Arctic Pollution 2006

Acidification and Arctic Haze

Arctic Monitoring and Assessment Programme (AMAP)


Pacific Ocean
Aleutian Islands
Pribilof Islands
Bering Sea
Okhotsk Sea
Gulf of Alaska
Prince William Sound
Anchorage
Yukon River
Bering Strait
Fairbanks
USA
Alaska
CHUKOTKA
Chukchi Sea
Wrangel Island
Kolyma
Indigirka
Brooks Range
Barrow
YUKON
Prudhoe Bay
Beaufort Sea
East Siberian Sea
Mackenzie River
Athabasca River
Peace River
Great Slave Lake
Slave R.
NORTHWEST TERRITORIES (NWT)
Amundsen Gulf
Canada Basin
Canadian Basin
Mendeleev Ridge
New Siberian Islands
Tiksi
Lena
SIBERIA
CANADA
Victoria Island
Bathurst Island
Laptev Sea
Arctic Ocean
Makarov Basin
Alpha Ridge
NUNAVUT
Canadian Arctic Archipelago
Churchill
Lomonosov Ridge
Amundsen Basin
Eurasian Basin
Nansen-Gakkel Ridge
Severnaya Zemlya
Taymir Peninsula
Kharanga R.
Norilsk
Yenisey
RUSSIA
Hudson Bay
Devon Is.
Lancaster Sound
Ellesmere Island
Agassiz Ice Cap
Alert
Foxe Basin
Baffin Island
Baffin Bay
Nansen Basin
Franz Josef Land
Novaya Zemlya
Kara Sea
Vorkuta
Salekhard
Ob
Usa
QUEBEC
Hudson Strait
Iqaluit
Cumberland Sound
Station Nord
Fram Strait
GREENLAND
Ny-Ålesund
Svalbard
Lomonosovfonna
Pechora Sea
Pechora
URALS
Davis Strait
Barents Sea
Spitsbergen
Bjørnøya
LABRADOR
Nuuk
Greenland Sea
Labrador Sea
Jan Mayen
Nikel
Murmansk
Kola Peninsula
Tromsø
Lapland
White Sea
Arkhangelsk
Severnaya Dvina
Oulanka
Abisko
Karelia
Denmark Strait
Reykjavik
ICELAND
Norwegian Sea
FINLAND
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FAROE ISLANDS
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SWEDEN
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Oslo
Skagerrak
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Preface

The Arctic Monitoring and Assessment Programme (AMAP) is a group working under the Arctic Council. The Arctic Council Ministers have requested AMAP:

- *to produce integrated assessment reports on the status and trends of the conditions of the Arctic ecosystems;*
- *to identify possible causes for the changing conditions;*
- *to detect emerging problems, their possible causes, and the potential risk to Arctic ecosystems including indigenous peoples and other Arctic residents; and*
- *to recommend actions required to reduce risks to Arctic ecosystems.*

These assessments are delivered to Ministers at appropriate intervals in the form of 'State of the Arctic Environment Reports'. These reports are intended to be readable and readily comprehensible, and do not contain extensive background data or references to the scientific literature. The complete scientific documentation, including sources for all figures reproduced in this report, is contained in a related report, 'AMAP Assessment 2006: Acidifying Pollutants, Arctic Haze, and Acidification in the Arctic', which is fully referenced. For readers interested in the scientific background to the information presented in this report, we recommend that you refer to the AMAP Assessment 2006 report.

This report is the third 'State of the Arctic Environment Report' that has been prepared by AMAP in accordance with its mandate. It presents the results of work conducted during the period 1998-2004 in relation to Arctic acidification, which has been identified as a priority issue of concern at the sub-regional level. The assessment described in this report builds upon the previous AMAP assessment that was presented in two volumes, the comprehensive 'Arctic Pollution Issues: A State of the Arctic Environment Report' and its related scientific background document 'AMAP Assessment Report: Arctic Pollution Issues', published by AMAP in 1997 and 1998, respectively.

A large number of experts from the Arctic countries (Canada, Denmark/Greenland/Faroe Islands, Finland, Iceland, Norway, Russia, Sweden, and the United States), together with experts from indigenous peoples' organizations, from other organizations, and from other countries have participated in the preparation of this assessment.

AMAP would like to express its appreciation to all of these experts, who have contributed their time, effort, and data; especially those who are involved in the further development and implementation of the AMAP Trends and Effects Monitoring Programme, and related research. A list of the main contributors is included in the acknowledgements on the previous page of this report. The list is based on identified individual contributors to the AMAP scientific assessment, and is not comprehensive. Specifically, it does not include the many national institutes, laboratories and organizations, and their staff, which have been involved in the various countries. Apologies, and no lesser thanks, are given to any individuals unintentionally omitted from the list.

Special thanks are due to the lead authors responsible for the preparation of the scientific assessments that provide the basis for this report. Special thanks are also due to the author of this report, Carolyn Symon, and to the staff of the Finnish Environment Institute (SYKE), in particular Marjut Nyman and Satu Turtiainen, for their work in supporting this assessment and producing the reports. The author worked in close cooperation with the scientific experts and the AMAP Secretariat to accomplish the difficult task of distilling the essential messages from a wealth of complex scientific information, and communicating this in an easily understandable way.

The support of the Arctic countries is vital to the success of AMAP. AMAP work is essentially based on ongoing activities within the Arctic countries, and the countries also provide the necessary support for most of the experts involved in the preparation of the assessments. In particular, AMAP would like to express its appreciation to Finland for undertaking the lead role in supporting the Acidification and Arctic Haze assessment. Special thanks are also offered to the Nordic Council of Ministers for their financial support to the work of AMAP, and to sponsors of other bilateral and multilateral projects that have delivered data for use in this assessment. Finances from the Nordic Council of Ministers and some countries also support the participation of indigenous peoples' organizations in the work of AMAP.

The AMAP Working Group, who are responsible for the delivery and content of the AMAP State of the Arctic Environment Reports, are pleased to present their third assessment for the consideration by governments of the Arctic countries. This report is prepared in English, which constitutes the official version.

Salekhard, October 2006.

John Calder
AMAP Chair

Lars-Otto Reiersen
AMAP Executive Secretary

Executive Summary

The first AMAP assessment – *Arctic Pollution Issues: A State of the Arctic Environment Report* – documented direct evidence of acidification effects on the Kola Peninsula and in limited areas of northern Norway and Finland, and around Norilsk in the Taymir region of Russia, mainly related to emissions from smelters in or close to these arctic areas. Acidification effects were also seen in some sensitive low-deposition areas of the European Arctic receiving pollutants from long-range transport. Data for areas of the North American Arctic and eastern Siberia that, due to their geology, are potentially vulnerable to acidification were generally lacking. So although the assessment did not find evidence of acidification effects in these areas, it concluded that improved information on possible acidification effects in these regions of the Arctic was desirable.

The present assessment builds on information in the first assessment and fills several gaps in knowledge. In particular it examines information on trends over the ten-year period since the first assessment was completed. It also addresses the need for more information on local sources of acidifying pollutants within the Arctic that were previously unknown or insufficiently quantified; the need for more information on contaminant levels and trends in some areas; the need to integrate physical and biological models with information on environmental measurements of sources and pathways; and the need for more information on the combined effects of climate change and contaminant pathways on acidification in the Arctic and arctic haze, including improvements of models for assessments. This assessment also considers links to hemispheric pollution issues.

Arctic Acidification

Arctic acidification is a subregional issue, and is only of major concern in areas with both sensitive geology and levels of acid deposition elevated to a point that exceeds the system's acid neutralizing capacity. Arctic haze is a visible manifestation of long-range transported air pollution. Arctic haze is largely composed of sulfate aerosol and particulate organic matter, which builds up in the arctic atmosphere during wintertime and appears in springtime over large regions of the Arctic, both in North America and Eurasia as haze layers with reduced visibility.

Sulfur is the most important acidifying substance in the Arctic, with nitrogen of secondary importance. Significant anthropogenic sources of sulfur emissions, and to a lesser extent nitrogen emissions, exist within the arctic region. In addition, long-range transported air pollutants contribute to acidification and arctic haze in the Arctic. Emissions from natural sources within the Arctic (volcanoes, marine algae, and forest fires) are very difficult to quantify and almost impossible to project.

Studies to date have been unable to show any significant health effects that are directly associated with emissions from the smelters that are the main sources of sulfur pollution within the Arctic. Epidemiological studies indicate that differences in health status of populations in areas of the Arctic with some of the highest levels of acidifying air pollutants, the Norwegian and Russian border populations, are more associated with socio-economic conditions than environmental pollution.

Trends

Some air and precipitation monitoring stations have now generated time series datasets that are long enough to show whether concentrations are increasing, decreasing, or staying the same over time. Sulfate concentrations measured in air at monitoring stations in the High Arctic (Alert, Canada; and Ny-Alesund, Svalbard) and at several monitoring stations in subarctic areas of Fennoscandia and northwestern Russia show decreasing trends since the 1990s. In contrast, levels of nitrate aerosol are increasing during the haze season at Alert (Canada), and possibly also at Barrow (Alaska) but longer data series are needed to confirm this trend. The increasing trends in nitrate are particularly apparent in recent years indicating a decoupling between the trends in sulfur and nitrogen. These observations are supported by modeling results.

Although further improvement in the acidification status of the terrestrial and freshwater ecosystems of the Arctic can be expected during the period until 2020, this is dependent on the implementation of existing international agreements to reduce emissions of acidifying substances. The Gothenburg Protocol to the UN ECE LRTAP Convention is the most important agreement in this connection. However, model projections based on full implementation of the Gothenburg Protocol indicate that the decreasing trends in deposition observed between 1990 and 2000 are likely to level off. Measurement data indicate that downward trends in concentrations may already be leveling off at some sites.

It is therefore recommended that:

- **All arctic countries are encouraged to ratify the UN ECE LRTAP protocol to Abate Acidification, Eutrophication, and Ground-level Ozone (the 'Gothenburg Protocol') and to support its implementation.***
- **Arctic countries look into the need to strengthen the provisions of the existing international agreements, and consider the need for new instruments to reduce emissions of acidifying substances.**

Significant reductions in emissions from the non-ferrous metal smelters on the Kola Peninsula, and to a lesser extent the Norilsk smelters, in the Russian Arctic have been achieved over the past ten years. Chemical monitoring data show that lakes in the Euro-Arctic Barents region are showing clear signs of a regional-scale recovery from acidification. Lakes close to the sources on the Kola Peninsula are showing the clearest signs of recovery.

*** The Protocol entered into force on 17 May 2005. As of July 2006, Denmark, Finland, Norway, Sweden and the United States have both signed and ratified, accepted, or approved the Protocol, Canada has signed but not yet ratified the Protocol, and Iceland and the Russian Federation have neither signed nor ratified the Protocol.**

However, non-ferrous metal production remains the dominant source of emissions of acidifying gases to the atmosphere within the Arctic. Other significant anthropogenic sources of sulfur emissions within or close to the Arctic include energy production plants and mining industries. Sources of nitrogen emissions within the Arctic include transportation, in particular shipping, and oil and gas activities. Detailed information on all of these sources is generally lacking.

It is therefore recommended that:

- **Information on emissions from arctic point sources in Russia, in particular information on emissions from the non-ferrous metal smelters on the Kola Peninsula and at Norilsk should continue to be made available. Information on emissions in other arctic areas should be improved.**
- **The impacts of acidification from arctic shipping and oil and gas activities, including future scenarios for emissions associated with these sources should be assessed.**

Links between Acidification, Arctic Haze, and other Environmental Issues

The causes and the effects of acidifying air pollutants and arctic haze are closely linked to other environmental problems. It is not clear how climate change will influence future acidification and arctic haze pollution in the Arctic. The effects of haze aerosols on the arctic climate are complicated by feedbacks between aerosols, clouds, radiation, snow and ice cover, and vertical and horizontal transport processes. Whether the pollutant aerosols cause an overall warming or an overall cooling is not yet known.

The amount of haze precursors (haze-inducing substances) reaching Alaska and the Canadian Arctic appears to have increased since the late 1990s. The frequency, severity, and duration of boreal forest fires appear to be increasing and the pollution plumes from these summer fires can extend over vast areas. In intense fire years, boreal forest fires may be the dominant source of black carbon (soot) for the Arctic. The importance of Asian sources to acidification and arctic haze pollution in the Arctic is not yet clear.

It is therefore recommended that:

- **Future AMAP assessments view acidification and arctic haze in the wider context of air pollution and climate change. The issues addressed in this more integrated type of assessment should include hemispheric transport of air pollutants, emissions from forest fires, particulate matter, and climate change effects.**

Gaps in Knowledge – Monitoring, Research, and Modeling

Atmospheric monitoring

Acidification is not known to have serious impacts in the Arctic outside the Kola/Fennoscandia region and the Taymir region in the vicinity of Norilsk. However, knowledge of acidification status in the Arctic is far from complete, particularly in relation to future effects. While Fennoscandia has several background air monitoring stations for acidification parameters, most areas of the Arctic have few, if any, background air monitoring stations.

Remote stations that are not affected by local or regional air pollutants are useful for studying trends in the levels of pollutants transported into the Arctic from long-range sources. Under AMAP, a network of arctic air monitoring stations has been established to assess trends in a range of pollutants, including acidifying substances, persistent organic pollutants, and metals such as mercury; however in recent years the overall coverage of this network has been reduced such that coverage is limited, particularly in Russia and the United States.

It is therefore recommended that:

- **A critical review of the existing arctic air monitoring network be conducted to identify the optimal number and location of long-term background monitoring stations for air and precipitation chemistry.**
- **To the extent possible, this network should be integrated with other monitoring and research planning, with the aim of developing a network of 'multi-purpose' background air monitoring stations in the Arctic.**

Episodic events

Short-term events of high atmospheric concentrations of sulfur dioxide are responsible for direct damage to vegetation at varying distances from the smelters. At many sites a large proportion of the annual acid deposition is accumulated in just a few days.

Similarly, pollutants deposited onto the snow pack accumulate throughout the polar winter and are released rapidly into rivers and lakes with snowmelt in spring. These pulses of very acidic water can cause short periods of very toxic conditions. Freshwater biota can be critically affected during acidic episodes and therefore assessments need to address both average conditions and conditions that may occur during episodic events.

It is therefore recommended that:

- **Further studies, with high temporal resolution, be conducted on the ecological impact of pulses or episodic events.**

Effects on terrestrial and freshwater ecosystems

In the European Arctic there are clear direct effects of sulfur dioxide emissions on trees, dwarf shrubs, and epiphytic lichens. The present deposition of acidifying compounds resulting from long-range transport of anthropogenic emissions at lower latitudes does not appear to be a threat to terrestrial ecosystems in most of the Arctic. In terms of their effects on plants, it is difficult to differentiate between the effects of acidifying air pollutants and elevated heavy metal levels in soils. Habitat destruction and possible changes in food availability are strongly reducing biodiversity in the immediate vicinity of the smelters.

It is therefore recommended that:

- **Future studies be conducted on terrestrial ecosystems to address the combined effects of acidifying sub-**

stances and heavy metals and other relevant factors in an integrated manner.

Available terrestrial and freshwater monitoring data provide irregular and incomplete coverage of the Arctic, even in acid-sensitive regions. Similarly, assessments of biological effects of acidification in arctic surface waters are largely based on sparse and isolated data.

It is therefore recommended that:

- **Coordinated monitoring and research be carried out to provide more chemical and biological data on effects and trends in terrestrial and freshwater ecosystems in the most impacted areas of the Arctic.**

Modeling

Modeling is one of the most important tools available for gaining insight into the possible pollution status of the extensive areas of the Arctic where the observational networks are absent or poorly developed. Models also allow investigation of scenarios for future trends, and for linkages between contaminant pathways and, for example, climate change.

