IMPACTS OF SHORT-LIVED CLIMATE FORCERS ON ARCTIC CLIMATE, AIR QUALITY, AND HUMAN HEALTH

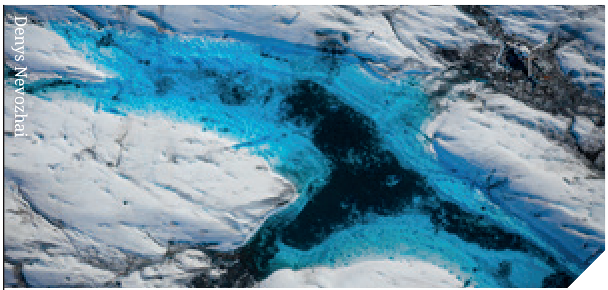
SUMMARY FOR POLICY-MAKERS

ARCTIC MONITORING AND ASSESSMENT PROGRAMME

ARCTIC COUNCIL | AMAP

KEY FINDINGS

This Summary for Policy-Makers is based on the *AMAP Assessment 2021: Impacts of Short-lived Climate Forcers on Arctic Climate, Air Quality, and Human Health.* The assessment focuses on emissions from Arctic Council Member and Observer countries and the impacts of black carbon, methane, ozone, and sulfate aerosols on air quality, health, and climate in the Arctic.



1 Reducing emissions of SLCFs will impact the Arctic climate in the short term, over the next 20-30 years. To limit Arctic long-term warming, steep and immediate reductions of carbon dioxide emissions globally are also necessary, including by Arctic Council Member and Observer countries.

Black carbon, ozone, and methane have contributed to Arctic warming. Sulfate aerosols from emissions of sulfur dioxide have a cooling impact on the climate and thereby mask some of the warming from carbon dioxide and warming SLCFs. However, declining global emissions of sulfur dioxide have unmasked some of the Arctic warming caused by carbon dioxide and warming SLCFs over the last few decades. In the period 1990-2015, the warming revealed by this unmasking effect from declining sulfur dioxide emissions is of similar magnitude to the Arctic warming caused by carbon dioxide emissions.

Health and environmental concerns nevertheless motivate further reductions in sulfur dioxide emissions. Immediate efforts to reduce emissions of black carbon, ozone precursors, and methane are especially important for ensuring both climate and health benefits from mitigation of SLCFs. Reducing emissions of SLCFs that contribute to warming can offsets the warming unmasked by health- and ecosystem motivated measures to reduce air pollution.

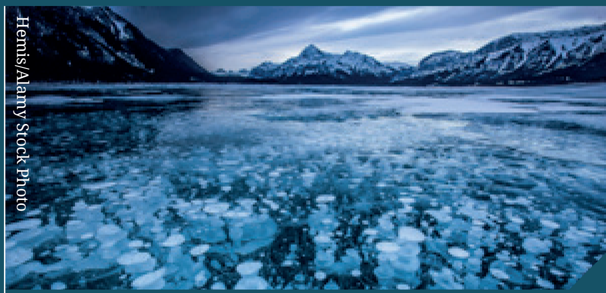
2 Further reductions in SLCF emissions would significantly benefit human health, globally and in the Arctic.

Globally, air pollution is the top environmental health threat and a major cause of premature deaths. Reducing air pollution from particles and ozone would reduce adverse health impacts. In the Arctic, primarily local but also regional sources of SLCFs can contribute to local air pollution and associated human health effects. More ambitious efforts than current legislation could prevent hundreds of thousands of premature deaths in Arctic Council Member and Observer countries.

3 Policies and technologies to reduce emissions of air pollutants have led to cleaner air in the Arctic compared to the early 1990s. The trend of declining concentrations of sulfate aerosols continues, but recently only modest reductions of ozone and black carbon concentrations in the Arctic atmosphere have been observed.

The scenarios of future emissions used for this AMAP assessment indicate that the Arctic Council's collective voluntary commitment for reducing black carbon emissions of 25-33 percent below 2013 levels by 2025 can be nearly achieved by implementing current policies. Significant further emission reduction potential exists and could be achieved by using best available technologies.

Continued reduction of sulfur dioxide emissions is important for improving air quality and safeguarding human health.



4 Global anthropogenic emissions of methane and levels of methane in the Arctic atmosphere continue to increase.

The Arctic Council's Framework for Action for Enhanced Black Carbon and Methane Emission Reductions includes a commitment from Arctic states to significantly reduce their overall methane emissions. Given that emissions are expected to continue to increase even if current legislation is implemented, meeting this commitment would demand applying best available technologies beyond that already required, especially in the oil and gas sector.

Emissions of methane from natural sources, such as wetlands, will likely be affected by further warming but estimates of future emissions from these sources are hampered by major uncertainties.

5 Tundra, peatland, and forest fires are increasingly important sources of particles of black carbon and organic carbon emissions in the Arctic, where a warmer climate may lead to larger and more frequent fires.

Managing fire risks with locally appropriate measures (fuel management, ignition reduction, wildland fire response) will be critical for limiting local and regional emissions of particles that are damaging to human health and can contribute to further warming. Boreal forest fires will need to be managed differently than fires in Arctic landscapes. Indigenous fire management practices will need to be considered.

KEY TO SYMBOLS:

- OBSERVED
- PROJECTED
- NEW FINDING
- UPDATED FINDING
- KNOWLEDGE GAP
- REINFORCING MESSAGE

INTRODUCTION AND BACKGROUND

Pollution from combustion of fossil fuels and biomass affects both air quality and climate. Poor air quality is directly detrimental to people's health and a major cause of premature death. Many air pollutants also play an important role in climate change. While the long-term temperature increase is mainly driven by global carbon dioxide emissions, changes in current global emissions of short-lived climate forcers (SLCFs) play an important role in the rate of warming for the next 20-30 years.

Based on earlier AMAP assessments, the Arctic Council, in 2015, adopted a Framework for Action for Enhanced Black Carbon and Methane Emission Reductions[1]. In addition to calling for improved emissions reporting and driving mitigation ambitions, it underscored the importance of continuing monitoring and research and called for a four-year cycle of scientific reporting, including assessment of the status and trends of SLCFs, with a focus on their impacts on Arctic climate and public health. The *AMAP Assessment 2021: Impacts of Short-lived Climate Forcers on Arctic Climate, Air Quality, and Human Health* is part of this effort and aims to inform further work under the Framework. It is also relevant for other important international fora for decisions related to SLCFs, such as the Air Convention[2] and the Climate Convention[3].

While earlier AMAP assessments of SLCFs have focused on the warming impacts of black carbon, methane, and tropospheric ozone, this assessment also includes extended analysis of precursors of other SLCFs emitted from the same sources, especially sulfur dioxide. An important aim of the 2021 AMAP SLCF Assessment is to use updated observations and new modelling efforts to better understand anthropogenic emission sources and their impacts on air quality and climate. It highlights how reducing SLCFs is important both for human health and for Arctic climate and identifies the actions that could most effectively reduce the health impacts of pollution and at the same time slow the rate of Arctic climate change. The 2021 AMAP SLCF assessment also provides a review of how fire risk may increase with climate change, which is an emerging topic with major implications for future emission of SLCFs and consequent impacts on both climate and health.

WHY ARE SLCFs IMPORTANT?

Short-lived climate forcers include greenhouse gases, particles, and other air pollutants that strongly influence the climate but have a relatively short atmospheric lifetime compared to carbon dioxide. Reducing emissions of SLCFs is also important for protecting human and ecosystem health. Reducing emissions of SLCFs will impact the rate of Arctic warming in the coming decades. The Arctic Council Member[4] and Observer[5] countries account currently for about half of the global anthropogenic emissions of black carbon, sulfur dioxide, and methane. Actions taken by these countries can thus have a significant impact on global emissions and on climate and health impacts of SLCFs. The results from an extended analyses of the cooling impacts of sulfate in the AMAP 2021 SLCF assessment highlight how reduced air pollution in source regions in Arctic Council Member and Observer countries affect the Arctic climate and that an integrated understanding of climate and health impacts of SLCFs is needed.

SLCFs IN FOCUS

Methane is a powerful greenhouse gas, especially on decadal timeframes. While it is 28-36 times as potent as carbon dioxide over a 100-year timeframe, it has a warming potential 84 times that of carbon dioxide over a 20-year timeframe according to the IPCC Fifth Assessment Report. Methane also affects air quality due to its role in ozone formation.

Ozone is an air pollutant that forms in the lower atmosphere when sunlight interacts with precursor gases: nitrogen oxides, carbon monoxide, volatile organic compounds, and methane. It is also a greenhouse gas and can affect the atmospheric lifetime of methane. It is harmful to human health and vegetation.

