere and other climate system components, and feedbacks between different cryospheric elements. Examples are discussed below. The list of major feedbacks is much longer than given here, however, and many remain poorly understood (see also Chapter 11, Section 11.1). A third level of feedback is that between the cryosphere and human systems. This feedback is extremely important but also highly uncertain – feedbacks at this level are discussed in Sections 12.3 to 12.5.

12.2.2.1. Feedbacks between cryospheric and other climate system components

Potential feedbacks between the cryosphere and climate include:

- Snow has an extremely high albedo (surface reflectivity). Albedo of snow and ice decreases as they melt and metamorphose, and/or as particulate matter (dust, soot, volcanic ash) is deposited onto them, and/or as particulate matter is exposed at the surface as it is released from snow and ice by melt. Increased heating of darker land and sea surfaces will occur as snow amounts decrease in time and space which, in turn, will exacerbate melting. This feedback is partly responsible for the accelerated rates of cryospheric change observed over the recent past, albeit with high uncertainty associated with them. The replacement of sea ice by open water over wide areas of the Arctic Ocean has substantially increased heat absorption by the upper ocean. This appears to have increased the rate of melting of the remaining sea ice, to have altered the Arctic climate system itself (heat storage and wind patterns), and to have accelerated changes in other cryospheric components. Moreover, higher ocean temperatures pre-set conditions for seasonally later sea-ice formation, ultimately resulting in a thinner and generally less consolidated sea-ice cover, and influencing the magnitude and timing of ice loss and seasonal melt the following year. This may be exacerbated by increased snowfall (which would insulate and slow seasonal ice formation); however, some effects may be modified by the increased freshening of the system, as less saline waters are more liable to freeze.
- From a total of 48 interactions (six cryospheric components and eight forcing mechanisms), present evaluation (Chapter 11, Section 11.1) shows that more feedbacks between the cryosphere and Arctic climate change have a warming effect (fourteen) than a cooling effect (eleven), and result in accelerated rates of climate change in the Arctic (i.e., 'polar amplification'). Of the remainder, three are uncertain due to conflicting evidence and 20 represent gaps in knowledge.
- Feedbacks operate at different spatial and temporal scales and so understanding their consequences is difficult and associated with high uncertainty. Additional uncertainty arises because effects from some feedbacks are expected to intensify over time, while others are expected to diminish.
- Spatial connections mean that the effects of cryospheric change within the Arctic will have implications for areas outside the Arctic and these effects may be large and possibly counter-intuitive. For example, sea-ice loss north of Eurasia may lead to colder weather in Europe and Siberia during late autumn and early winter (see Chapter 2, Box 2.1). Reduced summer sea ice, increases ocean heat absorption which is released back as the atmosphere cools in autumn. The lower atmosphere thickness is increased which thus increases pressure, resulting in de-stabilization of the Arctic boundary layer. Winter winds flowing out of the Arctic may therefore be more intense and affect lower latitudes to a greater degree than is typical, resulting in winters of greater severity in Europe and Siberia – a counter-intuitive effect of climate warming.
- The production and release of GHGs from Arctic stores or processes is likely to increase as the cryosphere degrades or changes. Changes in permafrost and lake ice, for example, can enhance the production of methane (which has great capacity to induce warming) and nitrous oxide and increase the seasonal window for their release. However, drying of the active soil layer can cause a methane sink in some cases. Overall, processes such as carbon dioxide fluxes are likely to have very small global effects. Others, such as those that may result in the release of subsea methane, could have large global effects, although in both cases the uncertainty is high.

12.2.2.2. Feedbacks among cryospheric components

Feedbacks among cryospheric components include:

- The occurrence of relatively warm open water near floating ice tongues from the Greenland Ice Sheet appears to have increased mass loss from the ice sheet through increased flow rates to the sea and thus increased calving of icebergs, particularly in western Greenland. Similarly, the degradation and complete loss of semi-permanent land-fast sea ice on the northern coast of Ellesmere Island in the Canadian Arctic appears to have contributed to the break-up of the 3000–6000 year old marginal ice shelves in the area, probably due to their exposure to a warmer and more open-water environment.
- Snow insulates underlying environments from atmospheric temperature extremes. As snow extent and duration decrease, and despite the likely increase in snowfall amounts, ice (lake, river, sea) and permafrost environments will probably both be exposed earlier in the season to generally warmer atmospheric conditions. If so, this will exacerbate spring thaws and increase active-layer depth in permafrost. Consequently, decreased integrity of ice and permafrost can be expected due to the insulating properties of snow.
- In the terrestrial environment, permafrost acts as a key element determining hydrology over great areas of the Arctic. As a result, changes in the permafrost will alter drainage and this could lead either to drying or to increased ponding over significant areas. Drying creates conditions

for wildfires in tundra and forested areas, which will be exacerbated by higher summer temperatures and increased evaporation. Fires may contribute to increased emissions of GHGs and other climate forcers.

- Decreased ice on land, rivers, lakes and the sea will result in greater evaporation of water. The likely effect will be an increase in clouds at mid-levels in the atmosphere. Clouds reflect incoming radiation, which means increased amounts of cloud may result in overall cooling of the atmosphere. Increased evaporation also affects precipitation regimes.

These feedbacks, as well as additional feedbacks noted in other chapters, generally exacerbate the effects of changes in the climate system and the cryosphere. Furthermore, as already noted, feedbacks also increase uncertainty in the timing, rates, nature, spatial scales and outcomes associated with climate change. The relevance of these feedbacks and their interactions with Arctic ecosystems are discussed in the following sections.

12.2.3. Effects of cryospheric changes on other aspects of the Arctic environment

Changes in the physical nature of the cryosphere have consequences for other components of the Arctic environment.

Snow: Changes in snow will have profound effects on terrestrial environments and their soil, plant and animal communities, as well as on aquatic environments influenced by terrestrial runoff (wetlands, rivers, lakes, coastal seas). Increased insulation resulting from greater snowfall may increase winter soil temperatures, thus increasing rates of biological processes, such as decomposition and nutrient release. In turn, where water is not limiting, there may be an overall increase in terrestrial productivity manifested by seasonally earlier, more intense and higher levels of production; as well as shifts in community types (e.g., greater shrubiness). These effects may be offset by earlier disappearance of snow, winter thaws, or rain-on-snow events. Winter-resident herbivores, such as rodents, rely on subnivean environments that, if affected by adverse events or if frozen, would lead to decreased population abundance. Follow-on responses by resident predators to declining food sources have effects throughout the entire food web. Similarly, consequences for large herbivores, such as musk-ox and caribou/reindeer that forage through the snow in winter, will reflect the combination of many local factors (e.g., winter mortalities due to limited access to forage, increased mortality due to moulds, possibly increased fecundity due to earlier forage availability in spring), but overall the net effect is likely be negative. Effects on peoples who hunt or herd could be substantive, with a significant decline in food security and traditional activities, particularly during winter. Conversely, increased nutrients and earlier production in terrestrial environments may result in greater local productivity with positive consequences for some animal species and people. Water from snow melt transports nutrients to aquatic systems, possibly enhancing local productivity, and if trapped on the landscape tending to counteract drying regimes.