It is therefore recommended that:

- **Existing air transport and deposition models be improved and further validated using measurements of sulfur compounds, nitrogen compounds, and black carbon in the Arctic, including measurements conducted during field campaigns.**
- **Studies be conducted to identify and provide estimates of sources of black carbon to the Arctic.**
- **Data sets gathered during aircraft and ground-based surveys, in particular, long-term data sets, be integrated for use in three-dimensional arctic climate models designed to evaluate climate forcing by arctic haze.**

Cooperation on monitoring

Close cooperation between AMAP and other international organizations involved with monitoring and modeling deposition and effects of acidifying pollutants within the European Arctic, such as programs under the UN ECE LRTAP Convention, have proven mutually beneficial. The new EANET (Acid Deposition Monitoring Network in East Asia) initiative represents an opportunity to develop similar cooperation in relation to monitoring in the Far East of Asia.

It is therefore recommended that:

- **AMAP continues to develop its cooperation with relevant international organizations, in particular to obtain more precise data on emissions from southeast Asia and to investigate the possible impact of these emissions on the Arctic.**
- **Resources be made available to ensure that relevant existing and future national data on acidification parameters, in particular from arctic monitoring stations, are reported to the AMAP database at NILU according to agreed procedures.**

Introduction

Acidification effects were first seen as early as 1850 in some northern European cities. However, widespread awareness of acidification as an environmental problem did not begin until the late 1960s when fish kills in Scandinavia, Canada, and the United States were all shown to result from acid rain and snow. Later studies showed that the acidity was almost always from sources a long way from where the rain and snow fell. This understanding led to the start of international discussions on ways to control substances that undergo long-range transport. The 1979 Geneva Convention on Long-range Transboundary Air Pollution was the first international legally binding instrument to deal with problems of air pollution on a broad regional basis (see the box to the right). This has since been extended by several protocols. The latest is the 1999 Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone. The Gothenburg Protocol is an effects-based protocol that sets new targets for emissions cuts of sulfur dioxide and nitrogen oxides based on scientific assessments of pollution effects and abatement options (see the box on critical loads and critical levels on page 2).

The Arctic Monitoring and Assessment Programme (AMAP) was established in 1991 to monitor identified pollution risks and their impacts on arctic ecosystems. The first AMAP assessment – *Arctic Pollution Issues: A State of the Arctic Environment Report* – concluded that there was direct evidence of acidification effects on the Kola Peninsula and in a limited area of northern Norway and Finland. The report showed that the widespread damage to forests, fish, and invertebrates on the Kola Peninsula was clearly linked to emissions from the non-ferrous metal smelters at Nikel, Zapolyarnyy, and Monchegorsk. The visible damage to the forests and tundra around and downwind of the non-ferrous metal smelters was mainly attributed to the direct toxic effects of sulfur dioxide and to the accumulation of toxic heavy metals in soils. Similar extensive damage to vegeta-

RAUNI PARTANEN

Mountain birch forest near Kilpisjärvi, Finland. Lakes and ponds are abundant in the subarctic Fennoscandian landscape.

Convention on Long-range Transboundary Air Pollution

The 1972 United Nations Conference on the Human Environment in Stockholm was the start of international cooperation to combat acidification. Between 1972 and 1977 several studies showed that air pollutants could travel thousands of kilometers before deposition and damage. This implied that cooperation at the international level was necessary to solve problems like acidification. A meeting within the framework of the UN ECE in November 1979 resulted in the signing of the Convention on Long-range Transboundary Air Pollution (the 'LRTAP Convention') by 34 governments and the European Community. This entered into force in 1983. The LRTAP Convention provides a framework for controlling and reducing environmental damage and damage to human health from transboundary air pollution. This was the first international legally binding instrument to deal with problems of air pollution on a broad regional basis.

The LRTAP Convention has since been extended by eight protocols. These include the Protocol to Abate Acidification, Eutrophication and Ground-level Ozone adopted in Gothenburg (Sweden) on 30 November 1999 and signed by 31 countries. The protocol entered into force on 17 May 2005. As of July 2006, Denmark, Finland, Norway, Sweden and the United States have both signed and ratified, accepted or approved the protocol, Canada has signed but not yet ratified the protocol, and Iceland and the Russian Federation have neither signed nor ratified the protocol.

The Gothenburg Protocol aims at controlling several pollutants and their effects through a single agreement and, among others, sets new targets for emissions cuts by 2010 for sulfur dioxide and nitrogen oxides. Countries whose emissions have the most severe health or environmental impact and whose emissions are the cheapest to reduce will have to make the biggest cuts.

tion was documented around the smelter complex at Norilsk in the Taymir region of Russia. Owing to the sensitivity of arctic ecosystems some acidification effects were also seen in some low-deposition areas of the European Arctic receiving pollutants from long-range transport. Data for the North American Arctic and eastern Siberia were extremely sparse. So although the assessment did not find evidence of acidification effects in these areas, it concluded that as the geology made parts of these regions potentially vulnerable to acidification, improved information on possible acidification effects in the North American Arctic and Far East of Russia was desirable. The assessment also addressed trends and impacts of arctic haze.

The present assessment builds on information in the first assessment and fills several gaps in knowledge. In particular it examines information on trends over the ten-year period since the first assessment was completed. It also addresses the need for more information on local sources of acidifying pollutants within the Arctic that were previously unknown or insufficiently quantified; the need for more information on contaminant levels and trends in some areas; the need to integrate physical and biological models with information on environmental measurements of sources and pathways; and the need for more information on the combined effects of climate change and contaminant pathways on acidification in the Arctic and arctic haze, including improvements of models for assessments. The assessment also considers links to hemispheric pollution issues.

Gothenburg Protocol, critical loads and critical levels

The Gothenburg Protocol to the LRTAP Convention is an effects-based protocol that uses ecosystem vulnerabilities to set emissions reduction targets. The vulnerability of ecosystems to sulfur and nitrogen deposition is quantified by ‘critical loads’ and ‘critical levels’.

Critical loads are defined as a quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur, according to present knowledge.

Critical levels are defined as concentrations of pollutants in the atmosphere above which direct adverse effects on receptors, such as human beings, plants, ecosystems or materials, may occur, according to present knowledge.

Critical loads for Europe are calculated at national focal centers following agreed methods. The data are collected, verified, and collated by the Coordination Centre for Effects (CCE), which produces maps of Europe and makes the data available for integrated assessments. Although the United States and Canada are both signatories to the Gothenburg Protocol, critical loads data for the United States are not yet available. An initial attempt at mapping critical loads has been made for Canada.

Areas where critical loads may be exceeded are identified by combining the critical load maps with modeled deposition data.

Acidification

A change in the environment’s natural chemical balance that results in an increase in the concentration of acidic elements, causing the environment to become more acidic, is referred to as ‘acidification’. The main compounds contributing to acidification are sulfur oxides, sulfates, nitrogen oxides, nitrates, and ammonium compounds. Sulfur is the dominant acidifying substance in the Arctic, with nitrogen of secondary importance.

Arctic haze

Arctic haze is a persistent winter diffuse layer in the arctic atmosphere whose origin is thought to be related to long-range transport of continental pollutants.

▼ Vegetation damage in a valley 25 km south of Norilsk, western Siberia. Winds funnel pollution plumes down the valley.

JUHA KÄMÄRI

Sources of Acidifying Pollutants and Arctic Haze

BRYAN & CHERRY ALEXANDER

◄◄
The smelter complex at Norilsk, western Siberia – the largest source of sulfur dioxide emissions within the Arctic region.

◄
Coal-fired power plant at Anadyr, Chukotka. Power plants are a major source of sulfur dioxide emissions.

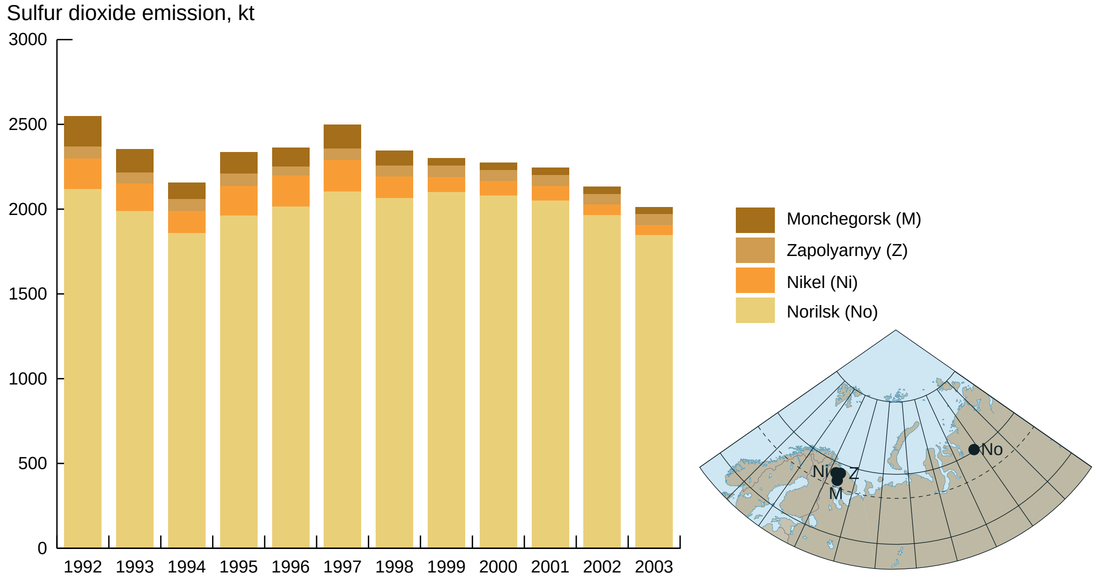
The Arctic is a sparsely populated area with many of its almost four million residents concentrated into a few large towns and cities. The major emissions of acidifying pollutants within the Arctic come from sources within these few areas of industrial activity and/or population. Except for oil and gas activities these sources are almost entirely within the northern territories of the Russian Federation. However, despite these local emissions most of the acidifying compounds in arctic air come from sources at lower latitudes, mostly in Europe, North America, and Asia. They are carried to the Arctic via the major wind systems.

Emissions from the non-ferrous metal smelters have declined significantly

Emissions from the non-ferrous metal smelters on the Kola Peninsula in northwest Russia and the smelter complex at Norilsk in northern Siberia have declined significantly since the early 1990s (see figure) but are still the largest source of sulfur dioxide within the Arctic. Changes in production and better technology for controlling emissions, particularly at Norilsk, should ensure that these emissions continue to decrease.

Sources

Sulfur dioxide, nitrogen oxides, and ammonia emissions have different sources. Sulfur dioxide is mainly emitted from point sources such as power plants, non-ferrous metal smelters, pulp and paper mills, and oil and gas activities. For nitrogen oxides, diffuse sources such as vehicles and shipping are also important. Ammonia is mostly from agricultural sources.



Although they remain the dominant source of sulfur dioxide (SO_2) emissions within the Arctic, SO_2 emissions from the smelters in Arctic Russia decreased by about 21% between 1992 and 2003. The greatest reductions in SO_2 emissions have occurred on the Kola Peninsula. At Nikel, emissions decreased by around 68% between 1990 (when emissions peaked) and 2003, with even bigger reductions at Monchegorsk where emissions decreased by around 82% over this period. Emissions reductions at Norilsk have been much less, decreasing by about 16% between 1990 and 2003.

JUHA KÄMÄRI

Prevailing winds spread the pollution plume from the Norilsk smelters.

Gas flaring at Yamal in western Siberia. Of the countries with probable oil and gas fields on the continental shelf, the Gothenburg Protocol has been ratified by Norway, accepted by the United States, and signed by Canada. Russia has neither signed nor ratified the protocol.

The impact of the oil and gas industry on acidification is low but may increase

Oil and gas related activities take place throughout the Arctic on land and at sea and acidifying pollutants are emitted at every stage – from exploration to the final closure of the field. Overall, the impact of the oil and gas industry on acidification is low but emissions may have some impact on the vegetation, soil, and surface waters near the emission sites. The Arctic has huge oil and gas reserves and is thought to contain around a quarter of the world's undiscovered petroleum resources: most of these in Alaska, northern Canada, Norway, and Russia, including substantial amounts in offshore areas. A continuing reduction in sea ice is likely to result in an increase in oil and gas activity offshore, particularly in terms of increased marine transport of oil (as the navigation season lengthens and new sea routes open).

BRYAN & CHERRY ALEXANDER

The relative importance of nitrogen oxides is increasing in the Arctic

Although nitrogen oxide emissions within the Arctic are very low, and their contribution to acidification effects is minimal, their importance relative to sulfur dioxide emissions is increasing. This is mainly due to the reductions in sulfur dioxide emissions from the Russian smelters. The increase in shipping and the expansion of the offshore oil and gas industry that are thought likely to follow warmer temperatures in the Arctic will probably enhance nitrogen oxide emissions within the Arctic.

Emissions from natural sources are very difficult to quantify

The major natural sources of acidifying pollutants within the Arctic are volcanoes (which emit sulfur dioxide) and marine algae (which emit dimethyl sulfide). The major natural source of arctic haze is forest fires (which emit soot). There are few natural sources of nitrogen within the Arctic and emissions are extremely low. Emissions from natural sources are very difficult to quantify and almost impossible to project. However, the frequency, severity, and duration of boreal forest fires do appear to be increasing and the pollution plumes from these summer fires can extend over vast areas.

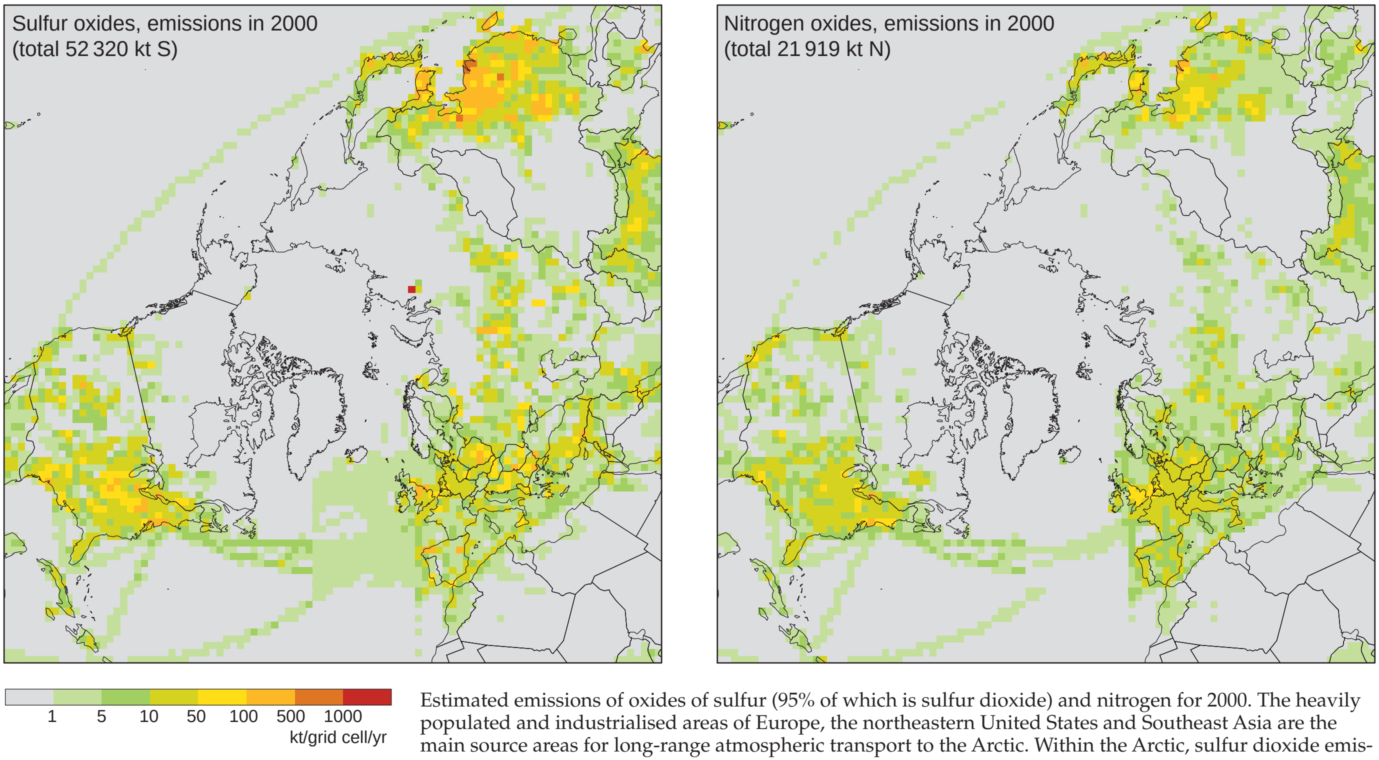
Most pollutants in arctic air are from sources outside the Arctic

Despite the many sources of acidifying pollutants within the Arctic the majority of the pollutants in arctic air come from sources at lower latitudes. These are carried to the Arctic by winds passing over the three main source regions – Europe, North America, and Asia. Winds carry these pollutants to the Arctic over periods ranging from days to weeks (see the section on arctic haze for more details on long-range transport). There are some indications (based on models) that south-east Asia is becoming an increasingly important source of soot to the arctic atmosphere. Other studies indicate that most of the soot being deposited in the Arctic is more likely to have come from boreal and temperate forest fires.