1 Formally, *Enhanced Black Carbon and Methane Emissions Reductions: An Arctic Council Framework for Action*

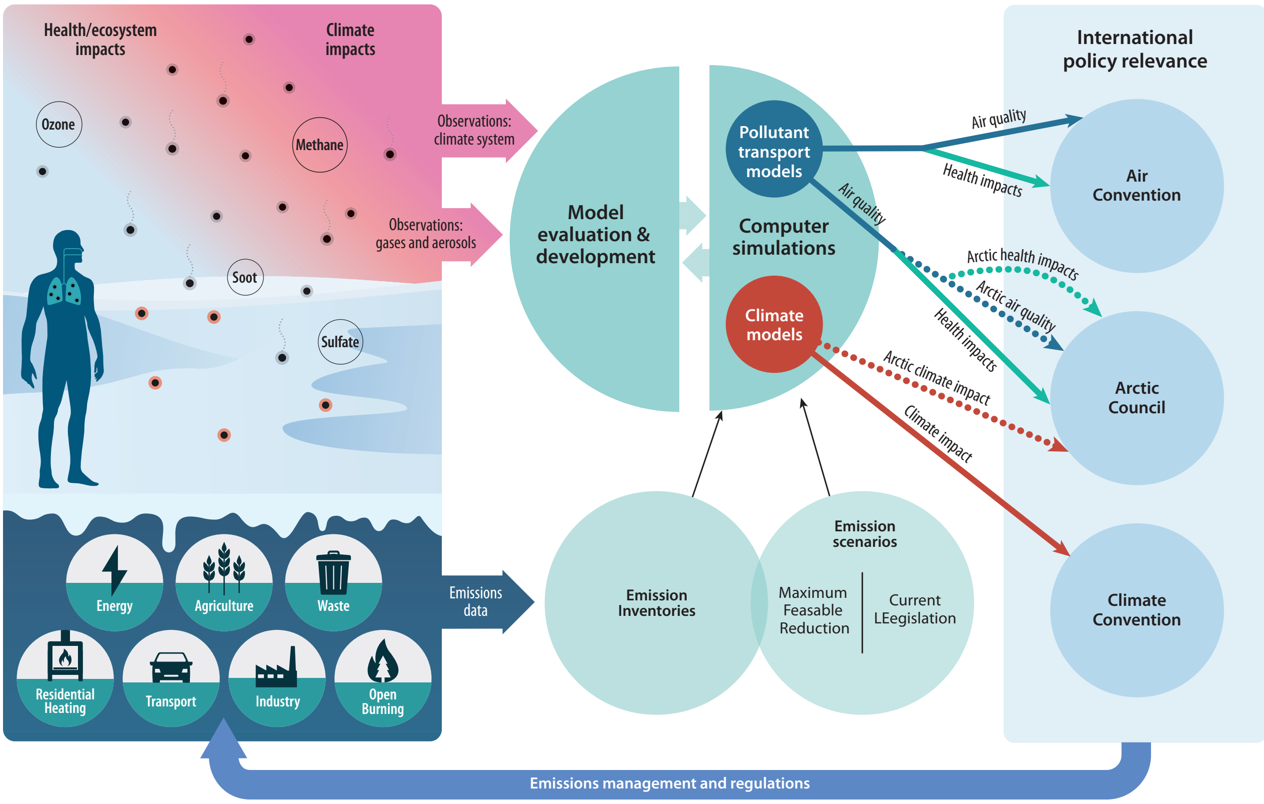
2 The Air Convention is also known as the UN ECE Convention on Long-range Transboundary Air Pollution (CLRTAP)

3 UN Framework Convention on Climate Change

4 Canada, Finland, Iceland, Kingdom of Denmark, Norway, Sweden, The Russian Federation, and The United States

5 France, Germany, Italian Republic, Japan, the Netherlands, People's Republic of China, Poland, Republic of India, Republic of Korea, Republic of Singapore, Spain, Switzerland, and United Kingdom

6 $PM_{2.5}$ refers to the particles that are 2.5 micrometers and smaller.



Simplified illustration of how the key finding and recommendations in the AMAP 2021 SLCF assessment are based on a combination of data from emissions and observations; scenarios of future emissions; and model simulations to estimate impacts on air quality and the climate, and how this information can feed into policy development.

Sulfate aerosols are formed from emission of sulfur compounds, such as sulfur dioxide. Sulfate aerosols make up a significant portion of the fine particulate matter in ambient $PM_{2.5}$[6], which is harmful to human health and covered by many air quality guidelines. Sulfate aerosols scatter sunlight efficiently and enhance the brightness of clouds. This causes a cooling of the climate, offsetting some of the warming impacts of greenhouse gases and other SLCFs. The climate impacts of clouds are a key uncertainty in climate modelling.

Black carbon (often referred to as soot) and ***organic carbon*** contribute to levels of ambient particles that degrade air quality and are harmful to human health. Black carbon absorbs sunlight and thereby contributes to climate warming, while organic carbon tends to reflect light. When deposited on snow, black carbon decreases the surface's ability to reflect sunlight, enhancing climate warming. The climate impact of organic carbon is small.

ASSESSING THE IMPACTS OF SLCFs

The AMAP assessment of the impacts of SLCFs relies on knowledge from a range of different sources that are mutually supportive:

- New inventories of anthropogenic emissions that include information both from country reports to international conventions and the Arctic Council's Expert Group on Black Carbon and Methane *and* estimates constructed from international energy and industrial statistics and shipping data.
- Scenarios of future anthropogenic emissions under different assumptions, see below for details.
- Observations of SLCF concentrations in the Arctic atmosphere and snow.
- Atmospheric transport models for assessing how SLCFs affect air quality in the Arctic and in source regions outside the Arctic.
- Climate models, including Earth System Models and a climate and air quality emulator (i.e., a rapid assessment tool) that enables specific analysis of how changes in anthropogenic SLCF emissions affect climate change in the Arctic. Potential future changes in natural and fire emissions of SLCFs were not included in the simulations. Some of the natural emission sources could potentially act to accelerate the warming while others could have a cooling impact.
- Literature-based exposure-response relationships between air pollution concentrations and adverse health outcomes.

SCENARIOS

To estimate future impacts of SLCFs, emissions scenarios were developed based on different assumptions about demographic, economic, technological, and policy development. AMAP's 2021 SLCF assessment has both similarities and differences with the approach used for the forthcoming IPCC Sixth Assessment Report and AMAP's *Arctic Climate Change Update 2021: Key Trends and Impacts*. The scenarios used in this assessment are based on middle-of-the-road assumptions about global socio-economic development and carbon dioxide emission pathway, consistent with the SSP2-4.5 scenario[1] used also in the IPCC assessment. In this scenario, global carbon dioxide emissions are stabilized around 2050. The major difference is that AMAP's SLCF model results are based on updated inventory and assessment of emissions of air pollutants, specifically including recent decline in sulfur dioxide and black carbon emissions in East Asia that are not well captured in the SSP2-4.5 scenario. The analysis of co-benefits of air pollutant mitigation for health and climate in the AMAP SLCF assessment uses data from the same Earth System Models that are used for the forthcoming Sixth IPCC assessment and AMAP's *Arctic Climate Change Update 2021: Key Trends and Impacts*.

To estimate the implications of different actions, additional assumptions about policy implementation and the introduction of best available technologies were made, based on two key air pollutant and methane policy scenarios:

- *Current LEgislation (CLE)*: This scenario assumes full implementation of current national and regional air pollution legislation as well as full implementation of commitments under Nationally Determined Contributions (as of 2018) towards the Paris Agreement.
- *Maximum technically Feasible Reduction (MFR)*: This is an ambitious scenario where best available technologies are introduced globally for all air pollutants and methane without any constraints related to investment or implementation costs while taking into account the lifetime of currently installed equipment and the technical feasibility of implementing best available technologies. The MFR scenario differs from the assumptions made in AMAP's 2015 SLCF assessment by including the potential for further reduction of sulfur dioxide and nitrogen oxide emissions along with targeted warming agents.