Snow insulates ice and blocks light penetration, whether the ice is on lakes, rivers or the sea. By insulating the underlying ice, increased snowfall will tend to result in the ice being thinner (although shorter snow durations may offset this to some degree, and increased snow loads on thin ice could promote snow-ice formation). Winter nutrient accumulation in the water column combined with light penetration during early polar spring 'jump start' the seasonal production in freshwater and marine ice-covered ecosystems. Greater snowfall, particularly during polar spring will reduce the light available for photosynthesis by phytoplankton below the ice, although this effect may be offset by longer open water conditions. This shading effect may also impede photosynthesis by sea-ice algal communities, which can represent a large fraction of the total annual primary production, and thereby alter marine food webs.

Permafrost: Permafrost affects the landscape drainage patterns, and is responsible for the vast range of tundra wetlands, ponds and small lakes present in the Arctic. Degradation of permafrost alters the nutrient processes in these systems and in many areas has resulted in the drainage and loss of lakes. Tundra water bodies are ecological and biogeochemical hotspots providing key habitats for biota. They are also significant sources of GHGs to the atmosphere, and permafrost degradation may alter GHG export from such areas. Permafrost degradation in terrestrial areas may also result in slope instabilities and subsequent failure; failures affect the receiving ecosystems (lakes, rivers) and also represent hazards to humans and built environments (roads, towns, industrial sites). High uncertainty surrounds effects of permafrost thaw on soil water content thus subsequent effects on ecosystems and on GHG emissions – projections are uncertain but models suggest that the tundra will continue to act as a weak carbon sink at least for the next 100 years (i.e., net balance throughout the Arctic will be slightly toward continued storage of carbon thus slightly ameliorating effects of GHG production). Up to 65% of the Arctic coastline is composed of unconsolidated materials with considerable ice-rich constituents and is therefore at risk due to permafrost degradation; this is particularly acute near the deltas of most major Arctic rivers. Alteration of coastlines due to slumping will be exacerbated by a decline in sea ice, longer open-water fetches, and increased effects of storms. Continental marine shelves and the nearby low-lying deltas of large northern rivers also hold large reserves of carbon, mostly in the form of methane capped by an impermeable layer of permafrost. Degradation of the permafrost may ultimately result in the abrupt release of large quantities of this potent GHG, representing an uncertain future threat.

River and Lake Ice: Second and higher-order effects of changes in freshwater ice (e.g., on gas exchanges, mixing regimes, contaminant capture, exposure to ultraviolet radiation, and overall biological productivity and diversity) will have numerous implications for the ecosystem health of aquatic systems. The effects of changes in river and lake ice are very likely to be closely coupled with nearby land-form changes due to permafrost thaw. Changes in ice-cover dynamics are likely to decrease the frequency and magnitude of spring ice-jam flooding in many areas of the Arctic, affecting the ecology of deltas, which is especially relevant to the overall production in the large Arctic rivers. Ice-jam flooding produced by mid-winter melt and ice break-up represents an increasing hazard to nearby communities and infrastructure. Predictions of ice-induced flood conditions, however, are confounded by uncertainties about the intensity and magnitude of future snowmelt runoff that affect the dynamics of river-ice break-up processes.

Mountain Glaciers and Ice Caps, and the Greenland Ice Sheet: The consequences of changes in these cryospheric components include exposure of new land and altered drainage patterns, initial increases in runoff followed by eventual declines as glacier area decreases, and water outbursts of several types if glacier lake dams fail. Increased iceberg formation and continued break-up of ice shelves (until they disappear completely from the Arctic) are also expected, and may create hazards in the marine environment. Also, release of materials stored in ice (contaminants, sediments, fine particulates) may affect downstream water quality (generally negatively). Increased water output during the summer melt period is also expected and may represent a positive benefit in some locations, at least in the near term.

Sea Ice: A progressive decline in the area of multi-year sea ice, its seasonal replacement by younger ice, lengthening of ice-free periods, and increased area of open water have profound implications for the Arctic. These physical changes will alter albedo and increase heating and gas exchange in marine waters. These effects will, in turn, have follow-on effects on the climate system, marine ecosystems and human activities. Some ice-associated ecosystems (such as multi-year sea ice and epishelf lakes) are at risk of complete loss; others will change significantly. Phytoplankton production rates in the marine ecosystem are likely to change, but to a variable extent among sites. In general, these rates are likely to increase as a result of sea ice loss and increased exposure to sunlight, although this effect may be offset to some degree by increased water column stability caused by freshwater inputs to the surface layer. In addition, ice-associated biota are likely to decline, while other biota will become more important. Both types of effect will alter structural and functional relationships within the ecosystems. Altered trophic relationships due to changes in pivotal components (ice algae, cryophilic zooplankton, Arctic cod) will induce effects in those species that prey upon them. As it is the higher-trophic level species (seabirds, marine mammals, predatory fishes) that are the most directly relevant to humans, changes in sea ice will ultimately affect human food and exploitation opportunities in the Arctic. Increased extent and duration of open water in the Arctic Ocean will also feed back to climate and affect coastal environments.

Induced Effects and Ecosystem Overview: Physical changes in the environment resulting from changes in cryospheric components induce follow-on effects, many of which ultimately cascade to ecosystems. The rest of this section reports wide-ranging and over-arching induced effects (for further details see Chapter 11, Sections 11.3 and 11.4).

- *Shifts in Terrestrial and Freshwater Ecosystems and Water Balances*: Greater precipitation overall (regardless of how delivered) primarily as snow, increased glacier and ice-mass shrinkage, shorter ice duration, and warmer winters, will all combine to result in an overall increase in the amount, temporal extent, and availability of liquid water in the Arctic (at least in the short term). Processes that increase drying (evaporation, drainage) will counterbalance this to a varying degree. High spatial variation is also likely, thus local water balances will be highly variable. Effects that increase water in the landscape will occur in the near future and most will continue at least until mid-century, although some will ultimately decline (such as water flow from smaller glaciers). Assuming warming feedbacks continue, mass loss associated with large glaciers and ice sheets will continue for centuries. As previously noted, these effects will also be modified locally by changes in permafrost, effects from ice, and similar linkages among cryospheric elements, all of which will affect local and regional hydrology. Moreover, higher air temperatures in summer will alter evaporation by increasing drying regimes. A change in the water balance will have significant follow-on effects on terrestrial ecosystems by creating new habitats. Responses in the vegetation may include greater productivity, northward shifts in distribution, increased invasions of pest and disease organisms, local extirpations of some endemic Arctic flora, and increased local biotic diversity but with species composition differing from present-day. Changes in the vegetation and productivity will then enable similar shifts in animal diversity within the terrestrial landscapes. Nutrients and other constituents (silt, contaminants) carried by water will affect freshwater ecosystems with similar consequences. Infilling of habitats due to sedimentation, and slumping and de-watering over large areas of tundra will also affect biota (waterfowl, freshwater fishes) that rely on these biological 'hotspots'. In some areas new aquatic and terrestrial habitats will be created as glaciers and ice sheets decay, and freshwater ice is lost particularly where it currently freezes to the bed or exists as perennial forms. Colonization of these new environments represents a microcosm of wider shifts that are likely to be forthcoming for many terrestrial and freshwater ecosystems in the Arctic.
- *Shifts in Marine Ecosystems*: Sea ice affects and controls element cycling in marine ecosystems (thus regulating primary production), water-mass mixing processes (including upwelling of deeper waters), and light penetration. Sea ice also acts as a physical habitat for some marine mammals and seabirds. As a result, shifts in the presence and types of sea ice present will have far-reaching consequences for marine ecosystems in the Arctic. These are likely to include: increased production in the central Arctic basin accompanied by a switch from light- to nutrient-limited conditions; a shift in primary production (and associated secondary production) from a high proportion of ice-based primary production to much greater plankton-based production, particularly over coastal shelves, with consequences for nearshore benthic production (possibly decreased) and unknown consequences for higher trophic levels such as fishes and marine mammals; and, northward shifts in marginal ice zones associated with highly productive sub-Arctic seas and general ocean warming, which are likely to be accompanied by changes in the distribution of marine biota of direct interest to humans (fishable species as well as new predators such as killer whales). Alternatively, the seasonal timing of sea-ice retreat will affect the availability

