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SWEDISH ENVIRONMENTAL
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AIR & ENVIRONMENT

ARCTIC

2015

AIR QUALITY AND CLIMATE CHANGE

CONTENTS

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AIR & ENVIRONMENT

WE AFFECT THE ARCTIC. THE ARCTIC AFFECTS US.

There have always been air pollutants on Earth, but until the industrial revolution they were primarily of natural origin. For example, major volcanic eruptions and forest fires have historically had a substantial impact on the environment and the living conditions of mankind. However, with the emergence of the industrial world, we now face a very different situation, where in many cases air pollutants[1] have a very adverse impact on the environment and human health and to a much greater extent than was previously the case.

These pollutants do not remain where they are formed, but are transported by winds both regionally and globally. Until now, the Arctic has in many respects been situated a long way from the emission sources, yet it has still not escaped the effects of air pollutants. Because of its sensitive environment and extreme climate, the Arctic is particularly vulnerable to air pollutants. Such pollutants can accumulate in the environment and in the atmosphere of the polar regions and, in the case of environmental pollutants, they can also accumulate in food webs. Both the climate and the living environment can therefore be affected.

The Arctic is particularly vulnerable to climate changes. The Arctic climate is warming approximately twice as fast as the rest of the planet. Conversely, changes in the Arctic climate are also impacting on Sweden and the rest of the world.

The environmental monitoring programme monitors the state of the environment. Sweden's northerly location means that the monitoring programme also provides us with important information which can help us to understand the possible consequences for the Arctic. The Swedish Environmental Protection Agency (EPA) has been monitoring air quality in Sweden for almost 40 years. The municipalities are responsible for monitoring in urban areas, while the responsibility rests with the EPA in the regional background, i.e. rural areas. This responsibility has increased over time, particularly since Sweden joined the EU in 1995, and now encompasses the monitoring of a large number of air pollutants across the country. Since 1989, the EPA has also been involved in the funding of monitoring on Svalbard, with a growing focus on climate issues over the past twenty years. The air monitoring carried out by the EPA is managed within the framework of the national air monitoring programme. See the end of this report for more information about this.

This report aims to highlight and raise the profile of environmental monitoring, both nationally and in a wider context. Without environmental monitoring, we would be unable to monitor the processes that are taking place in the Arctic or to reverse trends which are heading in the wrong direction. International collaboration is vital, not only with regard to measures, but also as regards environmental monitoring.

We hope you will find the report both interesting and useful!
The editorial team

1 Air pollutants are solid or gaseous substances in the air which have an adverse impact on humans and the environment. Many important greenhouse gases such as carbon dioxide have no direct toxic effect on humans, plants or other organisms (in the concentrations in which they occur in the atmosphere), and are therefore not usually considered to be air pollutants. Indirectly, they are air pollutants however, as they impact on ecosystems and human health and welfare as a result of their effects on climate.

FACTS: The canary of climate change

This expression refers to the use of canaries by mine workers in the past as an indicator of how dangerous the air in the mine shafts was. If the canary reacted to the air or even died, it was time to get out of the mine shafts quickly. In a similar way, the Arctic can act as an indicator for the climate changes that are occurring.

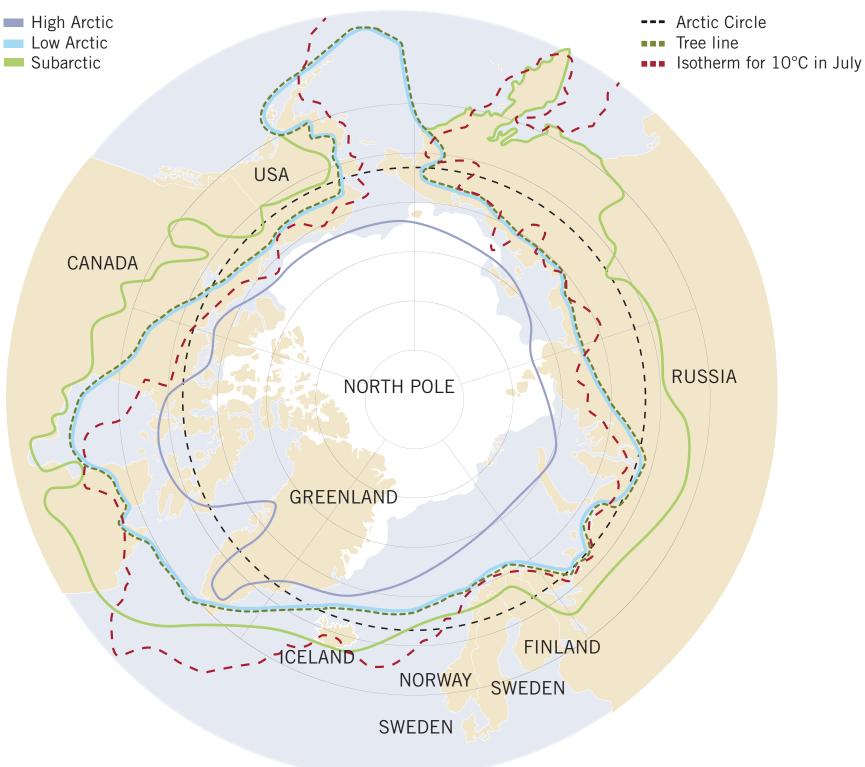
Calving glacier, Liefdefjorden, Svalbard.