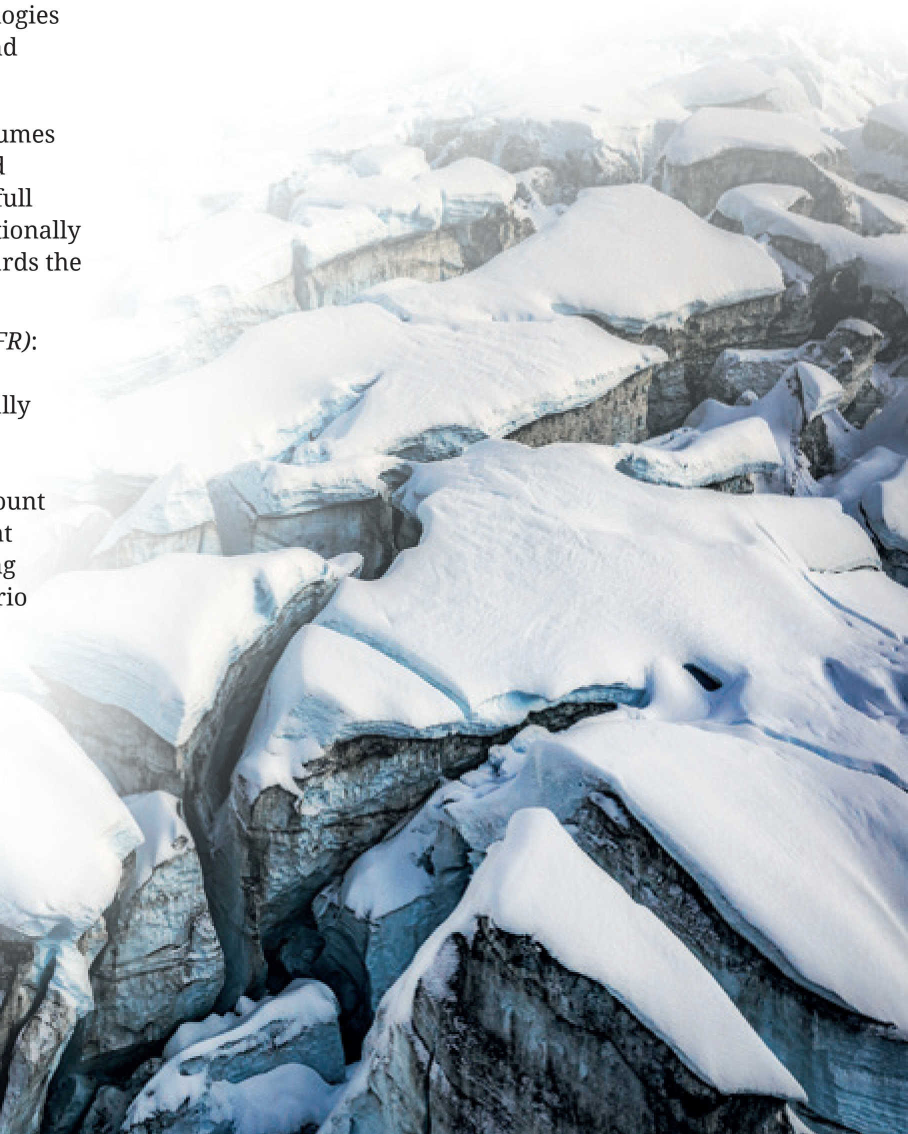
1 Shared-Socioeconomic Pathway 2 compatible with Representative Concentration Pathway 4.5.

RESULTS

CLIMATE IMPACTS OF REDUCING SLCFs

Emission of SLCFs have both regional and large-scale impacts on the climate. SLCFs *emitted in or transported to the Arctic* affect heat transport in the Arctic atmosphere and also lead to decreased albedo when dark particles, such as black carbon, land on snow and ice, which then absorb heat instead of reflecting it. Emissions that occur at high-latitudes have the strongest effect - on a per unit of emissions basis - on Arctic warming. However, because SLCF emissions, and thus concentrations at mid-latitudes, are much greater than concentrations in the Arctic, measures to reduce air pollution in mid-latitudes have the greatest potential to influence Arctic warming. However, per unit of emissions reduced, high-latitude measures still have the greatest effect.

To estimate the impact of different emission trajectories on the Arctic climate, the 2021 AMAP assessment used five Earth System Models together with a multi-model emulator to simulate Arctic temperature changes. In this Summary, best estimates of changes in historical and future Arctic warming due to changes in SLCFs and carbon dioxide are provided based on a combination of these models.



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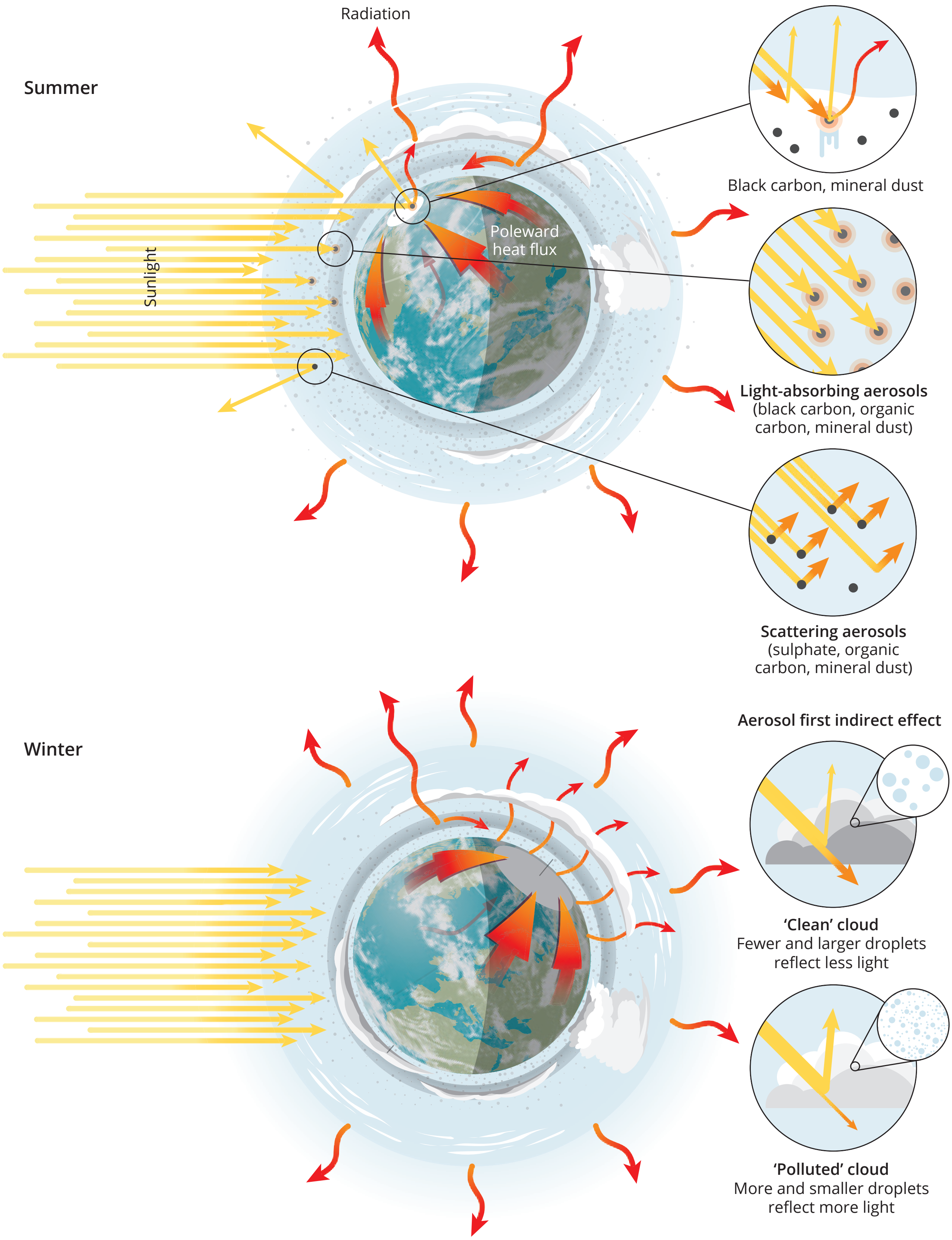


Mechanisms by which SLCFs can influence Arctic climate. They include the impacts on the region's heat balance as aerosols absorb or scatter the sun's energy in the atmosphere, as greenhouse gases absorb heat, and as particles darken light surfaces, such as snow and ice, making them less effective in reflecting the sun's energy. Aerosols also affect the properties of clouds and their ability to reflect light. In addition to impacts in the Arctic, the impacts of SLCFs on the heat balance at mid- and lower latitudes affect the amount of heat that is transported to the Arctic.