of ice-associated zooplankton and lipid-rich forage fish – critical resources for higher trophic levels. Negative follow-on consequences for Arctic-adapted biota may ensue. Mismatches in space and time between sea ice and Arctic ecology will have significant consequences for populations. For example, reproductive success in seabird populations is likely to decline in many locations as land-fast ice edges retreat or degrade earlier and as underlying fish quality changes as species distributions shift. Shifts in biodiversity may also result as sea-ice habitats change or are lost (see Section 12.3.5).

- *Contaminants*: Glacial ice and/or snowpacks, once considered semi-permanent sinks for contaminants will eventually become local sources as melting releases stores of long-lived contaminants to Arctic waterbodies, landscapes and the atmosphere (see Chapter 11, Section 11.3). This will increase the likelihood of these contaminants re-entering biological and human systems. Such contaminants include legacy persistent organic pollutants (POPs) and metals and possibly also radioactive elements. At least over the short term (to mid-century), degradation of multi-year sea ice is likely to alter contaminant dynamics. Shifts in snow characteristics are likely to alter the dynamics of volatile contaminants with greater transfer to the atmosphere and/or water possible. Altered landscape hydrology and drying of some landscapes may also release or expose contaminants stored in freshwater sediments. Increased exposure is likely to increase entrainment in seasonal flows and biota, thus encouraging contaminant re-entry into Arctic ecosystems. Accelerated remobilization of legacy POPs is very likely as the Arctic Ocean becomes more exposed and warmer; moreover, decreased ice is likely to increase this, whether or not winds change in the future. Uncertainties with respect to biotic degradation processes for POPs may alter rates; this is a significant gap in understanding. Altered ice dynamics will alter the mercury cycle in the Arctic Ocean. Enhanced entrainment and transport of contaminants is likely throughout the Arctic Ocean via greater amounts of seasonal first-year sea ice. Shifts in marginal ice zones, the sites of extensive biological production supporting most *in situ* trophic productivity in the Arctic marine system, will induce shifts in lipid pathways and transfers. As a result, contaminants preferentially stored and transferred in lipids are very likely to affect higher trophic levels (Arctic top predators such as seabirds, whales, and polar bears). Changes in foraging behaviors are also likely with altered trophic patterns and loss of key habitats such as sea ice. Follow-on health effects of contaminants on biota, as well as on humans relying on these organisms are possible but details are uncertain at this time. Colonizing and invasive species that are typically highly migratory will increase in the Arctic as thermal and ecological barriers decline; the proximate effect will be to alter contaminant pathways in unknown ways. In addition to the cryospheric linkages outlined above, human activities and the changing climate will also influence contaminants in uncertain ways, for example, increased human access and development may increase the potential for contaminant release.

12.3. Integrated consequences of cryospheric-driven changes on Arctic societies

The lifestyles and activities of humans in the Arctic are very closely associated with the environment; that is, the Arctic in general and the cryosphere in particular exert great and close control over when, what and how activities can occur (Chapter 9, Section 9.4 and Chapter 10). This is true irrespective of whether one lives on the land with a traditional lifestyle and a primarily subsistence-based livelihood, whether livelihood is primarily wage-based and thus life is oriented more toward urban centers, or whether one is a seasonal worker in the North. These forms of livelihood have different associations with the Arctic landscapes and seascapes, and cryospheric changes will affect each in different ways. Also, the nature and consequences of cryospheric change will differ depending on whether the area occupied is primarily inland or coastal. The various sectors from which livelihoods are derived will be exposed to different consequences of cryospheric change. The consequences include a combination of direct effects (access, hazards) and indirect effects (shifted or lost ecosystem services requiring adaptation or replacement), both of which sum to an overall effect. Finally, changes also have non-material consequences as they affect the overall experience, perception, cultural value and well-being of people living in close relation to the Arctic cryosphere.

12.3.1. Changes to access in the Arctic environment

Ice in its many forms represents the solid phase of water present throughout the Arctic cryosphere. Ice thus represents a barrier (or impediment) as well as a benefit to virtually all human activities in the Arctic. As a result, changes in ice alter aspects of human accessibility to local and regional land and aquatic areas, directly affecting how these are utilized. Altered accessibility has far-reaching social, cultural and economic consequences.

- River and lake ice, and permafrost in terrestrial landscapes offer relatively inexpensive seasonal transportation routes via ice roads between southern centers of supply and northern communities and industrial sites. Thus, changes in these cryospheric components (such as shorter seasons, altered routes, weaker or thinner ice) affect transportation options and result in increased costs for overland transport. Few viable adaptation options exist, especially for communities far from coasts or large river systems. Permanent all-weather roads or railways may ultimately be necessary at significant cost to regional and/or national economies. On the other hand, cryospheric changes may also result in increased opportunities for water-based transport (longer seasons, more water from increased precipitation), but these are mostly restricted to northward-flowing large rivers, large lakes, and coastal areas.
- Land-fast sea ice provides local transportation options when it is present, and negative effects result from its earlier seasonal degradation. Activities on land-fast sea ice include hunter travel to floe edges for wildlife harvesting, inter-community travel, and industrial activities. Land-fast sea ice also provides a stabilizing and protective feature for

coastlines and near-shore activities such as hydrocarbon development. Its degradation will require changes in how these areas are used and the duration of their use. Altered shorelines will also affect communities (see Section 12.3.4). Alternatively, the presence of land-fast sea ice inhibits summer marine transportation, often requires local ice-breaking activities, and affects the re-supply of communities and coastal shipping. Earlier seasonal disappearance is likely to benefit such activities. Shifts in seasonal sea ice will also permit earlier and later, and perhaps increased, overall ice-breaking to allow for longer operational shipping seasons. Ice-breaking activities affect sea-ice habitats and ecosystems and may also affect local human activities.