PHOTOGRAPH: MARK MARISSINK

The Arctic
– the canary of climate change

The Arctic is situated far from the major population centres, yet it is still very exposed to the effects of air pollutants and greenhouse gases. Over the past 100 years, the mean temperature of the Arctic has risen by approximately twice as much as the global mean temperature. The Arctic can be considered to be the 'canary of climate change'. The major changes which are already taking place will have an increasing impact on the climate and environment elsewhere in the world. We affect the Arctic and the Arctic affects us.

The Arctic has been inhabited by indigenous peoples for thousands of years. During the 16th century, European interest in the Arctic grew, in the first instance as an easier trade route between Europe and Asia. A E Nordenskiöld's Vega expedition from 1878 to 1880 was the first to pass through the Northeast Passage, but the conclusion drawn from this expedition was that the route was unsuitable for use as a trade route. A decade later, construction of the Trans-Siberian railway began. The railway diverted thoughts away from using the Northeast Passage as a regular trade route for a long time afterwards. Some commercial shipping undoubtedly passed through the passage during the 20th century, but it was not until the ice cap began to shrink more continuously that the idea of using the Northeast Passage as a trade route began to be taken



Source: The Encyclopedia of Earth, AMAP, CAFF.

FACTS: The Arctic

Unlike Antarctica, which is a clearly defined land mass, the Arctic consists of a marine area with an ice cover of varying extent and a number of adjacent land areas. As a result, there is no clear definition of the Arctic. One common definition is that the Arctic covers all the oceans and land north of the Arctic Circle (the 66th parallel north). Another common definition is that it encompasses all areas above the tree line. Another way of defining it is that it covers all areas with a mean temperature in July not exceeding 10°C. The Arctic is sometimes also divided into the High Arctic, the Low Arctic and the Subarctic.

Under some of these definitions, Sweden is not actually in the Arctic, unlike Svalbard, where some of the EPA's environmental monitoring is carried out. In political contexts, reference is often made to "the Arctic and the Arctic States", i.e. the region north of the Arctic Circle and the eight States which belong to this region: Denmark including Greenland, Finland, Iceland, Canada, Norway, Russia, USA and Sweden. Various definitions may have been used in the articles in this report.

PHOTOGRAPH: SHUTTERSTOCK

seriously again. The possibility of also using the Northwest Passage as a trade route lies somewhat further into the future.

NEW SITUATION

The Arctic has a harsh climate and a large proportion of the region is dark for many months of the year.

Despite this, the region is attractive, partly because of its minerals deposits and energy and oil resources, but also because of the potential time gains for shipping between Europe, Asia and North America.

As the ice cover shrinks, the region becomes increasingly accessible for such activities. The proximity of the industrial world and access to energy thus makes the region both attractive and vulnerable, and many countries have developed an interest in the Arctic region (Read more on page 16).

Of the world's as yet undiscovered oil resources, only a small proportion is believed to be located in the Arctic, but the gas resources may be as much as a third. Interest in extracting the Arctic's resources and the search for new shipping routes are impacting on the environment and could threaten the natural environment and traditional lifestyles.

These activities are also having an impact on the countries around the Arctic and may also have a global effect. A number of international collaborations have been established to protect the Arctic insofar as possible and to monitor trends (Read more on page 54).