BRIAN J. STOCKS / CANADIAN FOREST SERVICE

BRIAN J. STOCKS / CANADIAN FOREST SERVICE

As the climate continues to warm, the forest fire season will begin earlier and end later. Forest fires are likely to become an increasingly important source of soot to the Arctic.



Estimated emissions of oxides of sulfur (95% of which is sulfur dioxide) and nitrogen for 2000. The heavily populated and industrialised areas of Europe, the northeastern United States and Southeast Asia are the main source areas for long-range atmospheric transport to the Arctic. Within the Arctic, sulfur dioxide emissions from Norilsk, and the Kola Peninsula are evident.

Concentrations and Deposition of Acidifying Air Pollutants

The fate of the sulfur and nitrogen emitted to the air depends on what happens in the atmosphere. Light, moisture, and reactive chemical compounds in the air act together to transform the sulfur dioxide and nitrogen oxides emitted from the various sources into acidic rain and snow and into acidic particles that can settle onto surfaces that they encounter. Many of the transport and chemical processes in the sulfur and nitrogen cycles are strongly latitude dependent and in the Arctic are linked to the prolonged period of darkness during winter and the lack of precipitation.

Ice cores – vertical columns of ice obtained by drilling through an ice cap – have been used to reconstruct atmospheric conditions over the last 100 000 years. The cores are sliced into sections and the ice from each section is melted and analyzed. Each section reflects atmospheric conditions during a particular period in history.

DEPARTMENT OF GEOPHYSICS, NIELS BOHR INSTITUTE, UNIVERSITY OF COPENHAGEN

Widespread contamination of the Arctic began with the Industrial Era

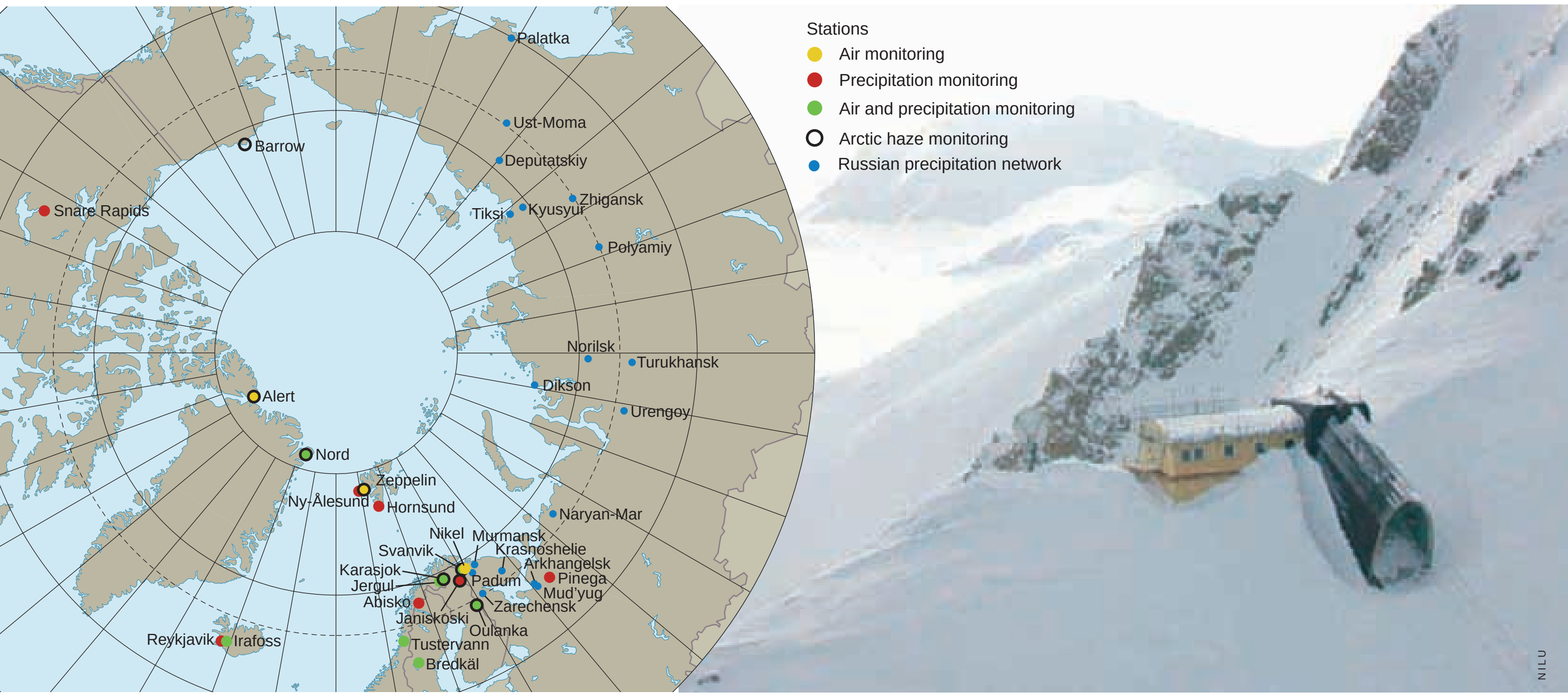
Ice cores are useful for indicating historical trends in the background levels of contaminants over wide areas. As snow and dust settle onto the arctic ice sheets they carry with them a record of the current levels of atmospheric pollution: snow scavenges pollutants from the atmosphere as it falls and the chemical composition of the dust reflects its source. Pollutants present in arctic ice cores show that significant changes in atmospheric pollution have occurred only since the beginning of the Industrial Era. Ice cores from Svalbard show the influence of human activities during the latter half of the 20th century. This is demonstrated by increased levels of sulfate, nitrate, acidity, fly ash, and organic contaminants. Levels of sulfate and nitrate in ice cores from the Canadian Arctic confirm these trends. There is no information on sulfate and nitrate levels in ice cores from the Russian Arctic.

Atmospheric monitoring data are mostly for 1980 onwards

Atmospheric pollutants in rain, snow, dust, and gases are monitored regularly at purpose-built stations throughout the Arctic. Most data are for the 1980s onwards although a few stations have operated for longer. Some areas of the Arctic have more stations than others: Fennoscandia has several background monitoring stations, while the vast Siberian region and the Canadian Arctic and Alaska have relatively few.

Sulfate levels in air and precipitation are decreasing in many areas of the Arctic

Some of the datasets from the background monitoring stations now contain time series that are long enough to show whether concentrations are increasing, decreasing, or staying the same over time. These data-



Air and precipitation monitoring stations around the Arctic have provided data used in this assessment. Background air monitoring stations such as the one on Zeppelin mountain, Ny-Ålesund, Svalbard (photo), are particularly important for monitoring long-range transport of pollutants.

sets mostly show that background levels of sulfate (from human activities) and sulfur dioxide in air are decreasing, both in summer and in winter. Sulfate concentrations in precipitation are also decreasing at many sites. There are no clear patterns for nitrate or ammonium (with positive trends at some sites and negative trends at others). Some stations (e.g., Svanvik and Nikel) are too near local pollution sources to monitor background levels.

Precipitation

Precipitation includes any of the forms of water particles, whether liquid or solid, that fall from the atmosphere and reach the ground. For example, rain, snow, hail, and sleet.

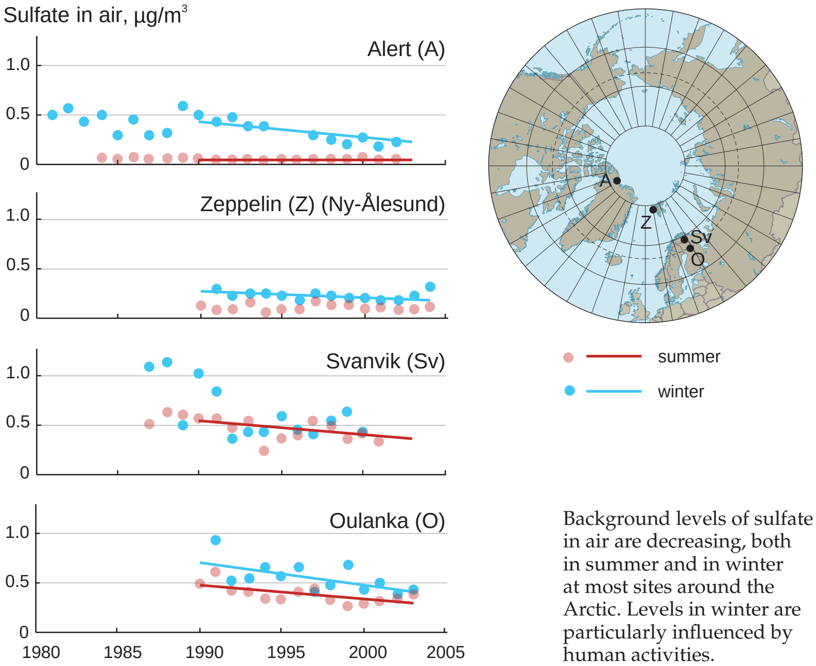
Background levels decrease from west to east across the Russian Arctic

Background levels in rain and snow show a consistent decrease from west to east across the Russian Arctic. Concentrations of sulfur from human activities are higher in precipitation falling in the western part of the Russian Arctic than in the central and eastern parts. There is a similar pattern for background levels of nitrate and ammonium. Precipitation falling in the western Russian Arctic is more acidic (regional average pH 5.6) than in the central Russian Arctic (regional average pH 6.7) and the eastern Russian Arctic (regional average pH 7.0). Snow cover samples from more than a hundred sites across the Russian Arctic confirm the west to east decrease in atmospheric sulfur and nitrogen levels picked up in the air and precipitation data.

There are too few data to show whether there are similar trends in the background levels of acidifying pollutants in air, rain, or snow across the North American Arctic.

pH

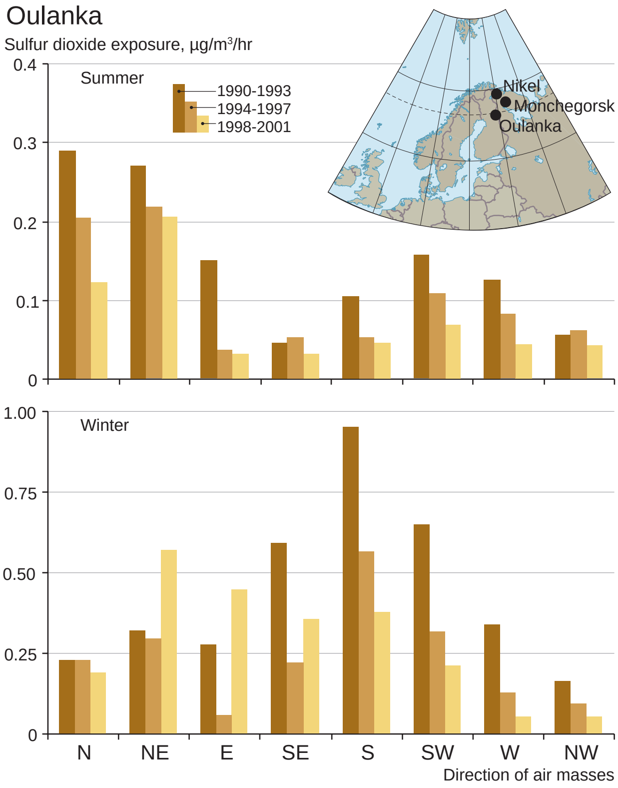
pH is a measure of acidity. It is represented by a value on a scale ranging from 0 (acid) through 7 (neutral) to 14 (alkaline). Rain with pH values of 2.1 to 4.0 is typical in polluted areas near the smelters.



Background levels of sulfate in air are decreasing, both in summer and in winter at most sites around the Arctic. Levels in winter are particularly influenced by human activities.

Peaks in concentration and deposition are particularly important

Monitoring sites collect such large amounts of data that the results are usually presented as averages – average daily, monthly, seasonal, or annual values. But this smoothing removes any peaks in the data and it is these peaks – short-term events of high concentration and high deposition – that are especially important for transporting contaminants to and within the Arctic. In the 1990s, between 20 and 30% of the sulfate deposited in a remote area of Finland arrived on just five days of the year. Peaks in air concentration also cause severe environmental damage in areas more used to lower levels of pollution (see the section on acidification effects in terrestrial ecosystems).



Although the prevailing winds at Oulanka, a background monitoring station in Finland, are from the west and southwest, sulfur dioxide concentrations are highest in winds from the north-east. The non-ferrous metal smelters on the Kola Peninsula occur to the north of Oulanka and are almost certainly responsible for the pulses of sulfur dioxide that arrive with the northerly winds in summer.

JESPER CHRISTENSEN

Station Nord in Greenland monitored trends in emissions from Eastern Europe and Russia until the station was closed in 2002.

Climate variability affects pollutant transport to and within the Arctic

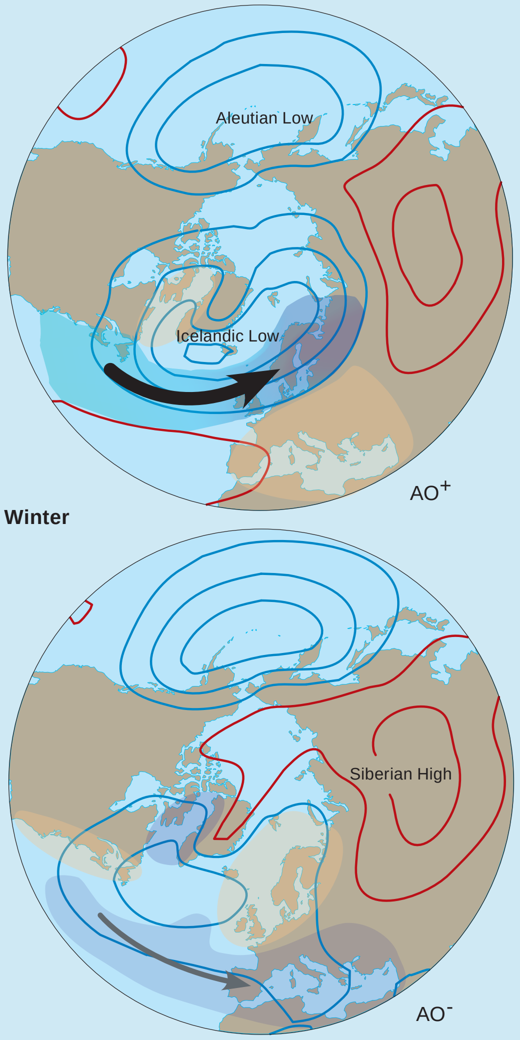
At certain times of the year winds bringing pollutants into the Arctic can arrive in a matter of weeks or even days after passing over source regions to the south. Much of the natural climate variability in the northern hemisphere – which affects the strength and persistence of these winds – is linked to the 'North Atlantic Oscillation'. When this is in a 'positive' phase, as occurred during the 1990s, transport into the Arctic from Europe, North America, and Asia (in order of significance) is enhanced, resulting in higher levels of arctic pollution. Given the widespread impact of its sudden and long-term changes the status of the North Atlantic Oscillation must be considered in any studies on trends in arctic pollution. Climate models predict that the frequency of positive phases in the status of the North Atlantic Oscillation is likely to increase.