- Pack ice, especially when highly consolidated and at its greatest seasonal extent during late winter, acts as a barrier to Arctic marine transportation and so restricts access by humans to many areas over much of the year. Decreased duration and areal extent of pack ice will thus facilitate marine transportation. Open areas in pack ice (polynyas and flaw leads) are key habitats for ice-associated Arctic biota but also represent access points for ice-capable shipping, and thus potential conflicts arise between habitat use by biota and economic endeavors.
- At the level of the individual (in contrast to the previous points which address the community level), over large areas of the Arctic access involves travel both on land and over local infrastructure such as roads. Similar to the consequences outlined above, changes in terrestrial and freshwater cryospheric elements will affect local accessibility. Permafrost degradation, changes in lake and river ice, glacier or ice sheet retreat, and changes in snow regimes will all affect the integrity of local landscapes and thus their suitability for overland travel. Poorer travel conditions increase hazard and may require a change in lifestyles, areas and timing of use, and traditional practices for indigenous groups. Changes are also likely to be required in local land use practices associated with industrial activities (e.g., seismic exploration). Where built infrastructure is present (roads, bridges, airstrips) cryospheric changes will affect local usage patterns and may require increased maintenance schedules or re-construction.
- Sea-ice affects marine vessel traffic whether this is destinational shipping to/from the Arctic, marine fishing, ship-based tourism, research cruises, military activities, coastal monitoring, or ultimately transpolar shipping. Altered sea-ice regimes for land-fast and pack ice will affect access associated with these activities. Although decreased sea ice can generally be expected to lengthen seasonal periods of access, ice regimes are expected to be highly variable in space and time. Moreover, larger areas of open water allow for increased consequences of wind and storms, and perhaps increased fog and icing events. Winds and storms also move large masses of unconsolidated ice, which represent a significant but highly dynamic local issue for shipping. Thus, while access may overall be longer or better, it may be offset by more rigorous operational conditions, greater probability for accidents, and associated requirements for safety and infrastructure. Also, feedbacks of human activities on the cryosphere from increased shipping may occur with increased production and deposition of contaminants and perhaps also engine soot in sensitive northern ice environments. Issues associated with Arctic shipping consist of those within territorial jurisdictions as well as those associated with the offshore environment. Given the connectivity among Arctic marine areas due to currents and present-day ice movements, accidents (particularly hydrocarbon spills) have the potential to affect large areas for long periods of time. Thus, cooperative pan-Arctic solutions to these issues are required.
- Overall reductions in sea ice will also allow for access to areas that were previously accessible only with great difficulty. Increased access may stimulate industrial activities (mines, sea-bed activities, hydrocarbon development), thus increasing local economic output, shipping, and further alteration of local lifestyles. These areas are likely to be those that persist for the longest, and thus within the next few decades may become remnant refuges for Arctic endemic biota. Modeled projections indicate that remnant multi-year sea ice is most likely to become associated with the northwestern margin of the Canadian Arctic Archipelago and northern Greenland, although substantive mobility may also occur. Action will be required to ensure the sustainable uses of such areas.
- Although limited at present, future glacial retreat, especially in Greenland, will expose new land allowing greater access to non-renewable resources. Economic benefits derived from increased access may be offset by the longer travel times required for hunters to reach wildlife populations. Thus, the overall balance of these changes to human activities is a dynamic consequence of potential positive and negative effects that cross many scales.

Altered accessibility within, to and from the Arctic is an inevitable outcome of cryospheric change and will affect many aspects of human activities in this area, albeit with uncertain timings. Even more uncertain are the local consequences of effects, whether these will be beneficial or detrimental, and whether the overall balance of effects will be negative or positive at a particular level or to a particular group in Arctic society, as well as collectively across all levels. The ability of humans to adapt to the challenges and opportunities associated with cryospheric change in the Arctic depends to a large degree on non-cryospheric factors and drivers of change. It is entirely possible that the overall balance of effects at one level may be negative (e.g., personal travel on sea ice) while at another level the effects may be positive (e.g., community re-supply and costs of purchased goods). Moreover, there may be local differences in adaptive capacity and involvement that will determine whether a change will be largely positive or largely negative. It is the sum of the effects that affect local cultural, economic and societal viability, and thus detailed examinations are required to better understand adaptation options to changes in the cryosphere.

12.3.2. Humans, biodiversity changes and land-use activities

Humans in the Arctic rely on ecosystem services and utilization of terrestrial and aquatic ecosystems for security of their local food supply, health and well-being, integrity of cultures and lifestyles, income, and economic development. Cryospheric changes generally affect all these aspects of life, however, the nature and potential effects of these changes, and whether they represent potential threats or benefits, depend upon the economic sub-sector to which the individual belongs. Examples of some possible consequences follow, but this list is by no means comprehensive.

- Changes in land-fast sea ice have affected travel to/from the floe edge to hunt, with subsequent effects on safety, food security and personal economies of indigenous peoples. Such effects are locally variable; for example, generally negative in Nunavut, Canada but positive in Greenland (where a switch to boats has increased local harvests of some marine mammals). These effects are likely to continue and become more acute, however, longer ice-free seasons may benefit new approaches to hunting, traveling and local fishing but this is likely to require financial and technological capacity building. Changes in traditional harvesting practices that are closely connected to indigenous cultures will also be required. Moreover, current knowledge (i.e., traditional knowledge) must be expanded to accommodate cryospheric change. Increased reliance on some forms of technology (e.g., personal GPS devices) may aid activities in changing environments, but these do have limitations.
- Terrestrial cryospheric changes also affect travel to hunting, fishing and harvesting sites. Moreover, these activities often rely on large land mammals, such as caribou, that also travel as migratory herds. Migration routes and timing may be altered due to cryospheric changes and a mismatch may occur in traditional timing or place, or in hunter or herder access to areas for these activities. Routes of migratory land animals which cross water bodies increase the likelihood of habitat contraction and catastrophic losses of large numbers as cryospheric changes occur. In the case of herding activities, adjustments in the timing of seasonal activities are likely to be required. These adjustments are also management issues and so require adaptation in governance and regulation.
- Changes in snowpack conditions will affect accessibility, and the forage base and its quality for reindeer and other land herbivores. Follow-on effects are likely to be negative overall for reindeer husbandry, herd survival and well-being, as well as for harvesting wild populations, and thus engender further effects on the cultural, economic and lifestyle significance of this activity.
- As sea ice retreats, shifts in commercial or locally harvested fish species may occur and fishing activities may require adjustment. These will be highly regional in nature and may be exacerbated by unrealistic expectations regarding the biomass and sustainability of Arctic fisheries. In freshwater ecosystems, shifts in productivity and colonization may increase overall fisheries production particularly in the more southerly areas of the Arctic, although this is likely to be at the expense of some Arctic-adapted species.
- Large shifts in biodiversity are expected as cryospheric changes continue (see also Section 12.3.5). These include the following changes (most of which have negative outcomes relative to the present situation): loss/extirpation of some organisms; changes and re-structuring of communities; loss of some unique habitats and communities; and colonization by invasive or pest species. Alternatively, some shifts in biodiversity offer opportunities, including: changes in ranges; higher productivity within some existing ecosystems; and new colonizing species some of which may be harvestable. The outcomes of biodiversity shifts are all highly uncertain, but it is reasonable to conclude that most Arctic ecosystems and communities will change substantively, ultimately with significant effects on humans. Also, given the rate and scope of cryospheric changes in the Arctic, it may be decades before ecosystems are sufficiently re-equilibrated and resilient to permit large-scale commercial exploitation. In the interim, some aspects of local subsistence resource harvesting may be seriously challenged.
- Cryospheric changes will also affect aspects of land use other than travel. Local hydropower options will be affected by snow changes (increased snow and more runoff is likely to represent a benefit) but altered lake (reservoir) and river-ice regimes will require adjustment to operations. Similarly, altered glacial mass balances imply short-term flow increases for some glacial-fed rivers and hydropower planning, as is happening in Greenland. Glacier retreat and changes in land drainage patterns, and eventually the complete loss of some glaciers will require planning to ensure water supply remains steady over the lifetime of the facilities.
- Ground subsidence in ice-rich permafrost areas affects travel, infrastructure, and long-term integrity of buildings. In addition to local economic consequences of infrastructure maintenance, repair and replacement, loss or rupture of containment structures or pipelines may have profound environmental effects including release of hydrocarbons or toxic metals into sensitive environments. This is exacerbated by aging and/or poorly inspected infrastructure, and follow-on consequences of permafrost changes such as altered flow regimes possibly facilitating wider movement of spilled materials.