CURRENT PROBLEMS

In addition to carbon dioxide emissions, air pollutants such as particulate matter and ground-level ozone are contributing to climate change and adversely affecting the environment in the Arctic and subarctic regions. High concentrations of air pollutants and climate changes in the Arctic are for example affecting ecosystem services and threatening traditional lifestyles. The conditions for reindeer husbandry, fishing and hunting may change.

The Arctic's cold climate also contributes to the deposition and accumulation of environmental pollutants such as mercury and organic environmental pollutants in food webs. (Read more on pages 36 and 46). This particularly affects animals and people who live on fish and seal. The exploitation of oil and gas and the increase in shipping and tourism are also affecting the living conditions of people in the Arctic in different ways.

The climate changes are taking place especially quickly in the Arctic and the natural environment in the region is particularly sensitive, partly because species adapted to the cold climate cannot move further north as the temperature rises. The region is also particularly vulnerable to ocean acidification, which is also caused by our atmospheric emissions of carbon dioxide, in addition to the changes in climate (Read more on page 49).

The warming of the Arctic is affecting the rest of the world. Melting of the Greenland inland ice, together with the Antarctic ice, may result in substantial sea level rises globally. The Arctic permafrost also holds a substantial proportion of the world's carbon stocks. As the Arctic thaws, a proportion of the carbon stock is released in the form of carbon dioxide and methane, a process which can further accelerate global warming (Read more on page 27).

To slow down the climate changes that are occurring in the Arctic and globally, the most important measure is to substantially reduce emissions of greenhouse gases, particularly carbon dioxide, methane, nitrous oxide and the air pollutants (including methane) which form ground-level ozone. As regards the reduction of ground-level ozone, there is also a combined effect which will lead both to better air quality, as ozone is harmful to health and vegetation, and also to reduced climatic impact. A combination effect similarly exists with regard to the reduction of particulate soot emissions, but not for particulate sulphate, whose occurrence in the atmosphere reduces the warming (Read more on page 10).

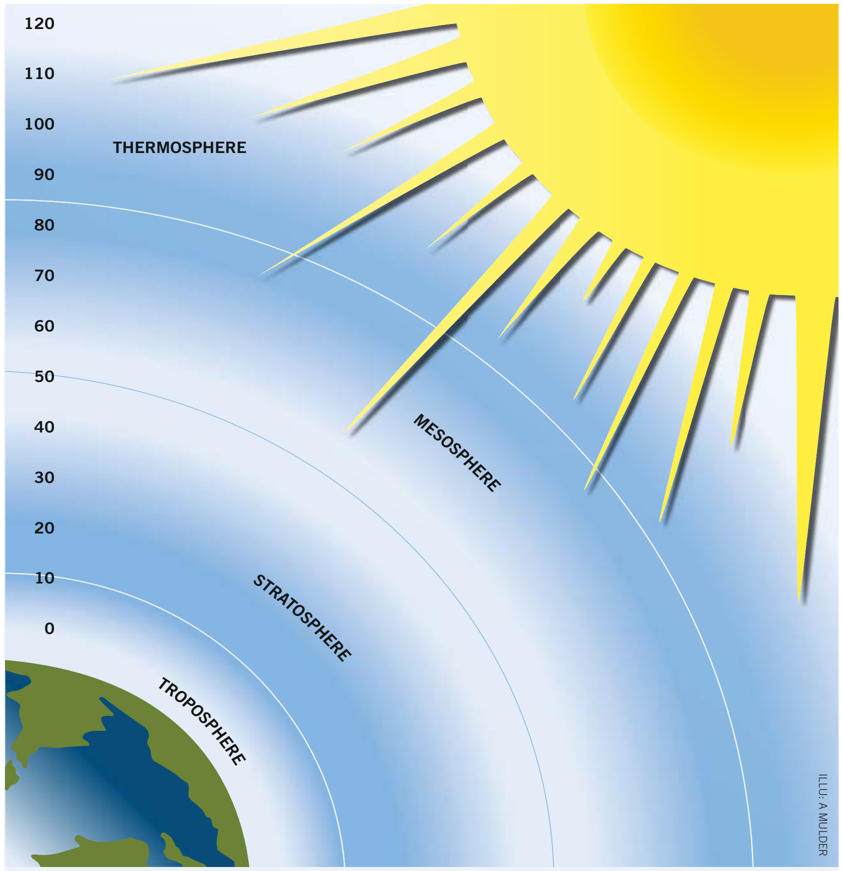
The group of substances which both impact on air quality and contribute to warming of the climate is often known as 'climate forcers' or SLCP – Short-Lived Climate Pollutants, because of their short life in the atmosphere compared with carbon dioxide, for example.