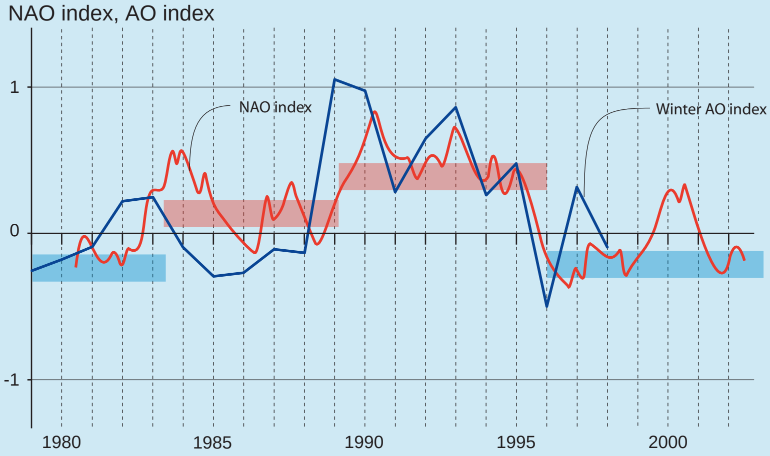
Remote stations are useful for monitoring trends in long-range transport

Remote stations that are not affected by local or regional air pollution are useful for studying trends in the amounts of pollutants transported into the Arctic from long-range sources. For example, monitoring data from Station Nord in northern Greenland have been used together with long-range transport models to study trends in the long-range transport of emissions from Eastern Europe and Russia.

Arctic air monitoring networks

Monitoring stations recording background levels of air pollutants throughout the Arctic belong to several networks. The AMAP network is based largely on ongoing national programmes and international programmes, such as EMEP (European Monitoring and Evaluation Programme). The EMEP network covers the European region from Iceland to the Urals in the east and provides signatories to the LRTAP Convention with data to support the development and further evaluation of international protocols on emissions reduction. A number of stations within the AMAP network are also EMEP stations. The Acid Deposition Monitoring Network in East Asia – EANET – was established in 1998 and has 12 participating countries but so far lacks stations in the Arctic area. The Russian national precipitation monitoring network has 110 stations measuring precipitation chemistry and acidity but relatively few are in the vast Siberian region.





North Atlantic Oscillation

The **N**orth **A**tlantic **O**scillation (and related **A**rctic **O**scillation) indices reflect the difference in surface pressure between the subtropical highs at the Azores and the subpolar lows at Iceland. A shift between NAO$^-$ (blue bars above) and NAO$^+$ (red bars above) conditions changes the balance and timing of winds from source regions to the Arctic.

Under NAO$^+$ conditions, the Azores high and Icelandic low pressure systems are stronger/deeper than normal. The result is more and stronger winter storms (black arrow on upper map), bringing warm wet winters to northern Europe (blue shading) and cold dry winters (orange shading) to Greenland. Conversly, weaker pressure systems under NAO$^-$ conditions mean fewer and weaker storms crossing the Atlantic on a more southerly track (grey arrow on lower map), bringing cold winters to northern Europe and milder winters over Greenland. The resulting differences in winds and precipitation will affect contaminant pathways, and processes that remove, in particular, particulate-associated contaminants from the atmosphere to the surface.

Models accurately represent the long-range transport of sulfur to the Arctic

The transport of air pollution to the Arctic since 1991 has been studied using long-range transport models. The box describes the DEHM model system – a widely used approach for studying long-range transport to the Arctic. Using actual emissions data for the source regions the model predicted that concentrations of sulfur oxides and total sulfur deposition across the Arctic would have almost halved between 1990 and 2000. This corresponds well with the general decrease in background sulfur levels recorded at many of the atmospheric monitoring stations across the Arctic. The model gave similar results for nitrogen oxides (although it is less accurate at modeling these because the model is not yet as good at representing the atmospheric chemistry of nitrogen and nitrogen oxides).

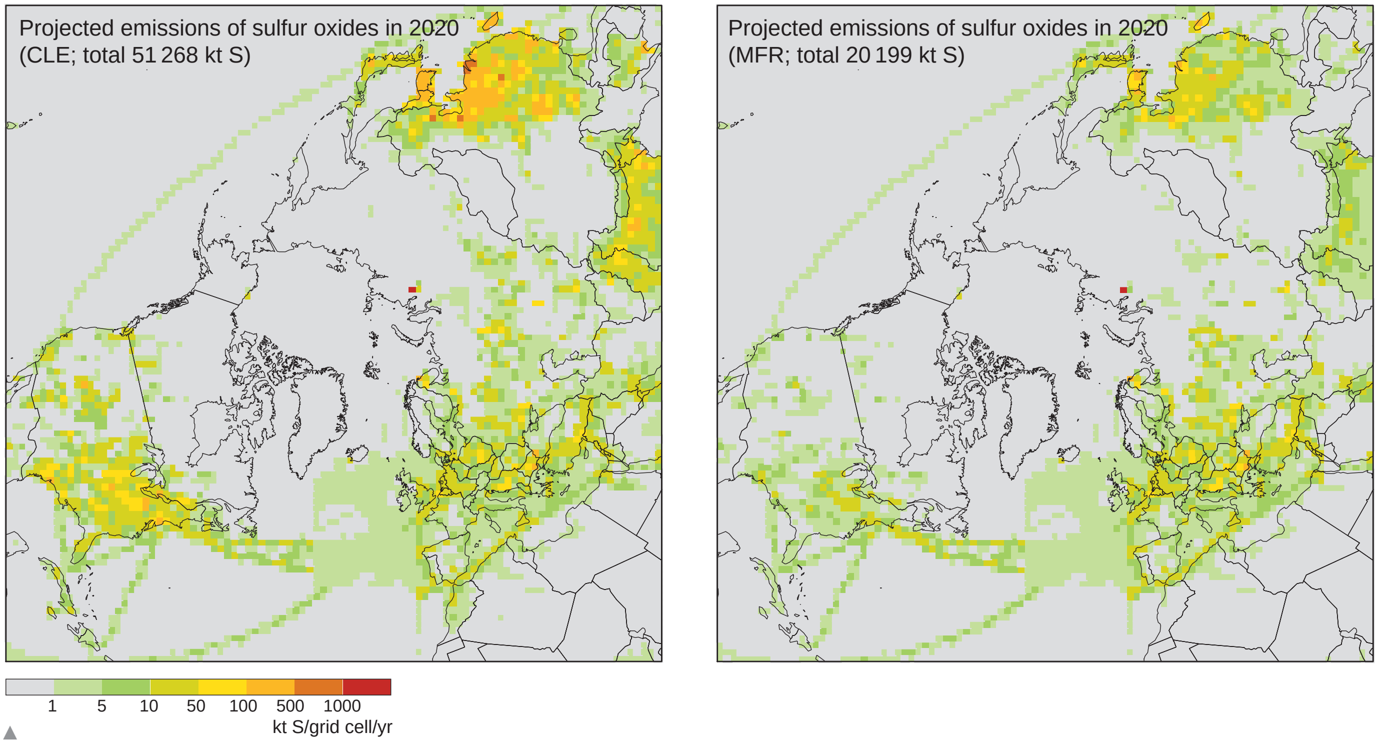
DEHM model system

The Danish Eulerian Hemispheric Model (DEHM) system comprises a three-dimensional atmospheric transport model (with a horizontal resolution of 150 km by 150 km and 20 vertical layers) and a weather forecast model driven by meteorological data from the European Centre for Medium-Range Weather Forecasts.

Air concentrations across the Arctic calculated by the DEHM system for 2000 compare well with data from the atmospheric monitoring stations, and the sulfur hot spots around Norilsk and on the Kola Peninsula are very clear. The monthly variation at most of the monitoring stations is also represented well. The DEHM system is not as good for nitrate, however, and overestimates concentrations at most monitoring stations.

To check its usefulness for projecting pollutant concentrations and deposition across the Arctic the model has been run using emissions data from the Emission Database for Global Atmospheric Research (EDGAR) modified to represent two future emissions scenarios for the northern hemisphere: the CLE and MFR scenarios. The CLE (**C**urrent **LE**gislation) scenario represents the current perspectives of the individual countries on future economic development and takes into account the effects of presently agreed emission control legislation in the individual countries, while the MFR (**M**aximum technically **F**easible **R**eduction) scenario assumes the full implementation of presently available emission control technologies, while maintaining the projected levels of anthropogenic activities.

A comparison of the actual sulfur dioxide and nitrogen oxide emissions in 2000 with the CLE and MFR scenarios for 2000 shows that the CLE scenario results in little change in emissions while the MFR scenario results in large emissions reductions.



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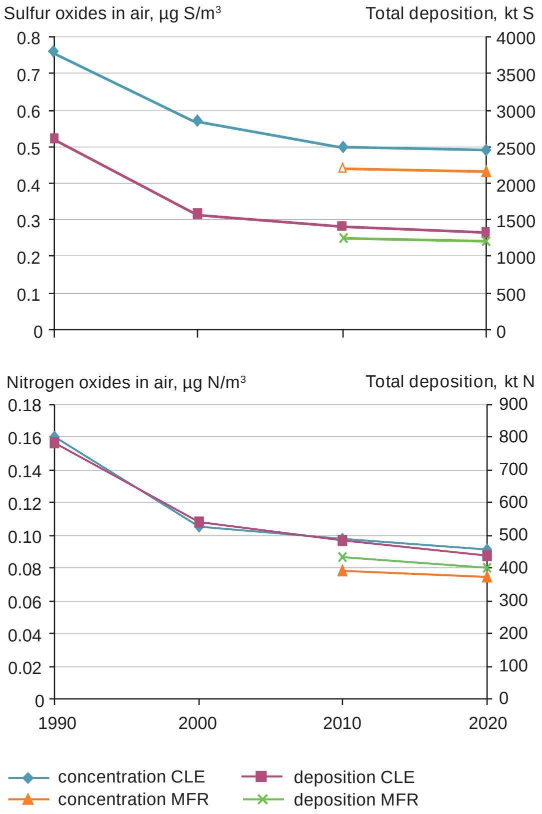
Projected emissions of sulfur oxides in 2020 for the CLE and MFR emissions scenarios.



Under modeled emission reduction scenarios, pollution levels continue to reduce but there is a levelling off after 2010.

Further recovery in affected arctic areas may require more stringent international legislation

Long-range transport models can also be used to project the effects of future changes in emissions from the source regions. The effects of a range of emissions scenarios on concentrations and deposition in the Arctic have been projected by the DEHM model system. The results suggest that implementing the Gothenburg Protocol will result in further reductions in concentration and deposition in the Arctic over the next decade, but that, even if fully implemented, these measures will have little effect in the Arctic after 2020. Emissions from Europe and Asian Russia make the greatest contribution to acidification in the Arctic and it is future changes in these emissions that are likely to have the greatest impact on concentrations and deposition of acidifying pollutants in the Arctic. This implies that, beyond 2020, further recovery in affected arctic areas will require international legislation to become more stringent.

Arctic Haze

In the mid-1950s, pilots flying over the Canadian High Arctic began to report periods of reduced visibility due to a brown-tinged haze. This became known as 'arctic haze' and was seen on many occasions at different altitudes and in different areas. Together with research studies, weather reports showed that the haze in the high Arctic was seasonal, peaking in early spring, and was most severe during periods of clear, calm weather.

As its source was not obvious, the haze was initially attributed to natural factors such as ice crystals and windblown dust from river beds. This view was overturned in the 1970s when 'chemical fingerprinting' showed that the source was clearly related to human activities. Since then, studies have shown that the haze is mostly due to emissions from industrial activities in Europe and the former Soviet Union.

Arctic haze peaks in spring

Several meteorological conditions combine to cause the spring peak in arctic haze. First, the long-range transport of haze-inducing substances into the Arctic is greatest in winter and spring, when the major south-to-north winds are most frequent. Second, the strong temperature inversions during

Long-range transport of haze-inducing substances

Air pollution can be transported into the Arctic along three pathways: low-level transport followed by ascent in the Arctic, low-level transport alone, and uplift outside the Arctic, followed by descent in the Arctic. Only this last pathway is frequent for pollution originating from North America and Asia, whereas European pollution can follow all three pathways in winter, and pathways one and three in summer.


ANN-CHRISTINE ENGVALL


ANN-CHRISTINE ENGVALL

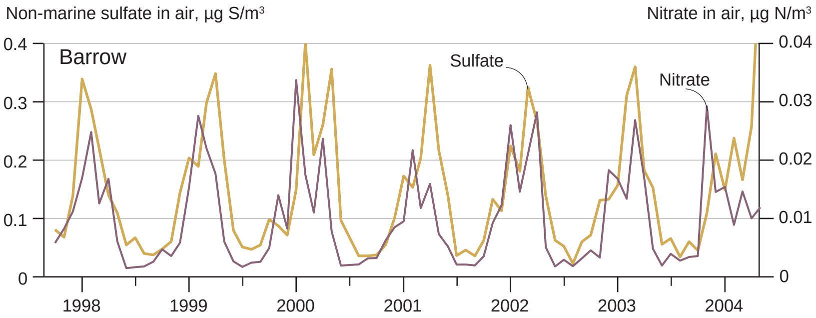
View from the Zeppelin station at Ny-Ålesund on Svalbard in spring 2006. Particles originating from agricultural fires in Eastern Europe combined with an extreme weather situation that transported the pollution to the Arctic were responsible for this pollution event.

▲
Main atmospheric pathways from the industrialised regions of eastern USA, Europe and Southeast Asia to the Arctic, and the position of the Arctic Front in summer and winter.

the long dark winter result in a cold, stable body of near-surface air that traps the incoming material for periods of up to a month. The boundary to this cold stable air mass centered over the Arctic – the Arctic Front – can extend far enough south in winter to cover large parts of Eurasia. This enables emissions from the smelters at Norilsk and on the Kola Peninsula to enter the arctic air mass directly. Also, wash-out of particles by precipitation occurs less often in winter and spring. By late spring, the temperature inversion begins to break down and the haze pollutants are released.

Haze levels in spring vary from one year to another. Studies show that large-scale climatic events, such as the North Atlantic Oscillation (see page 9), can have significant effects on wind patterns. Models predict that concentrations of some pollutants during winter can be up to 70% higher in years with stronger than normal winds (i.e., during positive phases of the North Atlantic Oscillation).

Monthly particulate sulfate and nitrate concentrations at Barrow between 1998 and 2004, showing seasonal patterns.



Aerosols

Aerosols are tiny solid particles or liquid droplets suspended in the air that enter the atmosphere from either natural or man-made sources. They are typically between 0.01 and 10 µm in size.

Haze aerosols have complex structures

Arctic haze is a complex mixture of microscopically small particles and acidifying pollutants that mostly occurs in the lower 5 km of the atmosphere, particularly the lower 2 km. It often appears in the form of 'bands' or 'layers'. These bands are formed when industrial emissions are carried northward by winds to become trapped at a particular level of the arctic air mass; the lower bands develop earlier in the year and contain pollutants from northerly sources while the higher bands develop later in the year and contain pollutants from warmer source regions further south. The bands range in thickness from tens of meters to a kilometer and extend over distances of 20 to 200 km. Visibility within the bands can be as little as a few kilometers due to the way the haze particles scatter and absorb light.