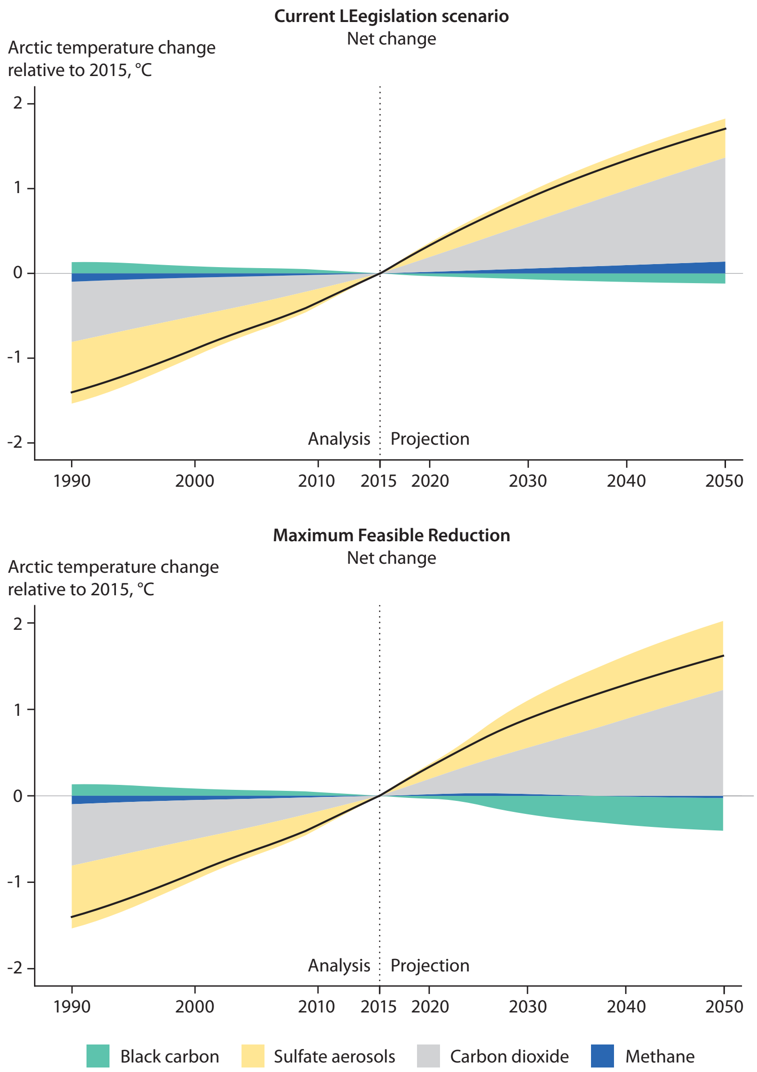
SLCF CONTRIBUTION TO PAST CHANGES

The model simulations for the period 1990 to 2015 show considerable reductions in sulfur emissions from fossil and biofuel sources among Arctic Council Members and the Rest of Europe while changes in emissions from Asian Observers and Rest of the World were small in this time period. Sulfate aerosols cool the atmosphere and have offset some of the warming caused by carbon dioxide and warming SLCFs. With declining levels of sulfate aerosol at mid- to low latitudes (improved air quality), the cooling or masking effect of sulfate aerosols has decreased. For these 25 years, the contribution to Arctic warming from global carbon dioxide emissions and unmasked warming (weakened cooling) from reduced sulfur emissions at mid-to lower latitudes appear as nearly equal in magnitude. Contributions of non-sulfur SLCFs to Arctic temperature trends from 1990 to 2015 were very small, largely due to the relatively small changes in the global emissions of these compounds over this time period. The simulated net Arctic warming over 1990-2015 from changing interactions of the SLCFs from global anthropogenic sources with radiation, clouds, and surface albedo is 0.275 °C per decade (see Figure on page 9). Declining interactions of sulfate with clouds likely had a net warming impact on the Arctic. The simulated magnitude of this warming is large but very uncertain. In detail, reductions in global sulfur emissions may have produced an Arctic warming impact of 0.290 °C per decade from diminishing interactions of sulfate aerosols with radiation, clouds, and surface albedo. Therefore, changes in global sulfur dioxide emissions dominated the impact of all SLCFs on Arctic climate. Furthermore, the model simulations conducted for the report provide evidence that global anthropogenic emissions of carbon dioxide and diminishing global anthropogenic emissions of sulfur contributed strongly and about equally to the net rate of Arctic warming from 1990 to 2015 (0.285 °C per decade for carbon dioxide). Model simulations for 1990 to 2015 provide evidence that the declining global anthropogenic black carbon emissions during this time period caused a cooling impact on recent Arctic warming (-0.053 °C per decade). At the same time, global anthropogenic methane emissions produced a relatively small warming impact (0.038 °C per decade).

SLCF CONTRIBUTION TO FUTURE CLIMATE CHANGE

All scenarios of anthropogenic emissions of SLCFs and all models used for AMAP's 2021 SLCF assessment show that the Arctic will continue to warm at a rapid rate, as future emissions of both long-lived and short-lived climate forcers will lead to an increase in global mean temperature with an amplified response in the Arctic. The projected increase in carbon dioxide abundance and reduction of global sulfur emissions will continue to have a notable warming impact on the Arctic. Depending on how SLCF emissions develop, continuing reductions in global anthropogenic sulfur dioxide emissions will produce a warming impact on Arctic temperature from 2015-2030 which could be between 69% (with the Current LEgislation scenario) and 103% (with the Maximum Feasible Reductions scenario) of the warming impact of carbon dioxide. Model results also show that maximum feasible reductions of black carbon and methane can nearly offset the warming impact of the additional reduction in sulfur emission. Specifically, maximum feasible reductions in global emissions of methane from all anthropogenic combustion sources could lead to a reduction in the Arctic warming rate of 0.047 °C per decade from 2015 to 2050, relative to only implementing current legislation. Reduced interactions of black carbon with radiation, clouds, and surface albedos could reduce the Arctic warming rate by 0.074 °C per decade from 2015 to 2050 in the Maximum Feasible Reduction scenario, relative to the Current LEgislation scenario.

Health concerns are the key driver for addressing air pollution, including emissions of sulfur dioxide. Health concerns will (and should) continue to motivate reduced emissions of sulfur dioxide into the future, despite the consequence of unmasking warming. This emphasizes the need to strongly reduce emissions of both carbon dioxide and SLCFs that contribute to warming, as such actions will slow the rate of warming compared to current emissions trajectories. The reduction of SLCFs is especially important for the rate of warming in the next few decades. To slow Arctic warming, it will be especially important to achieve maximum feasible reductions of global black carbon emissions from gas flaring, land-based transportation, and residential combustion. Reduced deposition of black carbon on snow and ice would increase the reflectivity of these surfaces and thereby cool the Arctic. Reducing emission of black carbon from the Arctic Council countries is particularly effective as these emissions occur in or close to the Arctic. Maximum feasible reduction of methane emissions from the oil and gas sector in Arctic Council countries is also critically important for offsetting the projected warming.



Arctic temperature change in two different scenarios of SLCF emissions: Current LEgislation and Maximum Feasible Reductions.

The solid line shows the net Arctic temperature change from combined changes in all emissions (black carbon, carbon dioxide, sulfur dioxide, methane). The shaded areas indicate how observed and projected changes in emission of SLCFs since 1990 contribute to net changes in Arctic temperature relative to 2015. Note that declining emissions of warming agents like black carbon manifest as cooling during this period. The Arctic is here defined as the area north of 60° N. The emission changes that have been used in modelling the two different scenarios are illustrated in the figure on page 14.

The take-home message is that past and projected future emissions of carbon dioxide (grey shaded area) play a dominant role for Arctic warming and will continue to do so.

For sulfate aerosols (yellow), a net decrease in emissions since 1990 has contributed to recent Arctic warming. The magnitude of this contribution is similar to that of carbon dioxide. Expected further reductions in sulfate aerosols will continue to contribute to Arctic warming in the next 20-30 years. This warming impact from declining concentrations is especially pronounced in the Maximum Feasible Reduction scenario.

Black carbon (green) contributes to warming, but decreases in emission of black carbon since 1990 have decreased its relative warming impact. Further net reductions in black carbon emissions would continue to decrease its warming impact and counteract some of the future warming from carbon dioxide and reductions in sulfate aerosols, more so in the Maximum Feasible Reduction scenario than in the Current LEegislation scenario.

Methane (blue) contributes to Arctic warming and an increase in methane emissions has accelerated methane's contribution to warming since 1990. It will continue to do so in the Current LEgislation scenario. In the Maximum Feasible Reduction scenario, there will only be slight net changes in methane emissions, and the contribution to future Arctic temperature changes is therefore minimal. In absolute numbers, methane will still contribute to Arctic warming, though this is barely discernable in the figure.

COMPARING 2015 AND 2021 METHODS FOR ASSESSING CLIMATE IMPACTS OF SLCFs

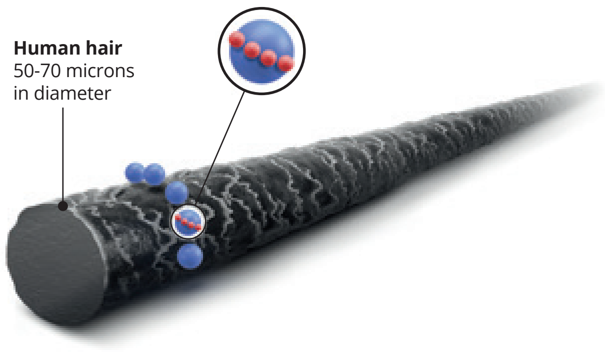
The AMAP 2015 SLCF assessments separately modelled each SLCF to estimate the potential of changes in methane and black carbon emissions to affect Arctic climate and to compare impacts of different regional emission sources. AMAP's 2021 SLCF assessment uses a greater number of models that incorporate improved knowledge of regional climate sensitivities and more detailed representation of the processes that alter climate. It is furthermore based on updated emissions inventories and projections and includes more attention to changes in emissions of, in particular, sulfur dioxide. As a result, it has been possible to provide a more nuanced picture of how the integrated effect of SLCFs change over time and to accurately place the impact of reducing SLCFs into context of the impact of reducing emission of carbon dioxide. The simulated reduction in Arctic warming impact in 2050 from the implementation of maximum feasible SLCF emission reductions in the current assessment (0.16 °C per decade from methane and 0.26 °C per decade from black carbon radiative forcings) are comparable to temperature impacts estimated in AMAP's 2015 SLCF assessments.