With regard to the ozone layer high up in the stratosphere, there are also complex links and interactions with other environmental problems. For example, some greenhouse gases deplete ozone, which is itself a greenhouse gas. There is also a clear interaction between the thickness of the ozone layer, the temperature of the atmosphere and global wind patterns. As far as the Arctic is concerned, however, it is the greenhouse effect itself which has the greatest impact, as ozone depletion is increasing in the cold stratosphere, which paradoxically is actually becoming colder. (Read more on page 31.)

The ozone in the stratosphere also affects the ground-level ozone, as some of the ozone in this layer can be transported down to the troposphere over the Arctic, and thereby contribute to an increase in ground-level ozone concentrations.

THE IMPORTANCE OF ENVIRONMENTAL MONITORING

Under the EPA's national air monitoring programme, a large number of air parameters are monitored in rural areas in Sweden, e.g. nitrogen and sulphur compounds, particulate matter, ground-level ozone, organic environmental pollutants, pesticides, UV radiation and the thickness of



THE VARIOUS LAYERS OF THE ATMOSPHERE (outline division)

The troposphere – a 6 to 18 km high layer, depending on where on the Earth you are. The temperature decreases with distance from the Earth's surface and is around -50°C in the upper part of the layer. The troposphere contains virtually all the water that occurs in the atmosphere and it is in this layer that what we call 'weather' happens. It is primarily in this layer that air pollutants are transported.

The stratosphere – up to an altitude of around 50 km. In the lower part of the stratosphere, the temperature is relatively constant (approx. -50°C), while in the upper part, the temperature rises to close to 0°C when ozone absorbs the sun's rays and warms the atmosphere.

The mesosphere – at an altitude of 50 – 85 km; the coldest layer with temperatures down to approx. -90°C; this layer is at its coldest during the summer.

The thermosphere – from an altitude of 85 km to several hundred kilometres out from the Earth's surface. A few tens of kilometres up, the temperature rises rapidly; how much depends on the activity of the sun. This air is very thin here and is easily heated to well over 1500°C in the upper part of the thermosphere. Source: Swedish Meteorological and Hydrological Institute (SMHI).

the ozone layer. This monitoring takes place through measurements, sampling and modelling. The programme also carries out monitoring outside Sweden, in Pallas on the border between Sweden and Finland and on Svalbard. These are our most northerly monitoring stations and are situated closest to the Arctic. (Read more on page 60.)

In addition to the air monitoring carried out by the EPA, Swedish environmental monitoring and research are also carried out under the direction of other organisations in the Arctic. A topical example is SWERUS-C3, an international research expedition involving the icebreaker Oden in the Arctic Ocean. In a Swedish-Russian-American collaboration during 2014, a total of around 80 researchers conducted research in various fields, including climate change and in particular the importance of the methane that occurs in the Arctic and how the Arctic was formed.

A fundamental motivation behind the environmental monitoring is to demonstrate the link between impact and effects in order to propose the right measures. It is also important to be able to carry out follow-up to ensure that measures and decisions are having the desired effect and to identify new disturbances. A cornerstone of Sweden's strategy for the Arctic region is to continue to improve the coordination of environmental monitoring in the Arctic.

FUTURE DEVELOPMENT

The Arctic is a unique region which has a harsh climate just like Antarctica, but it is not as isolated from the rest of the world. Unlike Antarctica, the Arctic also does not have a common protection system like the Antarctic Treaty. According to the Antarctic Treaty, Antarctica may only be used for peaceful and scientific purposes. Fifty states worldwide have acceded to the treaty. A corresponding Arctic Treaty has been discussed by the European Parliament and others, but rejected by the USA, for example, on the basis of the differences between the regions.