Key pollutants peak in spring

One of the reasons that arctic haze has been the focus of so much study is its role in the transport of pollutants to the arctic environment. Particles containing sulfate are a major constituent of arctic haze. Atmospheric sulfate levels can be up to 25 times higher in the haze season than at other times of the year. There is a similar dramatic seasonal increase in the levels of particulate nitrate and other contaminants from continental sources.

Although ground levels of aerosol pollutants in the Arctic are around ten times lower than in the industrial source regions further south, the areas affected within the Arctic are more extensive and are particularly sensitive to this type of pollution. The reasons for this sensitivity are discussed in the sections on acidification effects in terrestrial and freshwater ecosystems.

Natural aerosol components show very different seasonal cycles. Sea salt aerosol levels at Barrow (Alaska) are highest in summer when sea ice is at a minimum and aerosol formation at the open water surface is at its greatest.

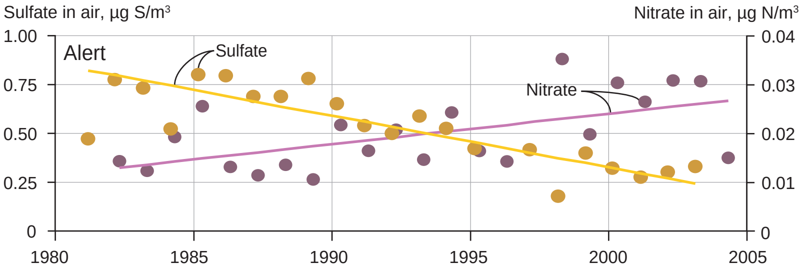
Recent trends in sulfate and nitrate have decoupled

Long-term monitoring at Alert in northern Canada showed little change in the spring levels of sulfate and several other haze pollutants during the 1980s, but a decrease of almost 60% in spring sulfate levels between 1990 and 2000. A decline in spring sulfate levels throughout the 1990s also occurred at several other arctic sites and probably reflects reduced emissions from the former Soviet Union during the early years of the new republics. Recent indications are that spring sulfate levels are still decreasing.

In contrast, spring concentrations of particulate nitrate at Alert increased by about 40% between 1990 and 2000. This difference in the trends for sulfate and nitrate aerosols during the haze season may also be occurring at Barrow in Alaska but longer data series are needed to confirm a decoupling of trends at this site.

Haze pollutants are retained within the Arctic

Because arctic haze develops at the same time as the snow pack, but haze concentrations decrease before the snow has fully melted, it is likely that the haze pollutants first enter the arctic ecosystem through deposition onto snow and ice. Ice cores and snow in Greenland and Alaska show peaks in sulfate and soot deposits in late winter that tend to support this. As the snow melts, pulses of contaminants enter the tundra and rivers. The effects of these episodic pollutant inputs on the freshwater and terrestrial ecosystems are discussed in later sections. It is not known how much of the pollution released from the haze is retained within the Arctic and how much is transported out of the Arctic.



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Long-term trends in sulfate and nitrate in air at Alert, Ellesmere Island, northern Canada, based on averaged values for April.


CHARLOTTE SIGSGAARD

Snowmelt and a running stream.


CHARLOTTE SIGSGAARD

Snowmelt on the tundra.

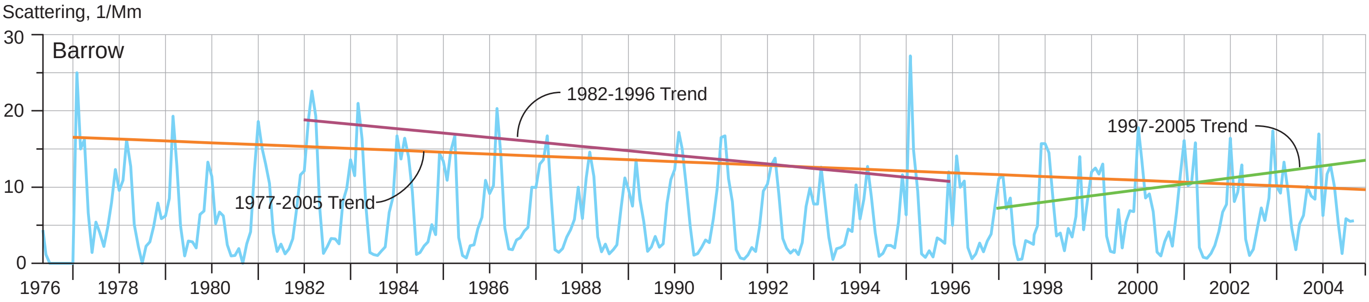
Soot may cause earlier snowmelt on tundra

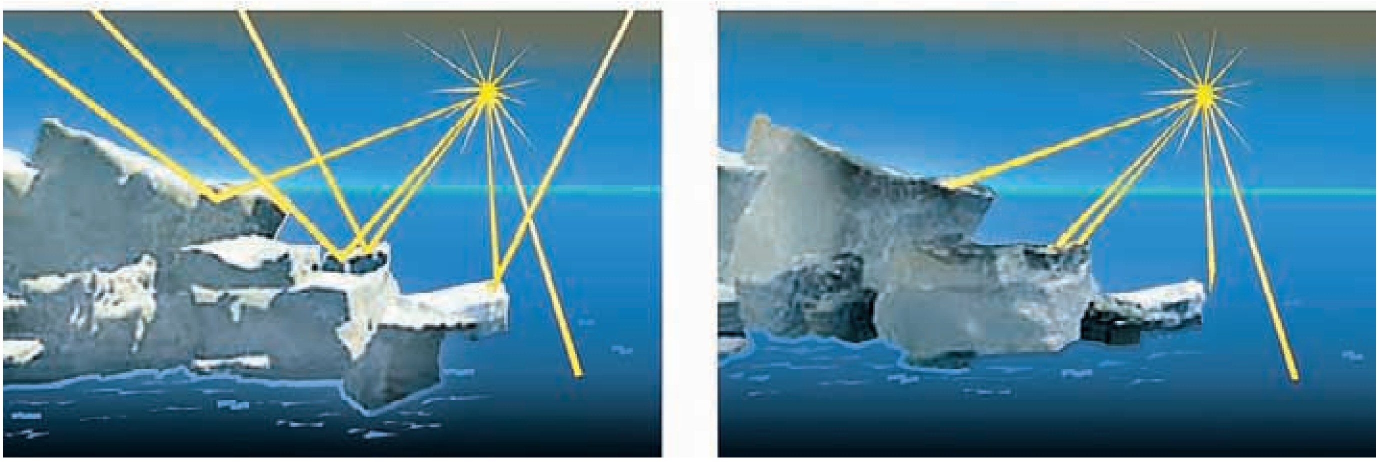
Snow and ice reflect light from the sun back to space. As snow and ice melt, less radiation is reflected and more is absorbed by the land and seas causing an overall increase in temperature and more melting. Darker, soot-covered snow and ice reflect less radiation than clean snow and ice and so enhance warming. There are some suggestions that soot deposited onto the land surface may be contributing to earlier snowmelt on tundra in Siberia, Alaska, Canada, and Scandinavia.

Light scattering and absorption appear to be increasing

Aerosols influence climate in two ways: directly through scattering and absorbing radiation, and indirectly by acting as condensation nuclei for cloud formation

Light scattering measured at Barrow, Alaska, showing peaks during spring when haze levels are at their highest. The long-term decreasing trend in springtime light scattering masks a more recent increase since the end of the 1990s. The cause of this recent increase is not yet known.





Polar ice reflects light from the sun back to space (left panel). Darker, soot-covered ice reflects less light and, thus, enhances warming (right panel).

or by modifying the optical properties and lifetimes of clouds.

Changes in the light scattering and absorbing properties of the haze – which depend on the amount of soot within the haze – directly affect the amount of sun's energy passing through the haze. Increased quantities of soot within the haze are thought likely to cause a warming of the atmosphere but a cooling at the earth's surface, except during winter when there is evidence that soot has an insulating effect and reduces heat loss.

Light scattering by haze particulates at ground level in spring decreased throughout the 1980s and most of the 1990s. Since 1997 there has been a progressive increase at Barrow (Alaska). There is also evidence of a possible increase in light absorption in winter since the end of the 1990s at Alert (Canada). More measurements are needed to confirm these trends and to identify their causes.

Haze aerosols and climate change

The effects of haze aerosols on the arctic climate are complicated by feedbacks between the aerosols, clouds, radiation, sea ice, and vertical and horizontal transport processes. The Arctic is thought to be particularly sensitive to changes in the overall heat balance due to the small amount of solar radiation normally absorbed in polar regions. Whether the pollutant aerosols cause an overall warming or an overall cooling is not known.

Effects on Terrestrial Ecosystems

The first AMAP assessment described the processes involved in the acidification of arctic soils and the direct effects of sulfur dioxide, nitrogen oxides, and acidifying deposition on terrestrial ecosystems. At the time there was little empirical evidence to suggest that soil acidification was anything other than a local problem in very limited parts of the Kola Peninsula. The visible damage to the forests and tundra around and downwind of the non-ferrous metal smelters on the Kola Peninsula – one of the largest human sources of acidifying pollutants in the Arctic – was mainly attributed to the direct toxic effects of sulfur dioxide and the accumulation of toxic heavy metals in soils. The present assessment looks beyond the visible damage to the vegetation around the smelters and examines the wider impacts of the smelter emissions on terrestrial ecosystems. Again, most of the information concerns the Kola Peninsula as information for other regions is still extremely limited.

Three regions in the Arctic may be susceptible to soil acidification

The Kola Peninsula, the Taymir Peninsula, and the Chukotka region in eastern Siberia are the three areas of the Arctic with the greatest potential for soil acidification. This is due to their proximity to the major sources of atmospheric pollution within the Arctic and to the transport pathways for the emissions. The effects of acidifying pollution on the Kola Peninsula soils are reasonably well known. Much less is known about the situation in the Norilsk area (on the Taymir Peninsula) despite the very high sulfur dioxide emissions from the smelter complex at Norilsk. It is not known whether soil acidification has occurred in the Chukotka region – a part of the Arctic that may receive significant inputs of acidifying pollutants from industrial sources in China, India, and other parts of eastern Asia. More information is required about the concentra-

Vegetation damage in the vicinity of Norilsk.

JUHA KÄMÄRI

tions and deposition of air pollutants in the Chukotka region, and of possible effects on the vegetation and soil.

Acidified soils on the Kola Peninsula are mostly restricted to the areas immediately around the smelters and coincide with the areas where the vegetation has been completely destroyed. Outside the area immediately around the smelters, there is no clear evidence of soil acidification due to sulfur dioxide emissions (and subsequent deposition of acidifying compounds), despite the very high emissions of sulfur dioxide from the smelters. This lack of soil acidification is usually attributed to the neutralizing effects of fly ash emitted from the smelters and their associated power stations and to the alkaline geology of the region. Since the pattern of base cation levels in Kola Peninsula soils follows that in mosses (which collect material deposited from the air) airborne dust is probably a more important source of base cations than the bedrock. The base cations in airborne dust come from many sources: fly ash from the smelters and power plants, open-cast mining near Zapolyarnyy, and marine aerosols from the Barents Sea. The low interception of acidifying compounds by the sparse cover of coniferous trees and the low rate of conversion of sulfur dioxide to sulfuric acid in the Arctic are also important factors.

Soil acidification

The extent to which the soils become acidified depends on their buffering capacity, i.e., their ability to resist a change in pH. This is strongly related to their base cation levels.

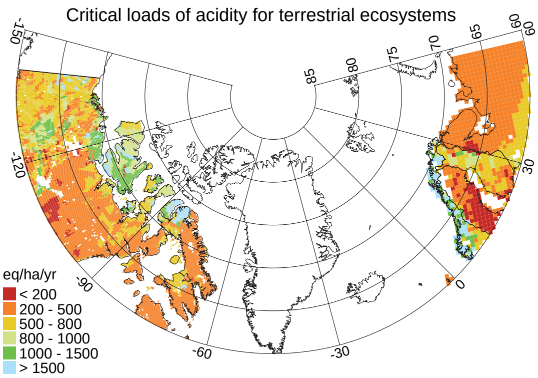
Base cations

Base cations are positively charged ions such as magnesium, sodium, potassium, and calcium that increase the pH of soils (i.e., make them less acidic) when released through mineral weathering and exchange reactions.

Around 1.8 million tonnes of sulfur dioxide are emitted each year in the Norilsk area, which is one of the largest point sources of sulfur in the world. Nevertheless, the impact of these emissions on local soil acidification appears to be less than might be expected. This is because the calcareous bedrock generates a relatively high buffering capacity in the overlying soils and so provides a degree of protection for these soils.

Long-range transport is unlikely to cause soil acidification now or in the future

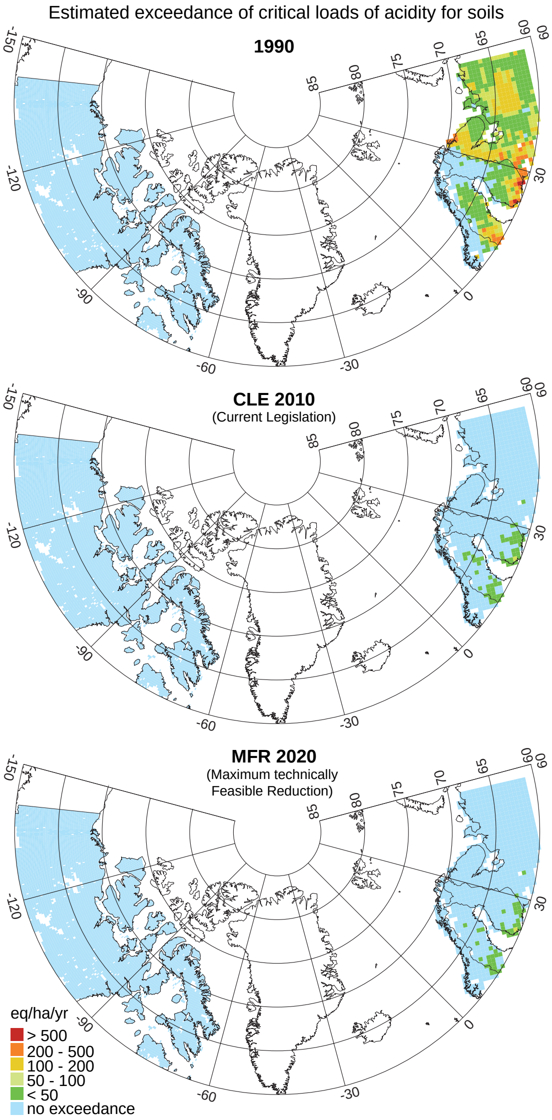
Winds from North America, Europe, and the Far East carry acidifying pollutants into the Arctic from human activities at lower latitudes, but the associated levels of sulfur and nitrogen deposition are considered unlikely to cause widespread soil acidification now or in the near future.



▸ Critical loads of acidity for terrestrial ecosystems in northern Europe and Canada north of 60º N.

Critical loads of acidity for soils may be exceeded locally, and regionally near the smelters

In northern Europe, model results using 1990 emissions data indicate that critical loads of acidity for soils were exceeded over large areas. The affected region would be considerably smaller following the implementation of currently agreed emission reduction measures (the 'CLE scenario'),



▸ Projected exceedance of the critical loads of acidity for soils for three emission/deposition scenarios: 1990 emissions data (upper), implementation of presently agreed emission reductions for the year 2010 (middle), and implementation of maximum feasible emission reductions for the year 2020 (lower).

and would almost disappear assuming the implementation of the maximum feasible emission reductions (the 'MFR scenario'). However, the critical loads of acidity and critical levels of sulfur dioxide in highly sensitive forest ecosystems are still expected to be exceeded locally and regionally near the non-ferrous metal smelters.

Critical loads of acidity for soils in Canada are not projected to be exceeded in any regions north of 60º N. The minimum critical load is about 84 eq/ha/yr and the maximum sulfur and nitrogen depositions are about 30 to 40 eq/ha/yr. Thus, not even the combined sulfur and nitrogen deposition will exceed a critical load in northern Canada.