AIR POLLUTION AND HEALTH

Ambient air pollution is among the 10 leading risk factors for premature death in Arctic Council Member and Observer countries. There are well established relationships between fine particles ($PM_{2.5}$) and cardiovascular and respiratory diseases, as well as premature death. There is also growing evidence that air pollution increases the risk for diabetes, premature births, and low birth weight. Ozone has been associated with increased risk for respiratory disease that leads to premature death and may be associated with increased risk for other adverse health outcomes (e.g., metabolic effects).

HEALTH IMPACTS IN THE ARCTIC

There are only a limited number of studies of the impact of air pollution on people living in the Arctic. Those that do exist for Alaska show that exposure to $PM_{2.5}$ is an important health concern. While estimating the contribution of air pollution to disease among people who live in the Arctic is a challenging task, current understanding of the cause-effect relationships indicates that most efforts to reduce emissions would have health benefits. Local sources are important and measures to reduce emissions from residential heating, waste burning, diesel generators, and surface transport would have local health benefits. Ensuring that increased marine shipping does not lead to local air pollution is also important. Another concern is the risk for more wildland fires in the Arctic and the associated health impacts of increased smoke emissions.



AIR QUALITY AND HEALTH IMPACTS IN ARCTIC COUNCIL MEMBER AND OBSERVER COUNTRIES

New studies conducted for AMAP's 2021 SLCF assessment have used estimates of future emissions to assess air quality and health, with a focus on the impacts of fine particles ($PM_{2.5}$) and ozone on premature death.

In places where air pollution levels are high, such as in many Asian Observer countries, implementing current legislation would lead to improved local air quality. In the Current LEgislation scenario, most of these reductions are projected to occur between 2020 and 2025. Applying best available technologies globally for all air pollutants and methane would improve air quality further, especially in regions that currently have high emissions. The potential for reducing concentrations of ozone in areas with high levels of air pollution is mainly linked to the reductions in methane emissions (methane is a precursor for ozone).

AMAP's 2021 SLCF assessment has also estimated the number of avoided premature deaths due to air pollution reductions under different emission scenarios using literature-based relationships between air pollution concentrations and adverse health outcomes. The take-home message is that fully implementing current legislation could reduce global premature mortality attributable to $PM_{2.5}$ by 24% in 2030 compared with 2015. The more ambitious Maximum Feasible Reduction scenario would result in further reductions of premature deaths related to air pollution, an additional 22% compared to the Current LEgislation scenario.

In the Current LEgislation scenario, ozone concentrations globally remain steady but the number of people dying prematurely from exposure to ozone is nevertheless estimated to increase due

Russia

Scenario, year	Projected premature deaths relative to the 2015 baseline estimate number
2015	55710
CLE 2030	
MFR 2030	
CLE 2050	
MFR 2050	

USA

Scenario, year	Projected premature deaths relative to the 2015 baseline estimate number
2015	52940
CLE 2030	
MFR 2030	
CLE 2050	
MFR 2050	

European Union (excluding Nordic)

Scenario, year	Projected premature deaths relative to the 2015 baseline estimate number
2015	81870
CLE 2030	
MFR 2030	
CLE 2050	
MFR 2050	

Canada

Scenario, year	Projected premature deaths relative to the 2015 baseline estimate number
2015	2580
CLE 2030	
MFR 2030	
CLE 2050	
MFR 2050	

Europe Other

Scenario, year	Projected premature deaths relative to the 2015 baseline estimate number
2015	99810
CLE 2030	
MFR 2030	
CLE 2050	
MFR 2050	

Nordic

Scenario, year	Projected premature deaths relative to the 2015 baseline estimate number
2015	4710
CLE 2030	
MFR 2030	
CLE 2050	
MFR 2050	

China

Scenario, year	Projected premature deaths relative to the 2015 baseline estimate number
2015	948700
CLE 2030	
MFR 2030	
CLE 2050	
MFR 2050	

Japan, Rep. of Korea and Singapore

Scenario, year	Projected premature deaths relative to the 2015 baseline estimate number
2015	37150
CLE 2030	
MFR 2030	
CLE 2050	
MFR 2050	

India

Scenario, year	Projected premature deaths relative to the 2015 baseline estimate number
2015	835300
CLE 2030	
MFR 2030	
CLE 2050	
MFR 2050	

Changes in premature death from $PM_{2.5}$ in Arctic Council and Observer regions in 2030 and 2050 compared to 2015 if emissions are reduced by implementing current legislation (CLE scenario) and by applying maximum feasible reduction in emissions (MFR scenario).

Ned Rozell/UAF Geophysical Institute


Michael Fouque / Alamy Stock Photo

to a growing population being exposed. Conversely, in the more ambitious Maximum Feasible Reduction scenario, global ozone-related mortality is projected to decrease compared with the present-day levels.

For Arctic Council Member countries, adhering to current legislation in order to reduce $PM_{2.5}$ and ozone would avoid an estimated 66,000 premature deaths in 2030 compared to 2015. In the more ambitious Maximum Feasible Reduction scenario, an estimated 97,000 premature deaths would be avoided in 2030. For Observer countries, maximum feasible emission reductions would avoid an estimated 880,000 premature deaths in 2030 compared to 2015. Only implementing current legislation would avoid 540,000 premature deaths in 2030 compared to 2015.

CONFIDENCE IN MODEL RESULTS

Individual models vary in how well they represent SLCFs compared to historical observations, but the multi-model average provides results that are close to or within the uncertainty range of observed levels of black carbon, ozone, and methane in the atmosphere. When modelling the climate impact of SLCF emissions, the confidence is high in the direction of change, but medium regarding the magnitude of change. A major uncertainty is in future emission trajectories, due to uncertainty in socioeconomic development paths. A critical uncertainty regarding climate impacts of emissions relates to changes in clouds and associated climate forcing. An evaluation of the implications of model uncertainties for the projections of near-term climate and health impacts show that:

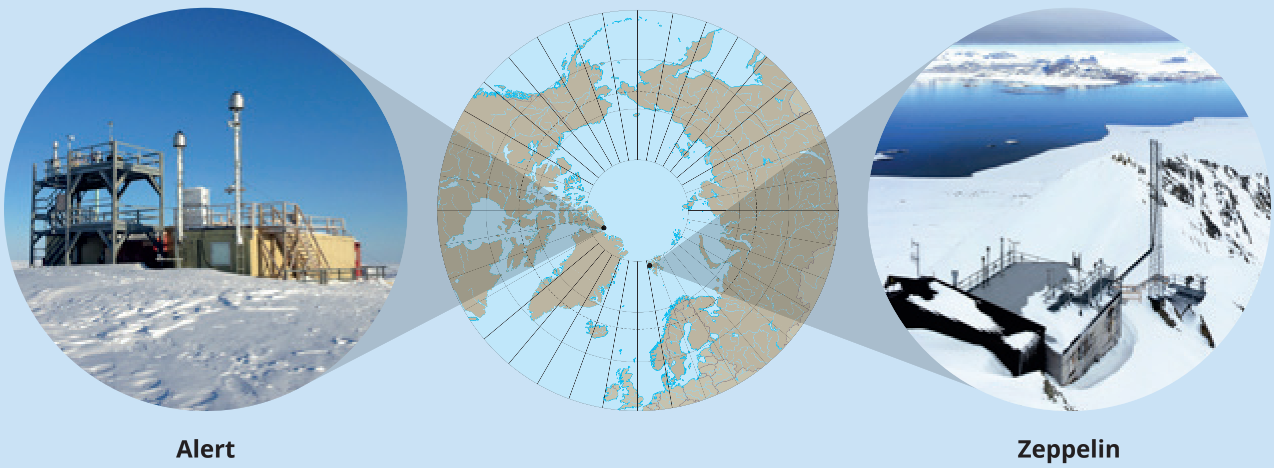
- Confidence in the warming from methane is high both globally and in the Arctic.
- The warming due to black carbon may be underestimated in the Arctic and is uncertain due to high variability across models.
- Cooling from sulfate aerosols in the Arctic may be underestimated. It is uncertain primarily owing to lack of observations throughout the atmospheric column and high degree of variability across model estimates.
- Confidence in the warming impact from ozone is fairly high globally and in the Arctic, but uncertainties exist in model simulations of ozone and its precursors.
- The climate impacts due to changing cloud properties are highly uncertain due to the large range in both modelled and measured clouds.
- Ozone-attributable respiratory mortality could be overestimated due to overestimation of ozone concentrations. The overall impact of ozone on health may be underestimated because other detrimental health outcomes were not included in the assessment for which the scientific evidence is building (e.g. metabolic outcomes).
- The health impacts due to PM2.5 exposure may be underestimated due to underestimation of concentrations, particularly in Asia and near population-centers, and because some detrimental health outcomes were not included in the assessment for which the scientific evidence is building (e.g. adverse birth outcomes, cognitive effects).