Sweden and other Arctic countries have developed national strategies concerning their approach to the Arctic. Common to the policy expressed in these national strategies is that the region must be stable from the perspective of security policy and characterised by environmental considerations, but other than this, the strategies differ somewhat, primarily as a result of special national interests, such as energy extraction and shipping channels. Sweden wishes to reinforce the Arctic Council both institutionally and politically by expanding its mandate to also cover issues other than the environment and climate, e.g. common security, infrastructure and social and economic development.

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PHOTOGRAPH: KJELL PETERSON

National air monitoring in Bredkälen, Jämtland County.

SUGGESTED READING:

Polar Research Secretariat
www.polar.se

Polaris – möte med världens poler
www.polarisen.se

The Antarctic Treaty. Secretariat of the Antarctic Treaty, www.ats.aq

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Sweden's strategy for the Arctic Region. Ministry for Foreign Affairs. www.regeringen.se under Publikationer

PHOTOGRAPH MARK MARISSINK

Black-legged kittiwake (Rissa tridactyla), Svalbard.

Polar bear, 14th of July Bay on Svalbard.

Polluted air is changing the Arctic climate

The Arctic's extreme climate makes the environment very sensitive to changes. In recent decades, the rate of warming of the Arctic has been two to three times that of the global temperature and the mean winter temperature on Svalbard has risen by 6°C over the past 20 years. New climate models based on environmental monitoring data have now started to give us an insight into how and why the Arctic climate is changing so rapidly. These models also show how air pollutants have affected and will continue to affect the climate in the region.

THE REASON WHY climate changes in the Arctic are taking place so rapidly compared with the rest of the world is still largely unknown. One hypothesis is that a small rise in temperature results in melting of the sea ice, which dramatically reduces the albedo (see fact box), which in turn accelerates the warming process considerably. Other observations indicate major changes in cloud cover, which increases the reflection of outgoing thermal radiation during the winter. This means that the cloud cover acts like an extra layer of thermal insulation over the Arctic in the winter and results in a higher mean temperature during the winter.

Carbon dioxide concentrations in the atmosphere are continuing to rise by about 2 ppm per year and are now above 400 ppm throughout the winter. Short-lived climate pollutants, such as soot, could be a contributory factor behind the rapid pace of climate change, but soot concentrations have actually fallen and then stabilised over the past decade.

Concentrations of air pollutants in the Arctic are generally low and most pollutants originate from sources thousands of kilometres away. They primarily consist of airborne particulate matter, often sulphates, organic pollutants and soot, frequently mixed together in a single particle.

In addition to the fact that the particulate matter transports pollutants which are deposited in and affect the Arctic environment, the Arctic climate is also affected, but in a different way than at lower latitudes.

FACTS: Albedo

Albedo is an indication of reflectivity or the proportion of radiation that is reflected by an illuminated body. The more ice that melts, the more reflection decreases, as pale surfaces are replaced by darker surfaces, which increases the warming even more.

Change in seasonal mean temperatures, Svalbard

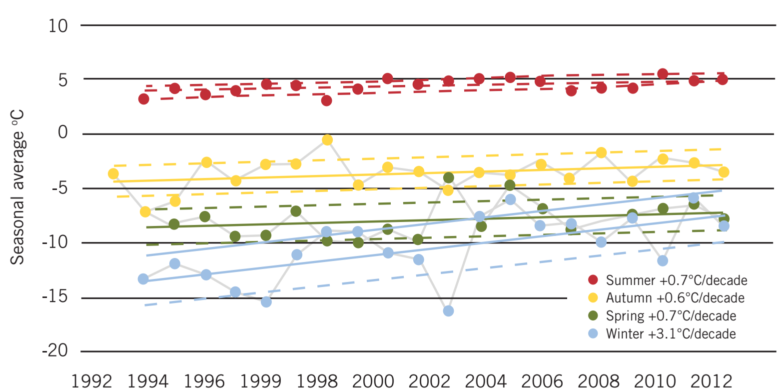

FIGURE 1. Change in seasonal mean temperatures measured in Ny-Ålesund, Svalbard. Source: Maturilli et al., 2014.