Acidic rain and snow only occur close to the smelters

Very low rain and snowfall in much of the Arctic and subarctic means that up to 80% of the sulfur carried in the air enters the terrestrial ecosystem via the fallout of atmospheric dust particles and the direct uptake of sulfur dioxide by vegetation. Most dust and large particles emitted from the smelters deposit quite quickly close to the source. Studies show that most of the sulfur in the leaves of small tundra plants on the Barents Sea coast of northern Norway comes from sulfur-carrying dust rather than sulfur dioxide.

Sulfur dioxide, emitted as a gas from the smelters, stays airborne for longer than the dust and large particles; some, however, is washed out by precipitation causing the rain and snow to become 'acidic'. A study on the Kola Peninsula found that acidic rain and snow falls only within about 30 km of the smelters; outside this zone, lower sulfur dioxide levels and the presence of alkaline particles in the atmosphere are apparently sufficient to prevent the precipitation becoming acidic. Thus, soils affected by acidic precipitation on the Kola Peninsula are restricted to relatively small zones around the smelters. The amount of sulfur dioxide entering soils through direct contact with the surface is not known but will also contribute to soil acidity.

Nitrogen inputs may affect plant communities

Nitrogen dioxide emissions on the Kola Peninsula are low and do not contribute to making rain or snow acidic. Only very small amounts of nitrogen gases are brought into the Arctic through long-range transport from lower latitudes and their impact on terrestrial ecosystems is minimal. However, since arctic ecosystems are very sensitive they may, over the long term, show an increased abundance of fast-growing species (especially grasses) at the expense of slow-growing species (e.g., lichens and mosses).

Adverse effects on soil organisms are concentrated around the smelters

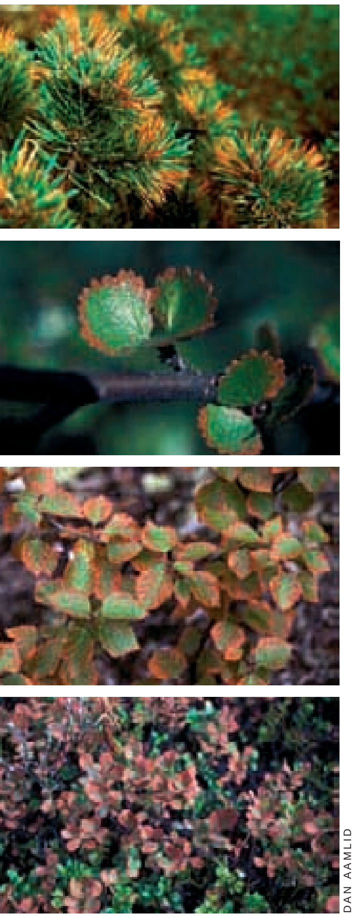
Microscopic soil organisms such as fungi help to maintain soil fertility by breaking down plant litter and other organic material. This allows the nutrients contained in this organic material to enter the soil. If the growth and activity of these soil microorganisms is decreased by pollution then the nutrient release to the soil will also decrease. Most of the negative effects on soil organisms seem to occur in the soils around the smelters. Reindeer lichens, which are particularly good at intercepting pollutants, have declined massively in the areas affected by smelter emissions and this may have contributed to the effects of air pollutants on the soil organisms there. Larger soil organisms like earthworms and millipedes also help to break down organic matter and these often disappear completely in severely polluted areas.

Vegetation damage near the Russian smelters is likely to continue

The extent of the vegetation damage in the area affected by the smelter emissions decreases with increasing distance from the smelters and roughly corresponds to a series of concentric zones: industrial barrens and the zone of forest death, and the zones of severe damage, intermediate damage,

Industrial barrens near the smelters at Monchegorsk. The toxicity of the soil prevents seedlings from establishing, leaving a bleak landscape devoid of large trees and bushes, with only small patches of vegetation surrounded by bare land.

BRYAN & CHERRY ALEXANDER



Leaf damage in pine, dwarf birch, mountain birch, and bog bilberry caused by sulfur dioxide near the Nikel smelter.

moderate damage, and minor damage. The areas affected by the smelter emissions are elongated in the direction of the prevailing winds.

There is a strong link between the visible damage to the vegetation near the smelters and the levels of sulfur dioxide in the air at ground level. Despite the continuing decrease in sulfur dioxide emissions from the Russian smelters these emissions are still having significant impacts on the vegetation: visible damage includes discoloration of birch leaves and brown tips on conifer needles, especially by the end of the growing season.

High levels of heavy metals (such as nickel and copper) in the soils around the smelters also contribute to this widespread ecosystem damage. However, because there is a strong correlation between the levels of heavy metals and sulfur dioxide and because they both result in visually similar detrimental changes in plants it is difficult to differentiate the damage that they cause. Their role is clearer in the industrial barrens, where vegetation cover declines as plants age and die but the high levels of heavy metals in the soils prevent seedlings from growing. There are also very low levels of many plant nutrients in the soils immediately around the smelters due to low organic inputs (e.g. low amounts of leaf fall) and the leaching of plant nutrients from the soil due to the atmospheric deposition of acidity and heavy metals.

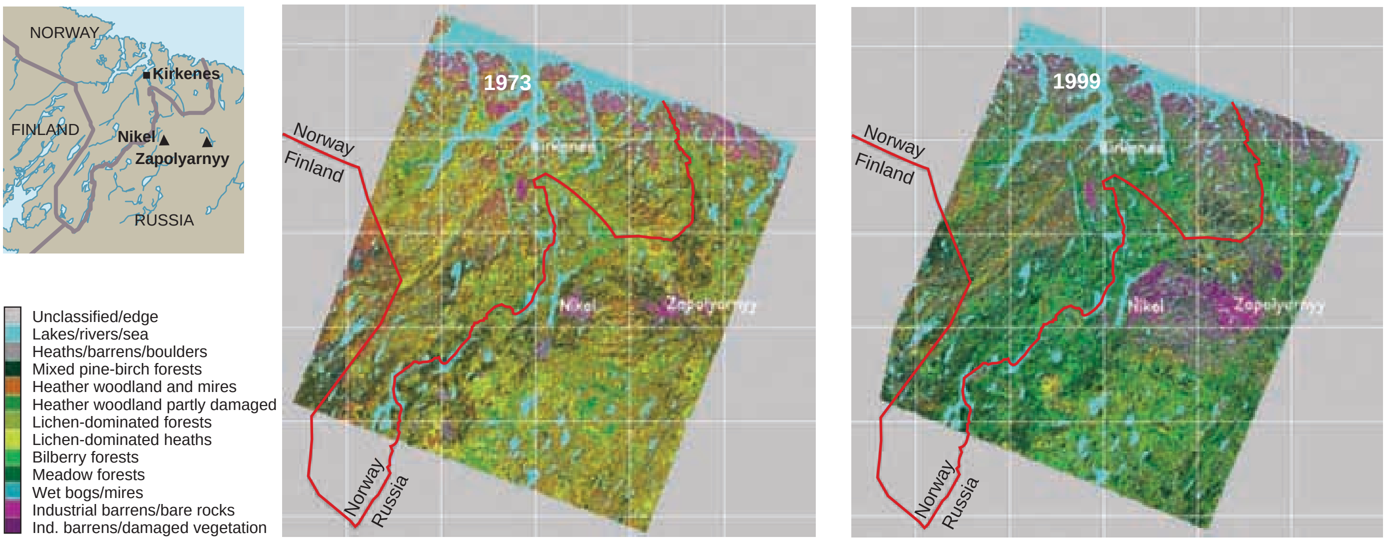
Changes in the structure of plant communities are common in polluted areas because plants differ in their ability to tolerate pollution. Lichens are particularly sensitive to sulfur dioxide and the once lichen-dominated heaths and forests in the border areas of Norway and Russia have been very badly affected. Many sensitive plants that would normally occur there, including lichens and mosses, have declined while a much smaller number of pollution-resistant plants have become more abundant. The change from the healthy lichen-dominated vegetation that predominated before 1970 to the bare rock and sparsely vegetated areas of today is greatest between 5 and 40 km from the smelters. By the 1990s, there were almost no lichens growing anywhere near the smelters. Although smelter emissions are now declining there has only been a very slight recovery. This is possibly due to a combination of lichens growing very slowly and, in northern Norway, grazing reindeer making it difficult for the lichens to re-establish.

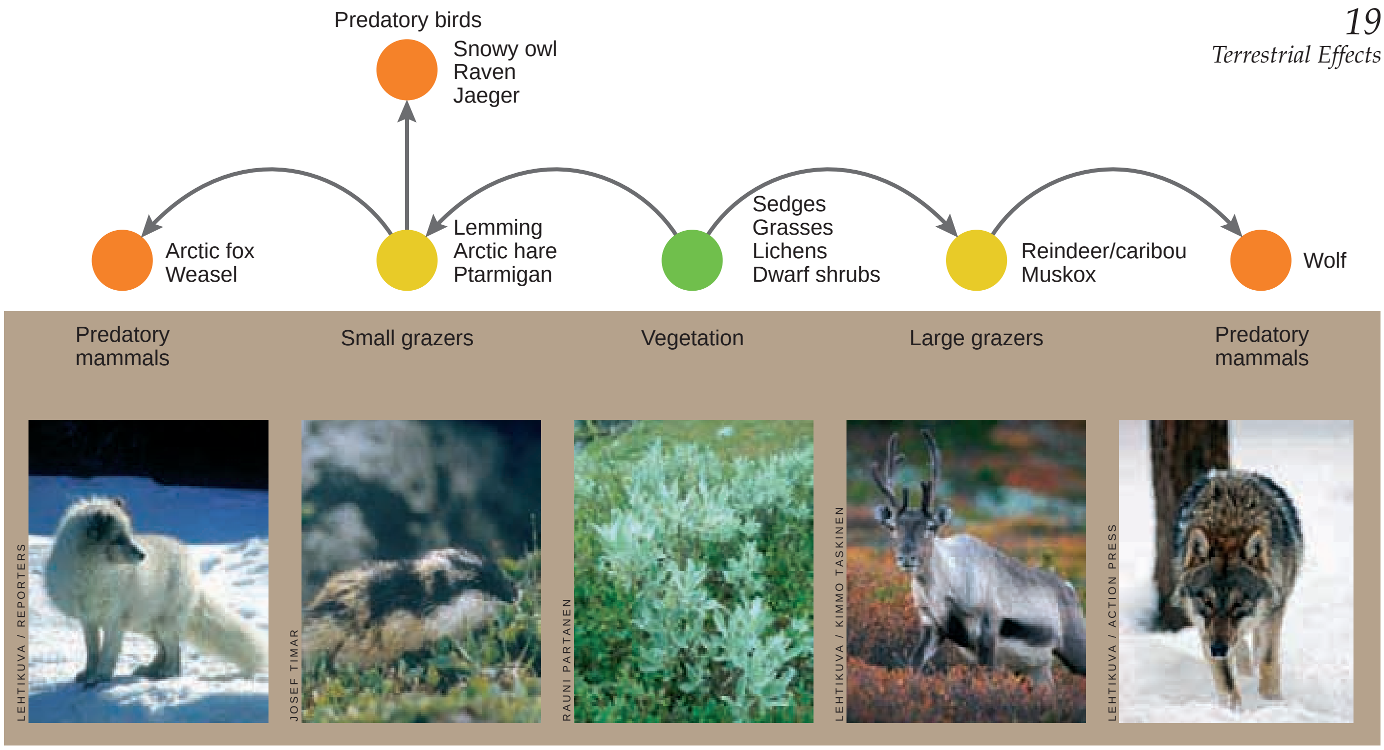
The impacts of past and continuing pollution will probably remain for many decades since arctic vegetation is both very sensitive to pollution and very slow to recover. Nevertheless, improvements are beginning to be seen, although if the most sensitive tundra plants are displaced by more tolerant forest species these changes in the plant communities may well have negative consequences for the animals that depend on them. If sulfur dioxide emissions do not increase again, the state of the vegetation around the smelters on the Kola Peninsula will probably continue to improve; but these changes will take decades and it is not clear whether the new vegetation will be the same as it was before the pollution began.

Peaks in sulfur dioxide are particularly damaging to plants

Some plants, such as mature mountain birch trees, can tolerate an increase in pollution as long as the increase is gradual. But sudden high sulfur dioxide levels can be very damaging, especially during the growing season. Sudden and unusual changes in

Land cover maps for the Pasvik-Nikel area in 1973 and 1999. The once lichen-dominated heaths and forests in the vicinity of the smelters have been replaced by more pollution resistant vegetation.





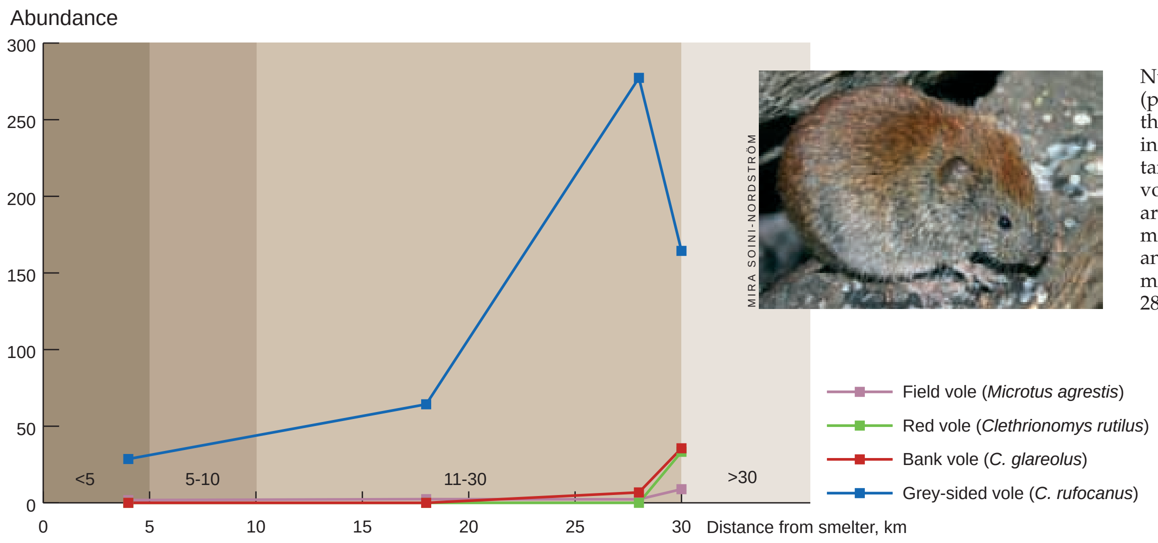
▲
Schematic representation of the terrestrial food web in the Arctic.

wind strength and direction have brought episodic pollution events that have caused visible injuries to birch leaves and Scots pine needles in an area of northeast Norway near the Russian border.

Animals are affected indirectly through changes in their habitat

The Russian smelter emissions have also had wide-ranging impacts on birds, small mammals, and invertebrates at the local scale. These impacts are mostly indirect and caused by changes in habitats. Damaged vegetation results in fewer nesting sites for birds, less cover for small mammals, fewer or poorer quality food and host plants, and changes in the ratios of predators to prey. For most species the end result of a change in habitat quality is almost always a change in population size. The arctic terrestrial food web is relatively simple and changes in population size, of key species in particular, can have follow-on impacts on other species.

Changes in most animal populations follow the different states of vegetation damage – with impacts greatest in the barrens and forest death zone and progressively less through the areas of severe, intermediate, moderate, and minor damage. However, for some species the picture is not as simple and population numbers are highest in the slightly-to-moderately polluted areas. This may be because the food plants are pollution-tolerant species that become more available in contaminated areas as competitors die-off. Some animals even prefer the



Numbers of grey-sided voles (photo) are lowest close to the Monchegorsk smelter and increase with increasing distance from the smelter. Bank vole, red vole, and field vole are effectively absent from the most severely damaged area and still only scarce at the moderately polluted area 28 km south of the smelter.