Perhaps the biggest challenge in the future will be to try to maintain environmental and ecosystem integrity in the face of more rapid, yet still uncertain, changes resulting from many causes: substantive cryospheric changes, additional environmental changes due to climate change, and shifts in human populations and the nature of their activities in the Arctic. Uncertainty of outcomes is extremely high, especially at the ecosystem level and is compounded by high variability in system drivers and potential responses. Feedbacks between human systems and the environment, both within and outside the Arctic, further increase the uncertainty of outcomes. These factors will combine to make planning and environmental stewardship extremely difficult.

12.3.3. Industrialization and development

Cryospheric changes can create opportunities for industrial development in the Arctic by increasing accessibility. These opportunities include those associated with non-renewable resources including hydrocarbon development on land and coastal shelves and slopes, new mining possibilities (primarily on land but potentially also in the sea), and transportation needs and opportunities. Opportunities also exist for renewable resource sectors, including increased potential for forestry and agriculture further north than at present, fisheries and aquaculture potential, and tourism.

Challenges to development opportunities also exist. These include high uncertainty in future states of the Arctic system and thus limited ability for predicting future potential (especially for industries that rely on renewable resources such as water). The overall system is rapidly following a trajectory of high change; high variability exists in the system, and the effects of changes on industrial and other human developmental activities are uncertain. Also, human responses to change are uncertain and the capacities to adapt to such challenges are highly variable across the Arctic. Nevertheless, appropriate planning and regulation are required to ensure that exploitation of new opportunities does not exacerbate changes in the cryosphere.

Aspects and challenges specific to many of these industrial or economic activities have been discussed or touched upon in other sections and will not be re-examined here. However, several have not and these are outlined below.

- **Tourism**: Increased ship-based tourism will be fostered by increased access associated with sea-ice changes, and existing evidence suggests a recent increase in this activity. Expectations of service, safety and positive experiences will be high and many local communities may be challenged to meet the capacity (e.g., in terms of providing local cultural experiences to meet demands). Regional or national governments may also face challenges (e.g., search and rescue needs). As components of the cryosphere continue to degenerate or re-equilibrate, the ice-associated animal species are likely to be reduced or re-distributed into smaller more northerly areas. Thus, access may become more difficult and, as species become rarer, disturbance will be an increasing problem that is likely to require responses to ensure sustainability both of species and their dwindling habitats. At the same time, land-based tourism to observe Arctic wildlife, experience adventures, or see cryospheric structures is a growing industry. As cryospheric degradation continues, however, the potential for this may be altered.

- **Forestry and Agriculture**: Increased precipitation and the resulting increase in local productivity may facilitate growth of harvestable renewable resources. This may also be positively affected by increased warning. Thus, along the southern margins of the Arctic and in many northerly sub-Arctic areas, increased production in renewable resource sectors is likely. Such increases, however, are likely to be highly variable in space and time, and effective increases in productivity may not be realized for decades. Moreover, in some areas drying will increase moisture stress on forests and exacerbate fires. Stressed trees are also more susceptible to pests.

- **Hydrocarbons**: Stores of oil, natural gas, and gas hydrates in the Arctic are significant and many are readily accessible in terrestrial and marine shelf environments, albeit with major technological challenges. Moreover, as access changes additional areas may become exploitable. As a result, hydrocarbon development, production, and transport to southern markets are very likely to increase substantially over the coming decades. Increased variability and uncertainty in cryospheric environments, the Arctic climate system itself, and long-term adverse consequences of accidental discharges of oil, drilling wastes, or contaminants in cold and ice-associated environments, all represent substantive issues to be addressed.

12.3.4. Hazards

Changes in the Arctic cryosphere either create new hazards or alter exposure to existing hazards. As with most consequences of climate and cryospheric changes, hazards cross a wide spectrum of relevance ranging from immediate physical and direct hazards to those that are less direct and perhaps secondarily derived. Increased potential or realized hazards will require increased personal vigilance and local risk assessments, mitigation where required, and direct responses to the hazards themselves. Moreover, some hazards are predictable or can be assessed through risk-based methods whereas others cannot. Preparedness to meet both types of challenge is required. In addition to the hazards previously discussed, examples across the spectrum of likely hazards include the following.

- Decline of summer sea ice will expose vulnerable shorelines to open water and storm events, thus contributing to significant erosion and flooding in some areas. Sea-ice declines will interact with other cryospheric changes (e.g., permafrost decline) and other climate-driven changes (e.g., increased runoff) to further affect coastlines. The result will be significant consequences for shore-based infrastructure, coastal communities, and some cultural sites. Reinforcement and stabilization of buffering systems on coasts and/or re-location of coastal communities may be required with significant costs incurred by individuals, local and regional governments, or local industries.

- Where increased ice calving occurs directly into the sea, iceberg transport into southern shipping lanes of the Northwest Atlantic represents a hazard, but uncertainties presently preclude projections into the future. This represents a knowledge gap.

- Glacial outburst floods and avalanches are all exacerbated by increased snowfalls, enhanced freeze/thaw cycles, and degradation of cryospheric components such as glaciers, ice and permafrost. Slope instabilities further increase the likelihood of such occurrences. Moreover, effects from such events can be locally widespread and reach distant locations downstream. As a result, infrastructure, towns, and habitation in such areas are at increased risk as the cryosphere continues to degenerate. Appropriate risk assessments and potential remedial actions are required.

- Ice- and permafrost-related travel is inherently risky and longer freeze-up or break-up seasons, perhaps thinner ice, and less stable conditions are likely to increase human strandings or mortalities. Increased loss of equipment, industrial loads, foodstuffs, and perhaps hazardous goods can also be expected. Reduced use of ice and permafrost, reduced loads, alternative transportation routes, enhanced search and rescue responses, and increased monitoring are required as local shorter-term responses. Longer-term responses may involve developing alternative transportation routes over great stretches of difficult terrain.