Concentrations of carbon dioxide in the atmosphere, annual mean values 1989 – 2014

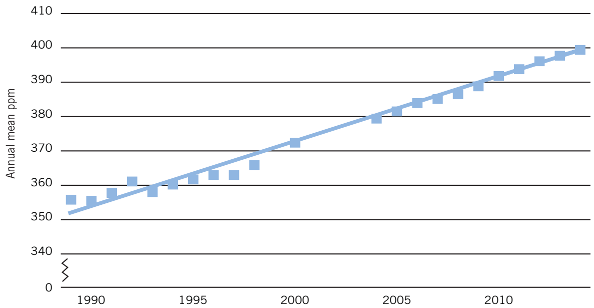

FIGURE 2. Annual mean values of carbon dioxide concentrations at the Zeppelin research station, Ny-Ålesund, Svalbard. Source: Aces, Stockholm University within the environmental monitoring programme

Particulate matter size and quantity. Svalbard 2000-2010

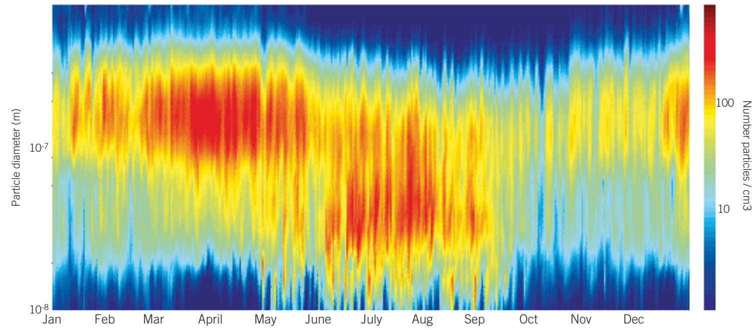

FIGURE 3. Airborne particulate matter and its size and quantity distributions. Mean of day concentrations measured at the Zeppelin research station. Ny-Ålesund, Svalbard, March 2000 – December 2010. Source: Tunved et al., 2013.

TRENDS IN THE ARCTIC CLIMATE

Measurements taken in Ny-Ålesund on Svalbard since 1992 indicate that the annual mean temperature has risen by an average of 1.3°C per decade. The winter mean temperature has increased by 3.1°C per decade – a dramatic change in the Arctic climate (see Figure 1). The reason for these substantial changes compared with the global temperature change is as yet unclear.

RISING CARBON DIOXIDE CONCENTRATIONS

With funding from the EPA and others, Stockholm University has been measuring carbon dioxide concentrations at the Zeppelin research station in Ny-Ålesund on Svalbard since 1989. In 2013, winter concentrations passed the 400 ppm mark. The increase has stabilised at around 0.5 percent or 2 ppm per year and during 2015 the mean value will pass 400 ppm (see Figure 2).

Carbon dioxide concentrations on Svalbard follow concentrations at other measuring stations, such as on Mauna Loa on Hawaii, which has the world's longest data series for atmospheric carbon dioxide concentrations. That the concentrations follow the same trend is down to the fact that carbon dioxide is a long-lived, and therefore well-mixed, gas in the atmosphere. Concentrations