MIKHAIL KOZLOV

Lapland leaf beetle (*Chrysomela lapponica*) adult and larvae.

polluted areas. For example, Lapland leaf beetles are rare in most subarctic forests, but outbreaks sufficient to strip entire bushes have been seen near the Monchegorsk and Nikel smelters. This is probably due to the combined effects of more food (many types of willow can tolerate the highly polluted conditions near the smelters and so increase in number) and fewer predators (high sulfur dioxide levels remove many of the beetle's natural predators). Some rare moths and butterflies also thrive in the very damaged areas. The lunar hornet clearwing, which was considered extinct in Finland until very recently, appears in great numbers in the barren areas near the Monchegorsk smelter.

Most birds follow the same pattern as for small mammals and decrease in number toward the smelters, although in spring there may be more birds in the very contaminated areas close to the smelters than in the less contaminated areas further away. This is possibly because snow melts earlier near the smelters making these areas seem more attractive for food and nesting. But breeding success is often low here and many birds abandon their nests during nestbuilding or before completing the clutch. Sometimes this is due to a lack of food. As well as less successful breeding, animals are also more likely to die in these highly contaminated areas as they become less able to cope with environmental stresses such as disease, low winter temperatures, and food shortages.

Biodiversity is often lower at contaminated sites. Since the 1970s, there have been no sightings of hazel grouse, eagle owl, Tengmalm's owl, or treecreeper closer than 40 km to Monchegorsk. These are all typical subarctic species.

The lichen decline since 1970 has affected the arctic food web

Lichens are a very important part of the arctic food web. Consequently lichen damage is one of the most significant impacts of acidification in the terrestrial Arctic. Pendulous lichens are an important winter food for bank voles and a decline in these lichens has been linked to changes in the regular 3- to 5-year peaks in bank vole populations. Voles are a key species in the Arctic and changes in their dynamics can affect the many predatory birds and mammals that feed on them. The long-term decline in vole numbers near the smelters is probably due to a decrease in the availability of food and natural shelter.

The breeding success of redstart (photo), pied flycatcher, and Siberian tit, three typically abundant hole nesting species in the Arctic, is severely reduced in areas affected by emissions from the non-ferrous metal smelters.

MARKUS VARESVUO / LINTUKUVA.FI

▶
Redstart (*Phoenicurus phoenicurus*)

PAAVO HELLSTEDT

PAAVO HELLSTEDT

▶▶
Voles, especially *Microtus* voles (e.g. field vole, upper), and the red vole (lower), are key species in northern vertebrate communities.

Effects on Freshwater Ecosystems

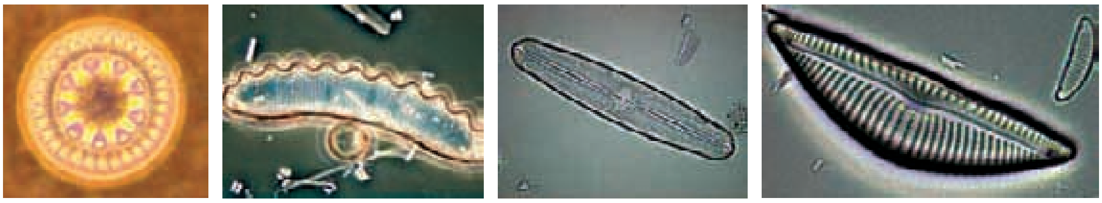
The first AMAP assessment focused on acidification of lakes and rivers in northern Fennoscandia and the Kola Peninsula. This area has been very badly affected by emissions from the non-ferrous metal smelters at Nikel, Monchegorsk, and Zapolyarnyy. Sulfate concentrations in some lakes in northern Fennoscandia in the mid-1980s were more than twice as high as in the 1960s and small mountain lakes were often very acidic. Many large lakes had little buffering capacity left. Some small lakes were too acidic to support fish. On the Kola Peninsula, acidified lakes occurred around the industrial centers and along the northern and eastern parts of the peninsula (although heavy metals were thought to be a bigger problem here than acidification). Between the mid-1980s and the early 1990s acidification stopped increasing and there were even indications of a reduction in acidification in a few lakes. This was due to decreasing sulfur emissions in Europe. Acidification of surface waters in the Canadian Arctic and Alaska was considered highly unlikely owing to the low deposition of acidifying pollutants and to the limited areas of sensitive geology.

Slow natural acidification is the underlying trend in most northern lakes

Pollutants began to arrive in the Arctic long before water quality monitoring began. So past environmental conditions are reconstructed using changes in the microscopic fossil record in lake sediments. Diatoms (a type of algae) are widely used for these reconstructions because their cell walls are abundant and preserve well in sediments. They are also excellent indicators of acidification: as a water body becomes acidified acid-sensitive species disappear and acid-tolerant species become more dominant. Diatom-based pH-reconstructions over large areas of Fennoscandia, the Kola Peninsula, the Norilsk area of Siberia, Svalbard, and the Canadian Arctic show that natural long-term acidification is a common feature in many arctic lakes. Changes in land-use and reindeer herding do not appear to have affected lake acidity over the last 1000 years.


JOHN P. SMOL


A vertical sediment core from a lake is extruded into slices which correspond to discrete time intervals. Preserved in this mud is an archive of information (such as microscopic diatoms) that can be used to interpret past environmental conditions at each 'slice' or interval.


JAN WECKSTRÖM

A characteristic feature of diatoms is their siliceous (glass) cell walls. Some are extremely beautiful and ornate.

KIRSTEN CHRISTOFFERSEN

Widespread acidification in recent times is not apparent from sediment cores

Top–bottom sediment studies using diatoms do not support the hypothesis of large-scale modern acidification in northern Sweden nor widespread acidification of arctic lakes due to sulfur pollution from the smelting and mining industries. Most lakes in northern Russia, including several within a few hundred kilometers of the large emission sources at Norilsk, are well buffered against acidification and this is reflected in their microfossil record. Diatoms and midge larvae in lake sediments from the Norilsk area have changed little since pre-industrial times and there is no evidence of widespread lake acidification. However, it could be that lake sediments do not indicate widespread acidification in recent times because many of the lakes studied are outside the areas of high deposition or are not particularly sensitive to acidification.

Sediment records

The top–bottom approach is a quick way to identify a change in acidification status since pre-industrial times. This is done by analysing two samples from each sediment core: a sample from the top of the core representing present-day conditions and a sample from lower down representing pre-industrial conditions. A comparison of the two samples shows the change since pre-industrial times.

This technique is also useful for determining the extent of lake acidification at the regional level.

Sediment cores show acidification is restricted to lakes very near the smelters

Sediment cores show recent acidification only in lakes very close to the smelters. Cores from three small acid-sensitive lakes: one 40 km west of the Nikel smelters, the second 150 km southwest of the Nikel smelters, and the third in western Lapland a long way from the smelters, show no real changes in acidity despite the high levels of acid deposition to the east. But cores from a small upland lake about 30 km from the Monchegorsk smelter do show recent acidification, with acid-tolerant diatoms becoming more abundant as general species diversity decreased. The changes began with the start of industrial development in the region. Another study near the Monchegorsk smelter found the usual midge larvae to have been replaced by species more able to tolerate toxic conditions at exactly the time that sediment metal levels started increasing. Similar studies appear to confirm that significant acidification effects on lake biology are restricted to lakes within a few tens of kilometers of the smelters.

Freshwaters vary widely in their sensitivity to acidification

The extent to which lakes can resist a change in pH and neutralize acid inputs – their buffering capacity – reflects the amount of buffering material entering from the catchment. The most important buffering materials in arctic waters are bicarbonate and organic acids.

Lake water pH

Most lakes have a pH of between 6 and 9. Acidification effects begin to appear in the lake biology below about pH 6. Low pH may be due to natural causes as well as human activities.

Freshwaters vary in their ability to withstand acid inputs and this can be determined from their water chemistry. Acid-sensitive lakes are scattered all over northern Fennoscandia and the Kola Peninsula, but are most common in the northern part of the Kola Peninsula, Norwegian coastal

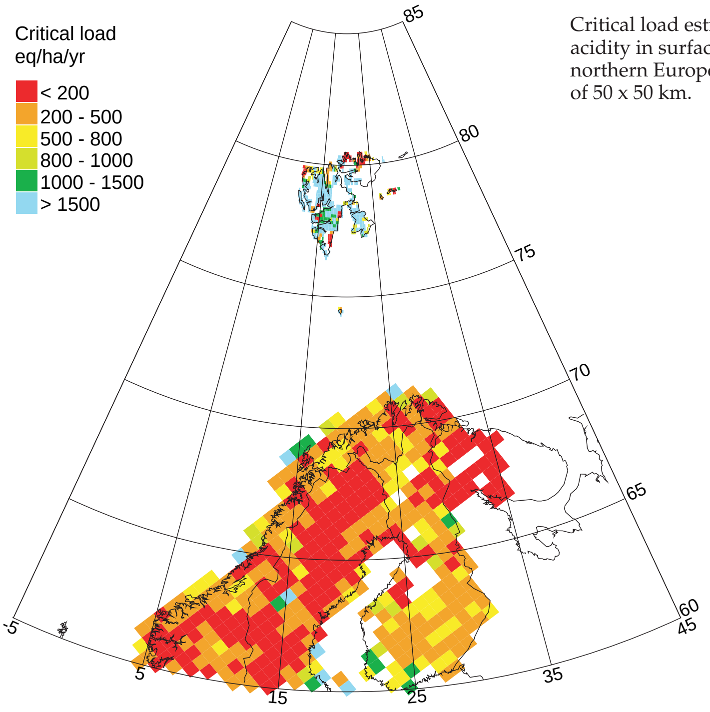
Acid sensitivity

A very acid-sensitive lake has an alkalinity of < 20 µeq/L, a moderately sensitive lake an alkalinity of 20 to 50 µeq/L, and a lake that is insensitive to acidification an alkalinity of > 200 µeq/L. The base cation concentration also indicates sensitivity to acidification. A very sensitive lake has a base cation concentration of < 100 µeq/L, a moderately sensitive lake a base cation concentration of 100 to 400 µeq/L, and a lake that is insensitive to acidification has a base cation level of > 400 µeq/L.

areas, northeastern and southern Lapland, and in the western part of Norbotten county in Sweden. Northern Norway has the highest percentage of acid-sensitive lakes, with around 40% of lakes classed as acid sensitive. Icelandic lakes are not acid sensitive, while some in northern Svalbard are very acid sensitive. Of the very few lakes in the North American Arctic that have been studied only a small number are acid sensitive and most of these are on Baffin Island or the central mainland. There is no information about the occurrence of acid-sensitive lakes in large parts of the Russian Arctic.

Critical loads for surface waters and their exceedance in the Barents region

Acidification is only a concern in areas with both high acidic deposition and sensitive geology. This means that the largest impacts on lake chemistry and biology mostly occur in small sensitive ecosystems in localized areas. Acidified areas and areas sensitive to acidification are quantified using critical loads (defined in the first box on page 2).

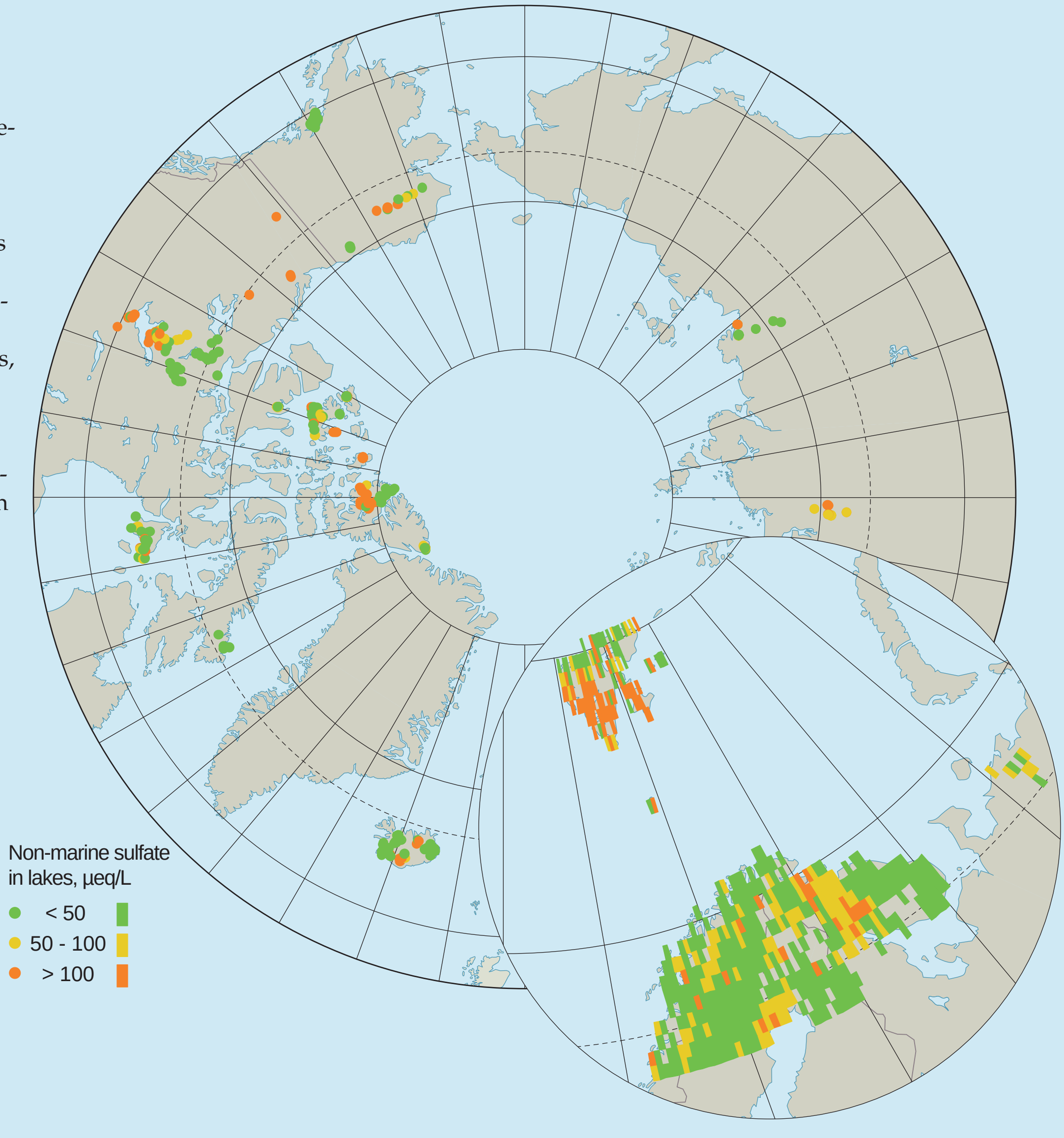


Critical load estimates for acidity in surface waters in northern Europe at a scale of 50 x 50 km.

Sulfate levels in Arctic lakes

High sulfate concentrations are common in lakes on the western part of the Kola Peninsula, particularly near the smelters in Nikel and Monchegorsk. High concentrations are also scattered around the Barents region as a whole (although some of these lakes were probably acidified by sulfate from catchment geology). Eastern Kola lakes have consistently low sulfate levels, due to low sulfur deposition.

As sulfate deposition in the Canadian Arctic is very low, the highly variable sulfate concentrations in Canadian arctic lakes show geological sources are important in many areas.



Exceedance of critical loads

The extent to which critical loads are exceeded is found by combining the critical load maps with modeled deposition data using the DEHM model system (described in the box on page 9).

Sulfate is the main acidifier of arctic lakes and streams. Nitrate concentrations are very low and probably have little impact on acidification of arctic lakes.

Critical loads of acidity for surface waters in northern Fennoscandia and the Kola Peninsula vary widely. When critical loads are exceeded acidification may occur. In 1990, critical loads for surface waters in northern Europe were exceeded almost everywhere. If the presently agreed emissions reductions are implemented it is very likely that by 2010 the area and extent of exceedance across northern Europe will be reduced substantially. It is also clear, however, that critical loads for surface waters in 2020 will still be exceeded in parts of the Kola region even if the maximum feasible emissions reductions are implemented.