- Cultural or archaeological sites on coastlines, and/or lake or river margins are likely to be lost as permafrost degrades. Also, loss or exposure of paleontological remains is likely to occur. In many cases these sites have neither been discovered nor explored, and so their loss represents a significant cultural loss of global relevance. Permafrost changes may also enhance industrial hazards such as containment failures, pipeline ruptures, and infrastructure failures ranging from personal housing to community services. Enhanced monitoring and risk assessment is required; replacement planning requires enhanced engineering protocols, implying greater costs.
- Spring ice break-ups, particularly on large northward-flowing rivers (the Arctic has five of the ten largest rivers in the world and a high number of smaller but still substantive rivers), are projected to become less dynamic (mechanical) in nature. Although decreases in break-up flooding will have negative effects on the ecology of productive deltas, overall the changes are expected to be beneficial to communities and infrastructure in vulnerable locations. If, however, break-up occurs much earlier, particularly during mid-winter, or if enhanced snowmelt runoff drives break-up, increased severity and impacts of ice-jam flooding will result. The potential interactions between these two cryospheric components, river ice and snow, remain to be fully resolved.
- Decreased sea ice and more open water could alter the probability of higher winds and the severity of storms over the Arctic Ocean. Such storms will also result in more energetic motion of remaining ice. These represent uncertain hazards to human endeavors in the Arctic and require better weather prediction for large areas of the Arctic.

12.3.5. Ecosystem and biodiversity losses

Some cryospheric components and their associated biota are unique and irreplaceable once lost or degraded. Ice shelves, most of which fringe the northern margins of the Canadian Arctic Archipelago have persisted for the past 3000 to 5500 years. Substantial areal loss has occurred over the past 100 years, including large changes since 2000 (e.g., 23% loss of total ice shelf area in the warm summer of 2008, relative to 2007). The epishelf lakes retained behind ice shelves are unique polar aquatic ecosystems, but are now almost completely lost from the Arctic, with only one remaining.

Changes in permafrost condition fundamentally change hydrological conditions on land, and unique elements in permafrost areas such as peat mounds with frozen cores and ice-cored hills have been observed to decline. Permafrost degradation in land areas is likely to increase slope instability, while permafrost thawing in coastal areas may increase coastal erosion. Permafrost degradation, both in land and coastal areas, is likely to cause significant ecosystem changes.

Permafrost contains viable life to at least 400 m depth, in some cases preserved for significant periods of geological time (millions of years in northern Siberia). Biological activity (bacteria, viruses) is evident after thousands of years of existence in permafrost. In many cases in deeper horizons these constitute ‘prehistoric’ floras of potential significance (e.g., ‘new’ genes predating humans, possibly suitable for molecular applications; re-emergence of human diseases); permafrost degradation will variously destroy or liberate such organisms.

Multi-year sea ice represents a unique, albeit spatially and temporally highly dynamic habitat. Many Arctic biota are highly ‘ice-adapted’ (e.g., iconic species such as ringed seal, narwhal, polar bear, ivory gull, walrus; specialized primary producers such as sea-ice diatoms; and ice-associated amphipods and copepods) and thus depend to a large degree on the presence of relevant sea-ice amounts and types. Others are highly ‘ice-associated’ (e.g., Arctic cod and seabirds such as thick-billed murre). Sea-ice degradation will significantly reduce habitat availability with consequences for population abundance, distribution, and persistence of many of these species. Spatio-temporal mismatches among ecosystem components are also likely to occur, with uncertain consequences for the remainder of the ecosystems. Similarly, although less obvious, semi-unique small-scale ecosystems and biota (e.g., seasonal melt-water ponds on multi-year sea ice) will be adversely affected. The sheer number of these small ecosystems, their intimate connection to productivity pathways to higher biota, and limited understanding all argue for their significance. Colonization by sub-Arctic biota and/or shifts in balance among obligate Arctic cryophiles and Arctic habitat generalists will tend to offset these losses of biodiversity, but will engender wide changes in the ecosystems. Substantive ecosystem and biotic consequences of cryospheric change are likely to involve widespread re-equilibration of existing Arctic ecosystems, and possibly the formation of completely new ecosystems which may take decades to stabilize. Follow-on consequences to humans will result and include conservation issues for Arctic biota, habitats and vanishing ecosystems. Also, there may be degradation or loss of supplies of local foods, traditionally relied upon by indigenous peoples. Tourism represents a renewable resource development opportunity for many areas of the Arctic – loss of key habitats and biota may diminish some of the attractiveness of this activity.

In addition to the above changes, some of which represent globally significant potential reductions or losses, many species, particularly birds migrate to the Arctic seasonally and winter in non-Arctic areas. Cryospheric shifts, particularly drainage of large terrestrial areas and shoreline impacts are likely to have significant impacts on such species. Similarly, changes in hydrology and altered vegetation and productivity regimes affect migrant terrestrial avifauna. The ultimate consequences are uncertain but migratory populations may decline, particularly if habitats are lost. Mismatches in food and key life history events such as nesting success in the Arctic will exacerbate such issues. This adds to the overall conservation needs required in the Arctic and beyond.

12.3.6. Shift in lifestyles, culture and socio-economics

Sustainability of some Arctic ecosystems as used for traditional activities, in particular food harvesting, is uncertain due either to difficulties in access or a declining resource base. Food gathering and traditional annual cycles provide a basis for the culture of Arctic indigenous peoples. Development, shifts to wage-based economies, human demographic changes, and associated embedded changes all affect traditional lifestyles and culture. Cryospheric changes are likely to exacerbate the magnitude and rate of such changes. Decreased applicability of traditional knowledge, and limits to adaptive capacity and potential responses are likely to be presently strained, and will become more so as further changes occur. Food security is at risk as are culture, health and well-being of peoples with lifestyles connected to the cryosphere. Temporal and spatial mismatches are/will be important in ecosystem contexts and also in human contexts. If prey do not occur where people traditionally hunt, or if they are of lower quality, then it may not be possible to harvest adequate amounts.

12.4. Integrated consequences of cryospheric changes for lower latitudes and the global system

The Arctic is part of the global climate system and is closely linked to key elements through heat exchange and carbon cycling. Thus, in addition to significant effects within the Arctic, change in the Arctic cryosphere will feed back in many ways to affect the entire globe. Such feedbacks have far-reaching implications on the global climate system, sea level, and humans outside Arctic. In addition, the Arctic is economically linked to the entire globe and increased access and activities will have effects locally and within the global context.

12.4.1. Climate system changes

The Arctic is closely linked with the global climate system primarily through heat exchange in the atmosphere and ocean, but also through carbon cycling (e.g., GHGs). Alteration of these processes within the Arctic cryosphere results in their alteration globally, with significant consequences to humans at this scale.

Albedo Effects: Reduced Arctic albedo, particularly for the Arctic Ocean, will increase surface heating within the Arctic but will also generally increase heat retention by the globe. This feeds back within the Arctic to effect more rapid and greater change in the cryosphere. Heating of the Arctic also reduces the temperature gradient between the Arctic and southern areas, and thus may affect the strength of atmospheric and oceanic transport mechanisms.