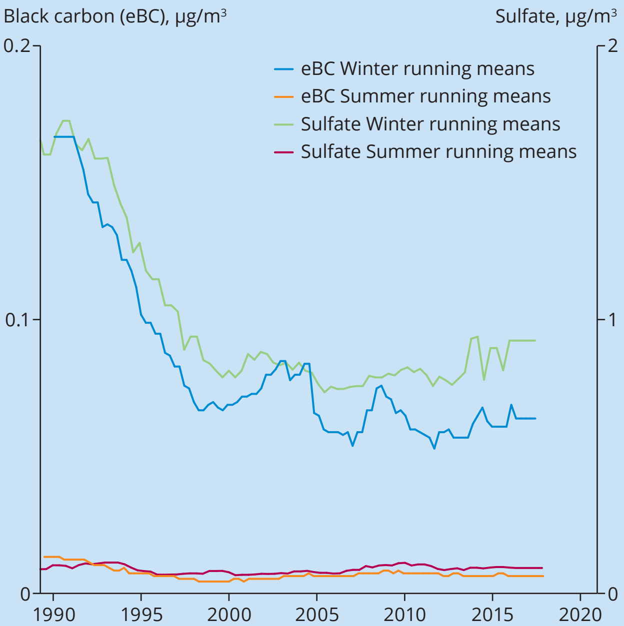
OBSERVATIONS AND TRENDS

Changes over time in the levels of SLCFs in the Arctic atmosphere show the impacts of air pollution policies and changes in industrial activity.

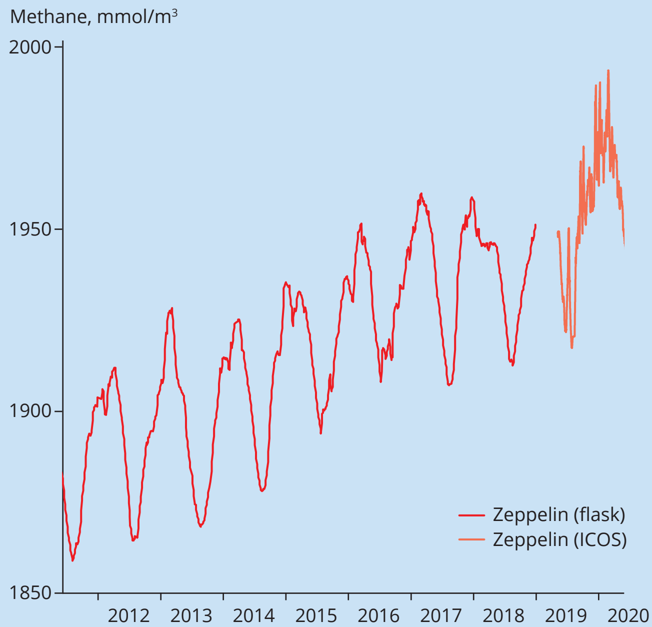
For example, long-term atmospheric measurements show that Arctic air quality improved after 1990 in response to air pollution policies put in place in Europe and North America and after a sharp decline in the Soviet Union economy. However, around this time emissions from China and the rest of Asia started to increase, to stagnate and slightly decline since the early 2010s. In the Arctic atmosphere, levels of black carbon decreased between 1990 and 2010, but this decline has stagnated in the past 10 years. For sulfates, continued decline in atmospheric concentrations is apparent at some Arctic monitoring stations, while other stations show the decline levelling off or a slight increase.

Methane levels in the Arctic atmosphere reflect global concentrations and have more than doubled since the pre-Industrial Era according to records of atmospheric methane levels from ice cores. From approximately 2000 to 2005 there was no increase but from about 2007, levels have increased again with an even more rapid growth from 2015. Long-range transport contributed to increasing levels in the Arctic atmosphere, but hot spots of Arctic anthropogenic emissions have potentially added to this growing trend.





Monitoring data from Alert, Canada showing the historic decline in black carbon and sulfate aerosols.



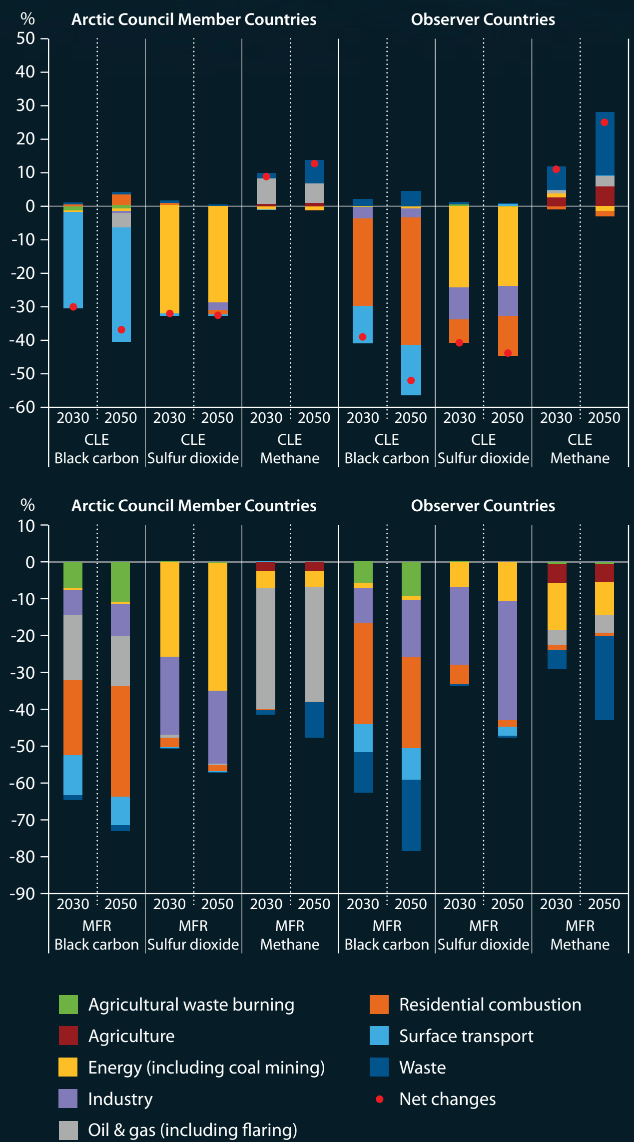
Trends in methane at Zeppelin (Svalbard).

EMISSION SOURCES

Arctic Council Member and Observer countries together account for about half of the current global anthropogenic emissions of black carbon, sulfur dioxide and methane. While there are differences between the available estimates of SLCF emissions, especially at the sectoral level, the relative contribution of different sources appears robust. Based on the emission inventories developed for this assessment, Arctic Council Member countries accounted for 8% of global anthropogenic black carbon emissions in 2015, with land-based transportation as the most important source, followed by residential combustion and gas flaring in the oil and gas sector. Observer countries accounted for 40% of global anthropogenic emission of black carbon in 2015, dominated by emissions from China and India and with residential combustion as the major source followed by land-based transportation. Arctic shipping is currently only a minor source of black carbon emissions overall.

For sulfur dioxide, Arctic Council Member countries accounted for 13% of global emissions in 2015 and Observer countries accounted for 30%. The energy sector and industry are the most important sources in both Arctic Council Member and Observer countries.

For methane, Arctic Council Member countries accounted for 20% of global anthropogenic emissions in 2015, mainly from the energy sector, especially oil and gas exploration and distribution, with substantial contributions also from waste and from agriculture. Observer countries account for 30% of global methane emissions. While emissions from agriculture currently account for nearly 50%, future growth is dominated by increase of emissions from waste management.



Relative changes in emissions under the Current LEgislation (CLE) scenario in 2030 and 2050 compared to 2015, and further reduction potential under the Maximum Feasible Reduction (MFR) scenario compared to the CLE scenario in 2030 and 2050.