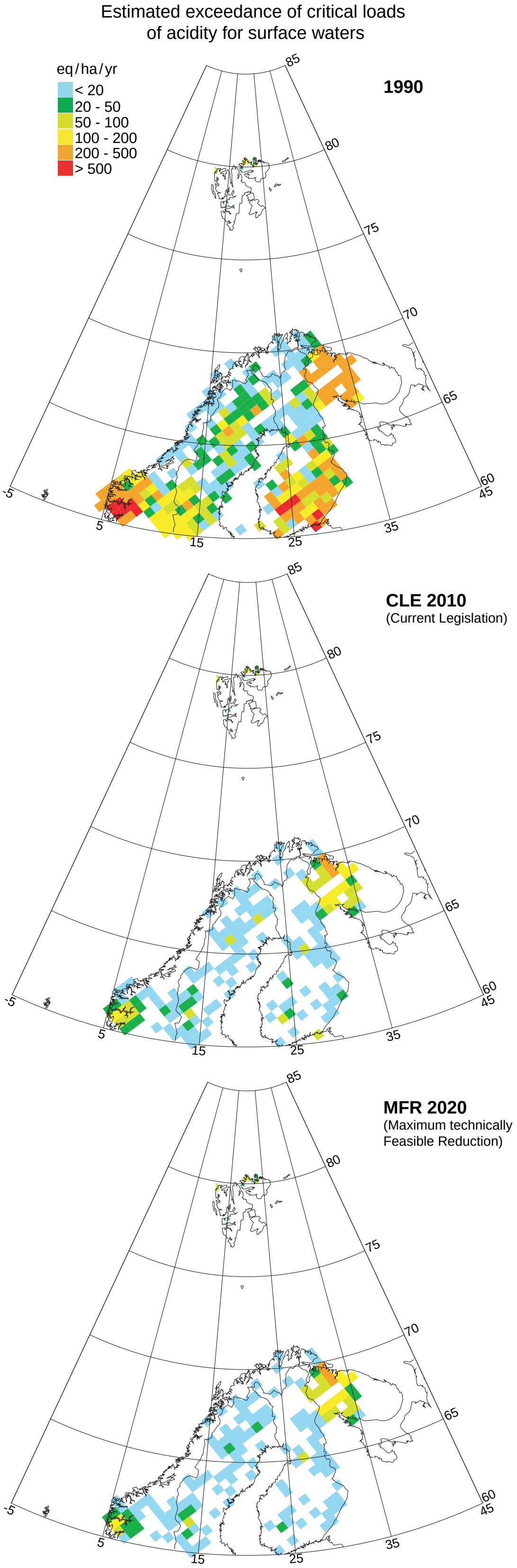
Lakes are showing regional-scale improvements in water chemistry

Long-term monitoring in the Barents region shows clear signs of regional-scale improvements in water chemistry. This is almost certainly due to the decrease in sulfur deposition over the last ten years. Lakes close to the pollution sources on the Kola Peninsula show the clearest signs of recovery.

Information on biological impacts and recovery is very limited

The potential for biological damage in acid-sensitive lakes can be predicted by calculating the acid neutralizing capacity of the water.

Most acidification studies in the Arctic focus on water chemistry. There are very few effects studies on freshwater plants and animals, except for studies of microfossils in lake sediment cores. The studies that do



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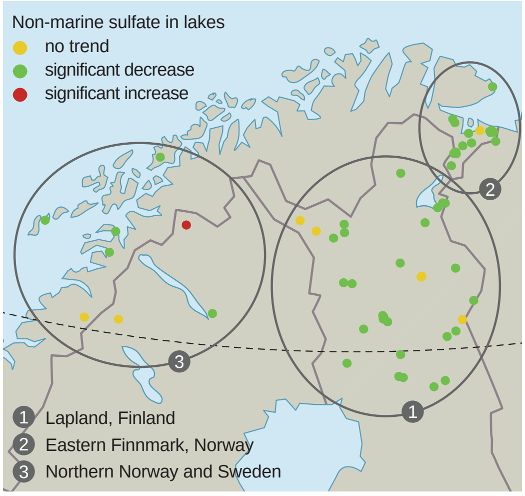
The figure shows exceedance of critical loads in surface waters for three emission/deposition scenarios: 1990 emissions data (upper), implementation of presently agreed emission reductions for the year 2010 (middle), and implementation of maximum feasible emission reductions for the year 2020 (lower).



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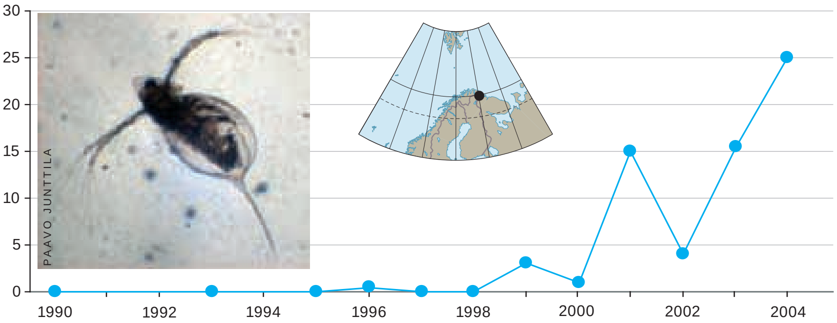
Water chemistry data from 59 lakes across Finland, Norway, and Sweden show a clear recovery in water chemistry since 1990. Sulfate levels decreased in most lakes between 1990 and 2004. The greatest decreases occurred in eastern Finnmark near the smelters. Although lakes in southern and central Lapland are more affected by inputs from long-range transport than local sources, sulfate concentrations in these lakes also decreased. The smallest decreases occurred in northern Norway and Sweden.

exist are mostly for areas of northeastern Norway and Finland that have been badly affected by emissions from the smelters on the Kola Peninsula. There is too little information to draw conclusions about biological effects on surface waters in the rest of the European Arctic. There are no biological data for any acid-sensitive areas of the North American Arctic.

Diatoms are excellent indicators of acidification and, outside the areas immediately around the smelters, there is no evidence to suggest that diatom communities are switching from acid-sensitive to acid-tolerant species in arctic lakes. Acidification effects on invertebrates living in or on the bottom sediments are rare but as acid-sensitive species are common in the Arctic the potential for future effects is high. An extensive study of midge larvae in lake sediments across Finnish Lapland showed no evidence of acidification. There is little evidence of widespread effects on fish communities in acid-sensitive parts of the Arctic.

Acidification of lakes directly downwind of point sources on the Kola Peninsula seems to be decreasing. Changes in the zooplankton community of an acid-sensitive lake in Finnmark (see figure) and in the fish populations of lakes and streams throughout northeastern Finland show a clear improvement in acidification status.

Daphnia longiremis as a percentage of the zooplankton community

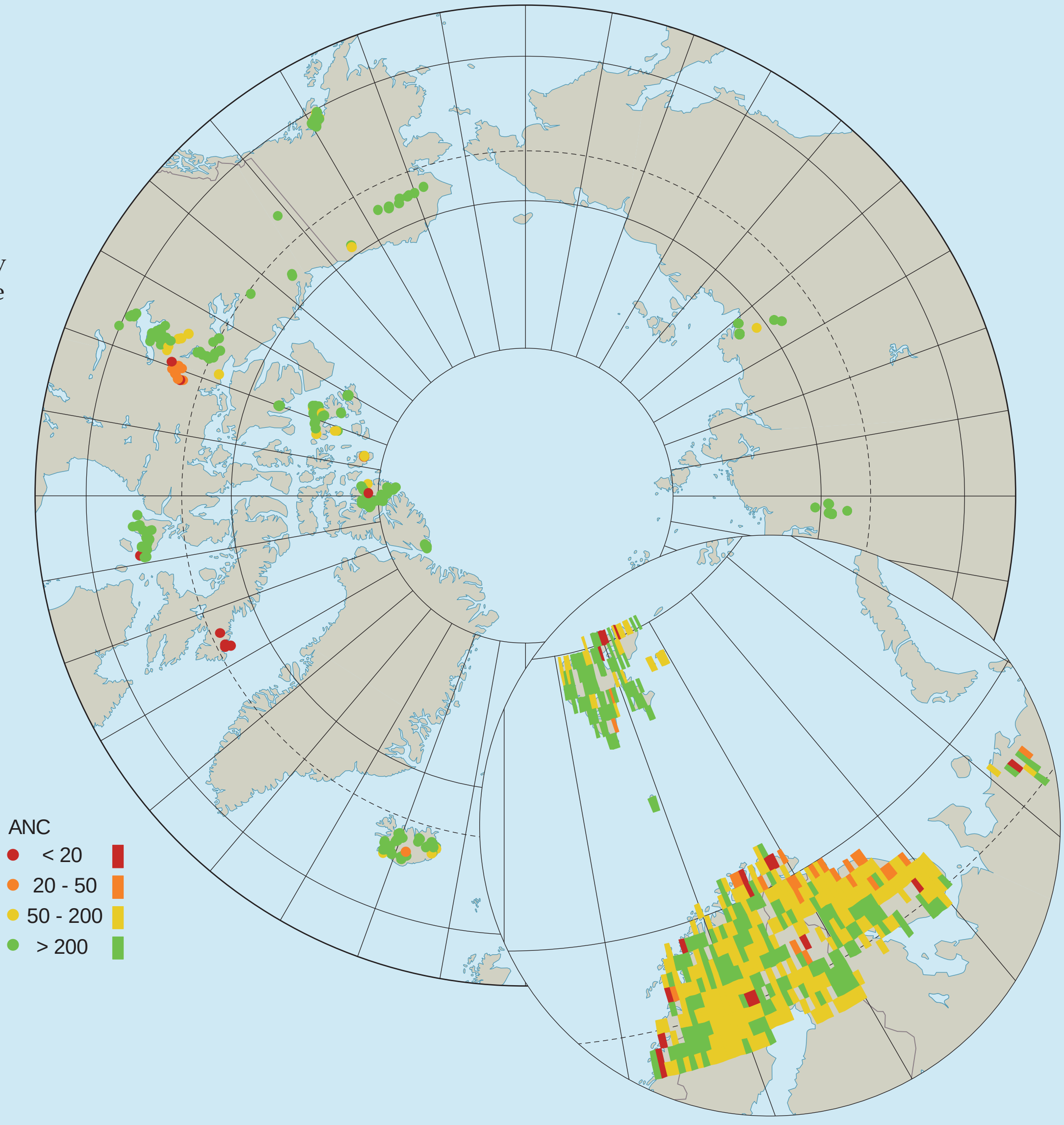


The acid-sensitive water flea *Daphnia longiremis* is not found in acidified lakes. It was first recorded in the lake Dalvatn on the Varanger Peninsula in Norway in 1995. Since then its numbers have progressively increased and it now comprises over 25% of the zooplankton community. This shows a big improvement in the acidification status of the lake.

Although changes in water chemistry suggest that the Barents region lakes are recovering from acidification, there is not enough data to show whether the biology is showing a similar recovery. But as many of the lakes that had large acidic inputs in the past were not necessarily acidified to the point where measurable damage to the biota could be observed, it might be that a biological recovery would not be seen anyway.

Acid Neutralizing Capacity

Acid Neutralizing Capacity (ANC) is a measure of the ability of the water to neutralize added acids. It is a good measure for establishing dose/response relationships between water chemistry and damage to the biological community. Waters with a low acid neutralizing capacity (< 50 µeq/L) indicate possible damage to the biota.



Freshwater ecosystems are very vulnerable to pulses of highly acidic meltwater

Pulses of very acidic water often enter freshwater ecosystems during snowmelt. Acidifying pollutants deposit from the air onto the snow and then build up during winter. When the snow melts, these pollutants are released in one big pulse during the short spring flood. This results in short periods of much lower pH than normal. On the Kola Peninsula, pH depression during spring flood is short usually lasting for no more than five to seven days.

Surface waters in areas with significant heavy metal deposition from smelter emissions, often experience simultaneous pulses of heavy metals during snow melt that can contribute an additional toxic stress. The greatest stress on freshwater biota occurs during spring flood periods, when pH is at its lowest and the concentrations of toxic forms of metals are highest. Acidic episodes have been reported from Sweden, Finland, Norway, and Russia.

Spring floods

In arctic regions, an abrupt drop in water pH in a short flood period is often accompanied by a pulse of metals. The leaching of metals during spring floods can account for up to 75% of their total annual load. Data on streams in the Kola North showed that in the periods of low pH during spring floods, the total metal concentration increased in all types of stream, despite dilution by snowmelt water.

Because episodic acidification is difficult to assess, many acidification recovery assessments have focused on changes in *average* lake conditions. However, a model able to predict pH in northern Finnish lakes from the sediment invertebrates, found the minimum pH during the short spring snowmelt to be more important for determining the general benthic community structure than the average pH. There have been several investigations of the relationship between the average pH of surface waters and pH during acidic episodes.

Many streams in northern Sweden have very acidic spring floods following snow melt. Although there has been no significant change in the average acidity of the stream water for the year as a whole, reduced sulfur dioxide emissions have caused significant improvements in water quality during spring runoff; episodic acidification decreased by between 40 and 80% during the period 1990 to 1999. A strong correlation between winter sulfate deposition and episodic acidification in northern Sweden suggests that future reductions in acid deposition will further reduce spring flood acidification in northern regions. A 65% reduction in sulfur deposition in northern Sweden between 1970 and 1990 has reduced the area of very acidic spring floods across northern Sweden by 75%.

Although large fish population losses are well documented in the most highly acidified regions of southern Norway and Sweden, there is currently little evidence of similar effects in the northern areas. A study of 13 rivers in northern Finland found no signs of acid-induced failure in salmonid reproduction and/or recruitment. Further research, focusing on the most sensitive sites and extreme conditions would be warranted to confirm these findings.

Climate change may delay recovery from acidification

The causes and effects of acidifying air pollutants are closely linked to other environmental issues. For example, climate change, the effects of heavy metals, and increasing exposure to ultraviolet radiation. The combined effects of these different stresses on ecosystems are difficult to predict and may be smaller or greater than expected. Climate change will almost certainly become a major environmental stress in the Arctic as conditions become warmer and wetter. Higher water temperatures, thawing permafrost, changes in ice cover, and higher pollution levels will all have major impacts on freshwater ecosystems.

Large-scale chemical recovery from surface water acidification in Europe and North America is widely accepted. Recovery from acidification is also clear in northern Fennoscandia. There is not enough information to draw any conclusions about recovery in the rest of the Arctic. Modeling studies based on current emissions reduction plans predict further chemical recovery. Uncertainties in these assumed reductions mainly concern the effects of climate change, including its effects on nitrogen cycling. Other uncertainties concern how the biology will respond to climate change. Present-day climatic conditions are commonly assumed in model projections, although large changes in climate are anticipated for the Arctic.

Effects on Human Health

Human health effects from air pollution in the Arctic mostly occur within the few large towns and cities. Because it is difficult to isolate the health effects of individual pollutants, researchers often consider the major groups of pollutants as 'indicators' of the mix of air pollutants present. The health effects of sulfur dioxide and acid aerosols, as well as the health effects of dust and small particles, include throat irritation and an exacerbation of cardiorespiratory diseases, including asthma.

Studies have not found any significant effects on human health of the general population that are directly associated with emissions from the non-ferrous metals smelters. In fact, human health in the Norwegian and Russian border areas that have been badly affected by emissions from the Kola Peninsula smelters seems more related to socio-economic conditions than to environmental pollution.

BRYAN & CHERRY ALEXANDER

BRYAN & CHERRY ALEXANDER

Workers in smelters are exposed to high levels of sulfur dioxide. However, studies have not found any significant health effects associated with smelter emissions in the general population in areas close to the smelters.

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