Patterns of Atmospheric Circulation: Shifts in Arctic sea ice and increased heating will warm the lower atmosphere in the Arctic. This change will affect weather at lower latitudes of the Northern Hemisphere, particularly in winter. However, incomplete understanding of the nature and the closeness of the coupling between sea-ice extent, Arctic lower atmospheric heating, stability of Arctic boundary fronts, and circulation responses at lower latitudes complicate the development of adequate models with which to project future trends. Rapidly changing, perhaps increasing extremes, and highly variable weather responses at lower latitudes may result. Recent 'outbreaks' of cold Arctic air masses (e.g., 2005, 2008, 2009, 2010) over lower latitudes particularly in Eurasia appear to have resulted from weakening of the 'polar vortex' which typically traps cold Arctic air near the pole. This variability may reflect an early shift toward altered Arctic, and perhaps northern hemispheric, climatic patterns.

Greenhouse Gas Releases: The Arctic is an effective moderator of the global carbon cycle with respect to storage capacity and local processes cycling GHGs. Over the recent geological past the GHG balance has been toward the storage of carbon (the Arctic has been a long-term sink). However, recent changes suggest the storage capacity is declining. Thus, GHGs are not as readily sequestered there and may contribute to global warming. Moreover, in some areas cryospheric changes are resulting in releases of stored GHGs and/or increased processing of GHGs. Permafrost degradation in some areas exacerbates this and its loss may potentially release large stores of trapped GHGs over decadal to centennial time frames. The significance of this feedback to the global system could be to further and very rapidly accelerate global climate change.

Contaminants: In parallel with the lessening of the temperature gradient between the Arctic and more southerly latitudes, the capacity for northward transport of contaminants is reduced, and thus accumulation in southerly areas is likely to increase. Also, it is very likely that the stores of legacy contaminants within the Arctic are being mobilized by cryospheric degradation. Their release from ice, snow, permafrost, glaciers and ice caps and subsequent re-entry into ecosystems appears to be occurring.

12.4.2. Global marine effects

Sea-Level Change: The issue of sea-level change, at local and global scales, is one of the more serious consequences of climate change, primarily due to the scale of potential effects. Sea-level change is a complex phenomenon resulting from many factors. Climate change affects sea level primarily through water mass changes and through density changes due to changes in temperature and salinity. Global sea levels are also affected by mass losses from non-Arctic glaciers and the Antarctic ice masses.

Present (2003–2008) mass losses from Arctic glaciers and the Greenland Ice Sheet contribute a total increase of 1.3 mm per year to the rise in global mean sea level. Increasing contributions from the Greenland Ice Sheet and other Arctic glaciers have occurred since 1995. Contributions from other sources (Antarctic Ice Sheet, non-Arctic glaciers) are added to these. Total projected sea-level rise resulting from all sources by 2100 cannot be estimated with high confidence at present. Lower and upper limits have a range of 0.79 to 2.01 m. A range of 0.9 to 1.6 m is considered the more plausible current estimate by the authors of the SWIPA assessment. Nevertheless, significant effects of the rising sea level will become increasingly evident by mid-century. High regional variation in sea-level rise will result from concurrent changes in other factors that include gravity fields, ocean temperatures, freshening, tidal effects and local isostatic rebound or subsidence of land. Rates will also differ, thus impacts may be highly regionalized and realized over varying time scales.

Mean sea-level rise increases possibilities of coastal flooding, erosion, infrastructure damage, environmental impacts on ecosystems, and saltwater intrusions into groundwater. Such effects may be accompanied or exacerbated by local additional effects. Ultimate global effects realized at the century scale and beyond include significant inundation of low-lying coasts and possibly complete submergence of small islands in some areas of the globe, although growth of coral atolls may offset this to some degree.

Atlantic Meridional Overturning Circulation (AMOC): Ocean circulation (thermohaline circulation) is a global phenomenon by which heat and water are transported between the polar and equatorial regions. This circulation is powered in part by density differences among water masses due to differences in temperature and salinity. Inflows to the Arctic resulting from this phenomenon consist of surface (lower salinity, warmer) waters entering from the Pacific via the Bering Strait, and surface (warmer) waters entering from the North Atlantic. These inflows are counterbalanced by the outflow of Arctic waters primarily through the Canadian Archipelago and along eastern Greenland, mostly as lower salinity, cold and freshened surface flows. Additional deeper outflows of Arctic Ocean water (high salinity, cold) occur in the northeastern area of the Atlantic. The North Atlantic thus has several mixing zones where warm surface currents from the south interact with cold surface and sub-surface currents originating from the north. Areas of deepwater renewal (Northeast Atlantic – Barents Sea / Fram Strait; Northwest Atlantic – northern Labrador Sea / Southern Greenland) are essential to return water to the south and to the present strength of North Atlantic surface currents (the so-called 'Gulf Stream') which transport heat to northern Europe.

Several changes in the Arctic cryosphere are anticipated to increase freshwater inputs to the Arctic Ocean, thus reducing its salinity (at least in surface waters). These include: increased direct precipitation, possibly increased inputs of low salinity Pacific waters, increased runoff from large Arctic rivers, reduction of ice stores on land, and degradation of perennial sea ice. The increased input of freshwater will have local effects within the Arctic primarily on coastal shelves, many of which are largely associated with increased stratification. Concern has also been raised that increased freshwater outflow from the Arctic (possibly as deeper water masses) will alter the dynamics of ocean circulation and mixing in the North Atlantic. That is, the AMOC may be weakened. The SWIPA assessment found no conclusive evidence to support significant effects of cryospheric change on overturn circulation or deepwater formation. Total increased outputs of freshwater are likely to be at least one order of magnitude less than present flows of the major currents; accordingly, impacts of cryospheric change are likely to have little influence on major ocean current patterns at least for the foreseeable future. This is particularly so in comparison to the direct atmospheric effects of climate change on the strength and patterns of this circulation.

Freshwater Outflow: Most effects of cryospheric change will result in increased presence of freshwater in Arctic environments, much of which will eventually enter the Arctic Ocean. Considerable entrainment of freshwater occurs on marginal shelves and deeper in the Canada Basin, with accompanying shifts in salinity. Recent estimates suggest increased storage of freshwater has occurred in the Canada Basin, while export of freshwater stores from the Eurasian Basin appears to have increased. Large-scale export of freshwater from the Arctic over geological time has been linked with large-scale cooling of the Northern Hemisphere. Factors that drive such export are poorly understood, although regional climatology is implicated. Thus, if storage turns to export, there may be significant surprises in store for the northern hemisphere climate.

Freshwater entry to coastal shelves and fjords decreases overall salinity and results in a mixed-layer of freshened seawater. Runoff, particularly from ice mass changes in Greenland, together with atmospheric forcing controls the depth of the mixed layer. As modeled freshwater outputs increased, mixed-layer decreased. This is likely to have profound consequences for nearshore productivity, although little research exists regarding likely changes on fjord and shelf ecosystems, or with respect to the shift of those effects to higher trophic levels of direct interest to humans. Also, as larger amounts of freshened water are expected to exit the Arctic seasonally (primarily as surface outflows in Baffin Bay / Davis Strait and along eastern Greenland), downstream effects on productive sub-Arctic seas are uncertain but may be profound. Better understanding of physical and biotic linkages is required for Arctic and sub-Arctic ecosystems, as well as cross-regional physical linkages to 'downstream' ecosystems.