FUTURE ANTHROPOGENIC EMISSIONS

Fully implementing current legislation would lead to lower emissions of SLCFs in both Arctic Council Member and Observer countries. For black carbon, a decline of 37% in Arctic Council countries and 52% in Observer countries is estimated by 2050 compared to 2015. The scenarios of future emissions used for this AMAP assessment indicate that the Arctic Council's collective voluntary commitment for reducing black carbon emissions of 25-33 percent below 2013 levels by 2025 can almost be achieved by implementing current policies, which are estimated to result in reductions of 22% by 2025[1]. Significant further emission reduction potential exists and could be achieved with best available technologies.

Emissions of methane are expected to increase by 13% by 2050 in Arctic Council Member countries and 25% in Observer countries even if current legislation is implemented. The estimated future emissions trend, considering implementation of current legislation, is not consistent with the commitment in the Arctic Council's Framework for Action for Enhanced Black Carbon and Methane Emission Reductions "...to significantly reduce our overall methane emissions".

For sulfur dioxide, the Current LEgislation scenarios indicate a strong decline in emissions of about 33% for Member Countries and 45% for Observer countries by 2050. Current clean air policies could reduce emissions of black carbon from the residential and transport sectors and to some extent from industry. Considerable additional emission reductions could be achieved by applying best available technologies. This is especially notable for black carbon from residential combustion (heating and cooking) and industrial oil and gas production, sulfur dioxide emission from energy production and industry, and methane emissions from oil and gas production, and improved management of municipal and industrial waste.

NATURAL EMISSIONS OF METHANE AND PARTICLES

Natural emissions of methane are important in the Arctic, in fact they are the dominant source due to the region's many wetlands. Nevertheless, these emissions are about 2.5 times smaller than global anthropogenic emissions of methane from fossil fuels. Future natural emissions are uncertain but increases in Arctic methane from natural sources under a range of anthropogenic climate warming scenarios are projected to be smaller than the potential reductions in global anthropogenic methane emissions. Potential future changes in natural emissions, e.g. due to warming leading to degrading permafrost or to a wetter environment, were not included in the modelling of climate impacts of SLCFs, due to large uncertainties in projections of future emission.

Emissions from the Arctic Ocean, i.e. of sea spray and marine biogenic gases that form particulate matter, will change with climate change thereby influencing Arctic climate. There is not yet sufficient understanding to quantitatively estimate these effects.

1 The Arctic Council's EGBCM utilizes nationally reported emissions and projections as a basis for evaluating the progress towards meeting the objectives of the Arctic Council's Framework for Action for Enhanced on Black Carbon and Methane Emission Reductions. For details of the information used in the AMAP assessment process see 'Assessing the impacts of SLCFs'.

FIRES AND CLIMATE CHANGE

An important source of black carbon and organic carbon to the atmosphere is wildland fires and intentional burning of agricultural fields, grasslands, and forests. Current estimates indicate that 12-15% of total deposition of black carbon in the Arctic originate from boreal forest fires in Siberia, Canada, and Alaska when compared to global anthropogenic and biomass burning emissions from all types of fires. The contributions of SLCFs to atmospheric concentration may change as the climate changes. Timing of fire emissions relative to extent of snow and ice is an important factor in relation to their Arctic climate impact. Altered seasonality and location of fires could lead to more soot deposition (earlier, northern fire regimes combined with open agricultural burning), or less soot deposition (summer to fall fires in boreal and temperate landscapes) on Arctic snow and sea ice. For the AMAP 2021 SLCF assessment, a literature review and comparison of published fire emission models, augmented by an AMAP-specific fire model, provide insight on current emissions and the future fire regimes and emissions.

While fires are a natural part of some Arctic ecosystems, climate change is expected to further increase the length of the fire season, possibly create drier conditions, and increase the risk that lightning will start fires due to a potential increase in lightning events. Other factors also play a role, including increased human activity in wildland areas, and high fuel load from earlier fire suppression and from pest damage. Global fire emission databases indicate a larger increasing trend in fires north of 60° from 2005 to 2018, more so than fire activity between 50° and 60°N, which has estimates of declining fire emissions in one model. A custom-made emissions model of current fire activity developed for AMAP's 2021 SLCF assessment indicates that most fire activity and emissions from fires occur between 50° and 60°N, corresponding to the southern extent of the boreal region. For the same period, very few open biomass burning emissions were observed between 70° and 80°N. Above 80°N latitude, no fires were observed due to limitations on satellite coverage.

There is increasing evidence that climate change has played a role in large, uncontrollable early season fires in remote boreal forests. It has also driven an early start to the fire season in the Arctic tundra, with extreme wildfires in more populated areas. Fires in western Greenland in the late summer of 2017 and 2019 after periods of warm, dry, and sunny weather are a new phenomenon. While still relatively small on a global scale, future warming of the Arctic could lead to more and larger fires in landscapes where wildfires have previously been uncommon.

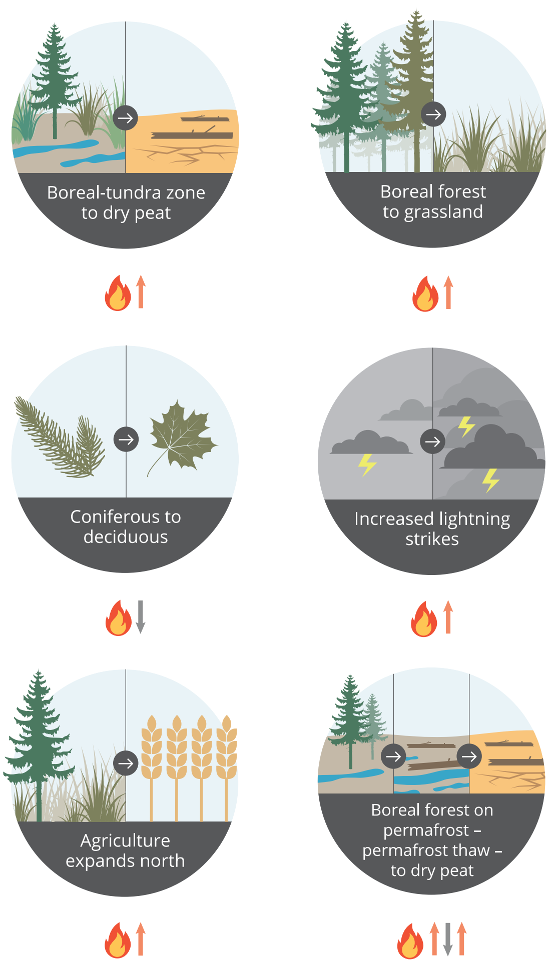
FUTURE OUTLOOK

Further climate change will affect future fire risks. In some cases, the fire could be become severe enough to cause shifts in ecosystems in ways that increase the likelihood of future fires. In addition to the potential for more ignitions from lightning and a longer fire season, permafrost degradation can increase the amount of dry vegetation and high carbon peat fuels. Peat fires can smolder for a long time, leading to large emissions of smoke. These fires are also extremely hard to extinguish, and can burn under the surface throughout the winter, and re-emerge in the spring. These have sometimes been called zombie or holdover fires. The total size of emissions from peat fires is difficult to estimate and predict. For example, thawing of discontinuous permafrost can increase the amount of peat fuel available to feed fires but may also rewet soils, limiting fire ignition and spread. Peat in the boreal and Arctic is a massive natural carbon sink, and peatland fires can release far more carbon dioxide than a typical wildland fire per unit of burned area, in addition to SLCFs.