12.4.3. Trade and economic development

Altered access (particularly that associated with changes in sea ice) increases possibilities for transpolar shipping and extraction of renewable and non-renewable resources. Changes in the cryosphere appear to be stimulating increased interest in exploration, development, and perhaps also migration from southern regions to the Arctic. Substantive follow-on effects will ensue if this occurs. Overall, reduction in polar sea ice can theoretically reduce intercontinental shipping distances by up to 40%, thus stimulating trade; realization of this potential is likely within the foreseeable future but benefits may take several decades to occur. Similarly, declines or shifts in some cryospheric components enhance development opportunities (albeit with many challenges remaining), many of which will benefit non-Arctic as well as Arctic residents. Coastal and some inland Arctic communities may realize benefits from increased trade (and in some cases these may offset effects of degraded land-based transportation). Overall, increased transport presents significant issues for resolution, such as development and implementation of a polar shipping code, establishing routes, mapping and development of appropriate services, and accident prevention and response.

12.5. Knowledge gaps and recommendations

12.5.1. Gaps in information and knowledge

Shortfalls in understanding and thus ability to project future states result from insufficient data (such as observational data) and the shortcomings of climate models. Each of the preceding chapters of this report noted discipline-specific gaps and issues, the resolution of which is required to ensure more accurate understanding in the future. In addition, an integrative section (Chapter 11, Section 11.5) focuses on many over-arching issues.

Some gaps are also explicitly or implicitly (through inferred conclusions) noted above. The following deficiencies are noted in the knowledge base.

- Although satellite observations of the cryosphere have expanded in type and quantity over the past decade, observational networks are still limited throughout the Arctic for many components, their key drivers and induced effects, and their linkages to human systems. This is particularly true for direct observations. Many important observations and monitoring efforts are research-based and in need of sustained funding. Coordination and common data linkages among observational networks are presently limited.
- There are considerable uncertainties in modeling some cryospheric processes. Permafrost models under-represent ice content and the insulating effect of the organic layer; climate models do not resolve the steep topography of the Greenland Ice Sheet margins; models of snow-vegetation interactions need to be improved; and models that link meteorology to glacier mass balance need to incorporate down-scaling techniques and satellite data.
- The effects of clouds on altering the nature and rates of change in the climate system, and particularly in the Arctic cryosphere, are very poorly known, and at present cannot be effectively modeled by many GCMs. Increased open water in a cold environment is likely to increase local cloudiness; how this may link to local cryospheric changes and thence to the global climate system is uncertain.
- Increased atmospheric carbon dioxide concentrations along with other GHGs fuel climate warming. They also have additional effects, for example carbon dioxide is sequestered within aquatic systems where acidification processes occur. Gas exchange between the atmosphere and waterbodies will increase as concentrations and temperatures rise and as duration and extent of ice covers decline. There is a need to better understand effects and model future situations, particularly for the Arctic Ocean.
- Cryospheric degradation will result in cascading effects on Arctic environments and peoples, their livelihoods, living conditions and quality of life, and the regional climate systems. It will also result in global consequences. The precise ways in which people and communities will be affected needs further study, particularly with regard to adaptation, changes in behavior, health, and resource development.
- Effective observations and monitoring across geographic and temporal scales, sectors and disciplines are all required in a linked inter-disciplinary fashion to provide measurement of change, assess efficacy of mitigative and adaptive strategies, and to prioritize needs for governance and other appropriate responses.
- Climate-driven cryospheric change is only one of many facets of overall Arctic change. Consequences of all drivers of Arctic change, including those in the cryosphere, need to be integrated into an overall understanding of the nature, rates and potential costs/benefits. This integration needs to include cumulative effects of multiple drivers, stressors or forcers on the Arctic system, and needs to cross the physical, ecological and human systems present in the Arctic, and within the latter to cross the various sectors of human society.

12.5.2. Recommendations

The focus for the SWIPA assessment report has been to summarize the evidence for recent cryospheric change in the Arctic, and the effects and consequences of this change for the entire Arctic system. The objective of the SWIPA program was not to focus on the ultimate cause of the cryospheric change (see Chapter 1). Instead, the syntheses embodied in the preceding chapters of this Science Report highlight the present state of knowledge within the various disciplines, and the follow-on effects of present and ongoing change on Arctic ecosystems and humans. The following recommendations aim to increase that knowledge base and facilitate its use.

Near-term needs

- Increase the nature, spatial and temporal resolution, and availability of data from all observational platforms, all continuing into the future – including data for physical, ecological and human elements of the overall system and with a specific focus on feedback linkages within the system (e.g., enhanced methane releases due to cryospheric change) and other gaps.
- Modeling approaches provide insight into future possibilities, but efforts are required to reduce uncertainties in projections and enhance their spatial resolution, to parameterize and incorporate important feedbacks; and to downscale model results to appropriate regional levels.
- Enhance existing efforts to understand causal linkages across all aspects of the Arctic system, both among cryospheric components and between the cryosphere and other components of the Arctic system.
- Integrate and foster seamless availability of data products associated with the cryosphere, the consequences of change, and additional potential drivers.
- Identify and resolve impediments to inter-disciplinary linkages within and among cryospheric components, thereby fostering cross-disciplinary and integrated studies of changes in this system and their consequences for the Arctic.
- Link existing or develop new quantitative models to provide an integrated perspective of climate and cryospheric changes for the Arctic.
- Assess risks, or develop approaches to do so, of cryospheric changes for ecological and human systems in the Arctic across all relevant scales to allow effective planning and remediation. Identify shortfalls in design or approaches presently in place to address future changes in the cryosphere.
- Assess the consequences of cryospheric change for other physical and ecological systems (e.g., enhanced gas exchange driving acidification of Arctic aquatic systems).
- Evaluate roles and cumulative effects of potential drivers of continued cryospheric change across spatial scales to better understand causation and interactions, thus informing mitigation efforts.

Medium-term needs

- Identify and resolve impediments to linking all drivers and consequences of Arctic change into an overall understanding ranging from the physical to human levels of the system.
- Link or develop quantitative and qualitative approaches to enable cross-disciplinary analyses of change, causation and consequences.
- Initiate regional assessments focused on inter-disciplinary integration of recent changes, drivers of change and consequences; and develop projections of future possible outcomes to better inform planning and preparedness.

Long-term needs

- Develop and implement an overall strategy to assess Arctic change from all causes on a regular basis within which major proximate drivers such as cryospheric changes can be assessed.
- Integrate regional and sectoral assessments into regular Arctic-wide assessments.

12.6. Conclusion

The findings summarized in the SWIPA Science Report provide insights into the scope and nature of cryospheric changes in the Arctic. These, in turn, in combination with widespread climate variability, over large spatial and temporal scales, and with human adaptive capacity will ultimately determine whether particular changes in the cryosphere are viewed as opportunities or challenges. The overwhelming consequence appears to be a highly variable and uncertain future for the Arctic. This is perhaps the main challenge resulting from cryospheric change in the Arctic. Strategies and approaches that incorporate such uncertainty as a basic consideration underpin effective solutions. Thus, past trends, expectations of smooth transitions, expectations of slow rates of change, and expectations of low frequencies of extreme events appear to be becoming less trustworthy predictors of future situations and risks. As a consequence, planning for surprises or unanticipated events is increasingly important.