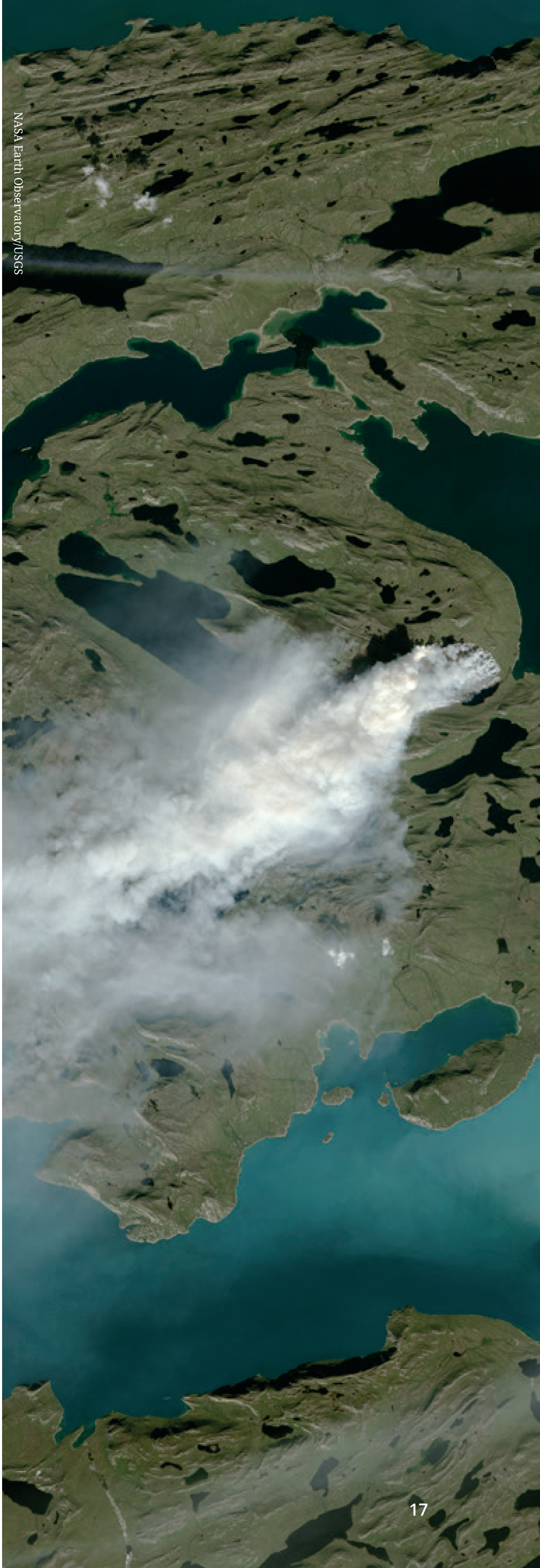
Matt Howard

Change in human activity is another factor, including increased tourism activity, increased logging, and the potential for agriculture further north. A northward movement of agriculture and its associated burning practices can also lead to increased emissions in or near the Arctic. Human activity remains the leading ignition source, even for the Arctic.

Climate change will affect forests and forestry with direct impacts on forest growth and changes in insect and weather-related damage. The overall assessment in the 2021 AMAP SLCF assessment is that future climate conditions are favorable for forest fires in the boreal zone, even for highly managed forests. High intensity fires that are difficult to control will become more likely, including intense megafires. Future fires in the Arctic Council region will continue to be Arctic and near-Arctic sources of black carbon, methane, and carbon dioxide and are projected to increase.



Changes in fire risk due to expected changes in ecosystems and weather patterns by mid- and late 21st century due to climate change; ‘up arrows’ indicate increase in fire risk and ‘down arrows’ indicate a decrease in fire risk. In transitions for boreal forest on permafrost, fire risks can first increase, then decline, and then increase again as the ecosystem changes, with soil moisture being a main driver of ground-level peat fires in the Arctic as well as boreal systems. Most studies of changes in fire risk are based on high emission scenarios.



NASA Earth Observatory/USGS

RECOMMENDATIONS

On the basis of its 2021 assessment of short-lived climate forcers (SLCFs) and their impacts on air quality, human health and climate in the Arctic, the AMAP Working Group recommends that:

1 CURRENT LEGISLATION SHOULD BE EFFECTIVELY IMPLEMENTED AND THAT THE TIMELY AND EFFECTIVE IMPLEMENTATION OF BEST AVAILABLE TECHNOLOGIES BEYOND CURRENT LEGISLATION TO REDUCE SLCF EMISSIONS FURTHER SHOULD BE STRONGLY SUPPORTED

- Effective implementation of current national legislation and international agreements to reduce air pollution will have substantial health benefits in Arctic Council Member and Observer countries. Additional health benefits, along with climate benefits, can be achieved by increasing the use of best available technologies for reducing emissions, especially in Arctic Council Observer countries.
- Full implementation of best available technologies for reducing emission of black carbon and methane will be required to compensate for the additional Arctic warming caused by reducing sulfur dioxide emissions in a scenario of maximum feasible reductions. Reducing sulfur emissions is well motivated by air quality and health concerns. Reducing black carbon and methane is especially important for reducing warming in the short term. To limit Arctic long-term warming, sharp and immediate reductions of carbon dioxide emissions by all countries remain critical.
- Projections of future methane emissions indicate that current legislation is insufficient to realize the commitment in the Arctic Council's Framework for Action for Enhanced Black Carbon and Methane Emission Reductions "...to significantly reduce our overall methane emissions." There is thus a need to strengthen ambitions for methane emission reductions, especially by preventing leaks of methane in oil and gas production (in the Arctic and elsewhere).
- To further reduce emissions of black carbon from Arctic Council Members, it will be especially important to target emissions from diesel engines, gas flaring, and residential combustion (including wood-burning stoves).

2 ARCTIC COUNCIL MEMBER AND OBSERVER COUNTRIES SHOULD SUSTAIN AND ENHANCE EMISSIONS REPORTING AND MONITORING TO EVALUATE PROGRESS IN REDUCING SLCF EMISSIONS

- Country reports of SLCF emissions to relevant international bodies support development of reliable emission and mitigation scenarios, emphasizing the importance of ensuring that timely, transparent and comprehensive information about SLCF emissions is shared in relevant international fora, even when reporting is not obligatory.
- There is an urgent need to continue and improve black carbon emissions reporting and projections through advancement of the science to support development of common methodologies, thus contributing to improved national inventories reporting as guided by the Air Convention and the Intergovernmental Panel on Climate Change.

ADDRESSING NEW FINDING | REINFORCING MESSAGE | ADDRESSING KNOWLEDGE GAPS

3 LOCAL ARCTIC EMISSION SOURCES OF BLACK CARBON SHOULD BE BETTER IDENTIFIED AND QUANTIFIED IN ORDER TO SUPPORT IMPLEMENTATION OF EFFECTIVE MEASURES TO REDUCE LOCAL AIR POLLUTION IN ARCTIC COMMUNITIES

- The use of best available technologies and operational practices could reduce local emissions of SLCFs from residential heating, burning of waste, and the use of diesel generators, and thereby reduce health impacts from poor air quality.

4 EFFECTIVE STRATEGIES TO LIMIT AGRICULTURAL BURNING AND WILDFIRES SHOULD BE IMPLEMENTED IN ORDER TO REDUCE FIRE EMISSIONS AND RELATED AIR POLLUTION AND CLIMATE WARMING

- Wildland fires and intentional burning within and in vicinity of the Arctic are a growing source of black carbon in the Arctic, with negative impacts on both health and climate. Climate change will likely increase the risk for larger and more frequent wildland fires.
- Human activity and communities in the Arctic will need to adapt to increasing fire risk. Understanding if or how much fire management techniques can reduce black carbon emissions needs to be better understood to support development of fire management strategies with broad buy-in from Arctic Indigenous and local communities.

5 THE KNOWLEDGE BASE FOR ASSESSING HEALTH AND CLIMATE IMPACTS OF EMISSIONS AND MITIGATION EFFORTS SHOULD BE SUSTAINED AND IMPROVED, IN PARTICULAR WITH RESPECT TO:

- Monitoring: It is imperative that observational systems are maintained and expanded in order to provide data for evaluation of emission policy effectiveness modelling of climate and health impacts of SLCF emissions and for environmental and public health surveillance, where the latter is especially important in populated regions of the Arctic. Furthermore, satellite monitoring and mapping of fires is an essential complement to official reporting of SLCF emissions from fires.
- Research: Further research is needed on the impacts of climate change on emissions of SLCFs from natural sources, such as methane from wetlands and thawing permafrost and sulfate aerosols from sea spray.
- Health impacts: While the scientific understanding of the health impacts of air pollution is robust, more studies are needed to quantify local emissions and their associated health risks in Arctic communities and to distinguish between the impacts of emissions from local and regional pollution sources that affect local air quality. More research is also needed to better understand exposure levels and associated health effects from residential solid fuel combustion, such as for home heating.
- Modelling: For robust estimates of impacts on both climate and air quality, the global climate models and atmospheric dispersion models need to be better integrated.
- Cost-benefit analyses: Building on the work undertaken by the OECD, there is need for further analyses of the economic costs and benefits of specific measures for reducing emissions of SLCFs.

AMAP, established in 1991 under the eight-country Arctic Environmental Protection Strategy, monitors and assesses the status of the Arctic region with respect to pollution and climate change. AMAP produces science-based policy-relevant assessments and public outreach products to inform policy and decision-making processes. Since 1996, AMAP has served as one of the Arctic Council's six working groups.

This document was prepared by the Arctic Monitoring and Assessment Programme (AMAP) and does not necessarily represent the views of the Arctic Council, its members or its observers.

The basis for this summary, the **AMAP Assessment 2021: Impacts of Short-lived Climate Forcers on Arctic Climate, Air Quality, and Human Health** report, is one of several reports and assessments published by AMAP in 2021. Readers are encouraged to review this, and the reports below, for more in-depth information on climate and pollution issues:

- *AMAP Assessment 2020: POPs and Chemicals of Emerging Arctic Concern: Influence of Climate Change*
- *AMAP Assessment 2021: Mercury in the Arctic*
- *AMAP Assessment 2021: Human Health in the Arctic*
- *AMAP Arctic Climate Change Update 2021: Key Trends and Impacts*

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