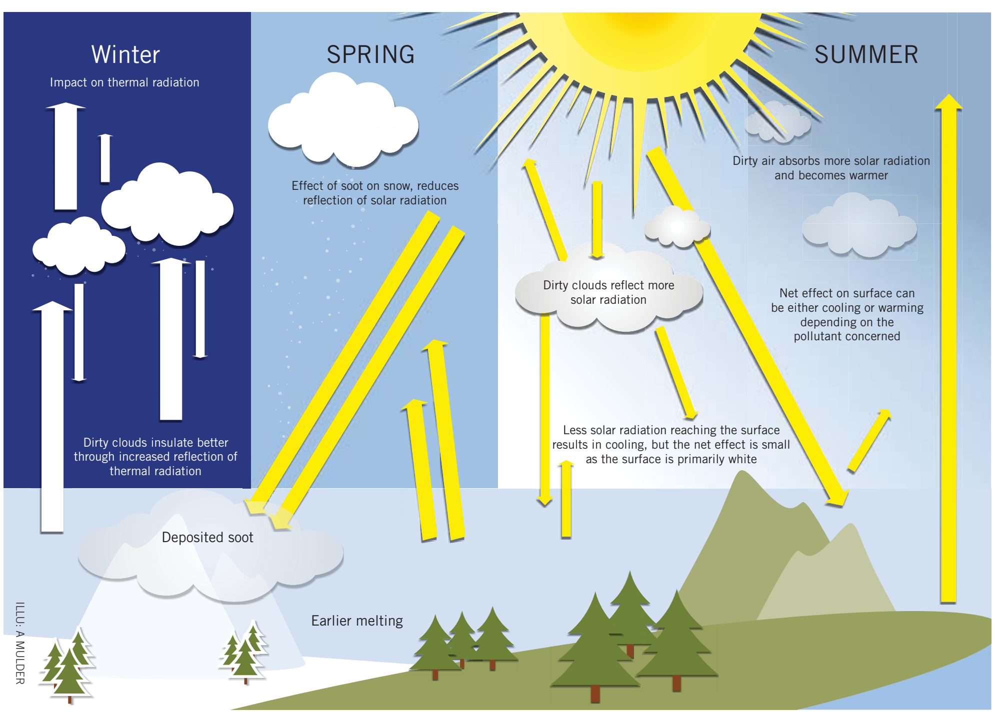

FIGURE 4. Aerosols, including soot, affect the Arctic climate. The figure shows the various climate-changing atmospheric processes which occur in the Arctic at different times of the year Source: AMAP, 2011.

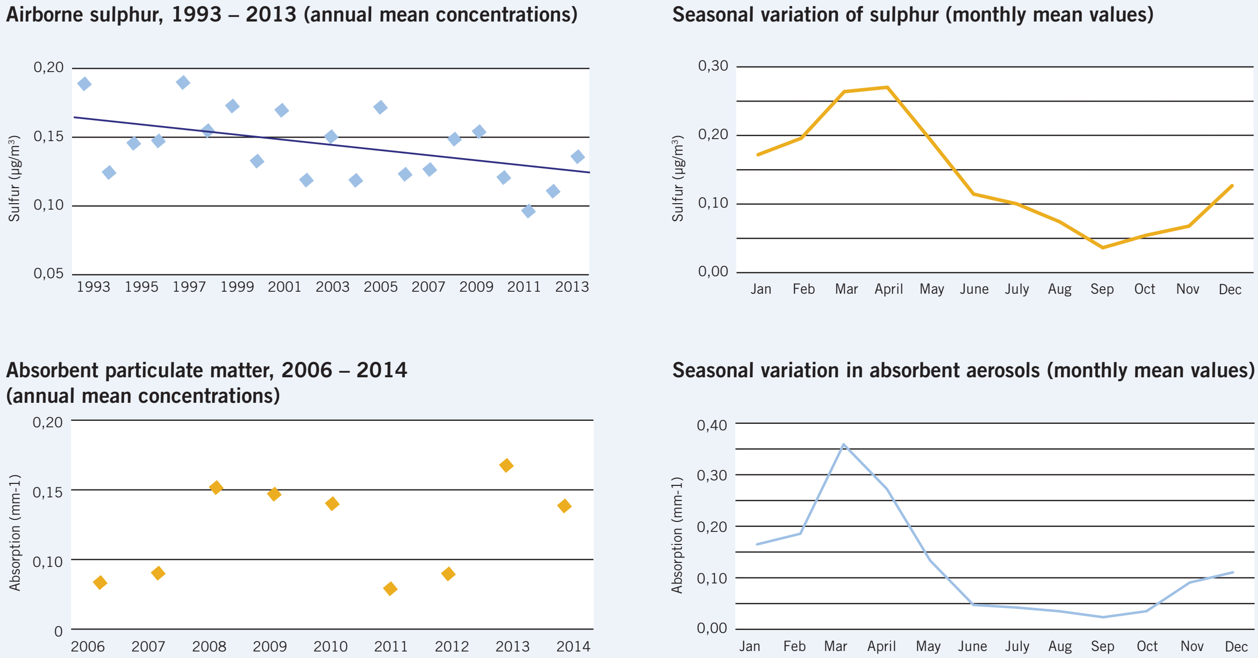

FIGURE 5. Concentrations of particulate sulphur and soot measured at the Zeppelin research station in Ny-Ålesund on Svalbard
Source: EBAS, NILU and Stockholm University.

on Svalbard are somewhat higher compared with Mauna Loa, as the measurements are taken further north and at a lower height above sea level, but the trend is the same.

HIGH CONCENTRATIONS ARE RESULTING IN ARCTIC HAZE

In the most northerly parts of the Arctic, there is total darkness for about four months of the winter. The length of the days then increases to 24 hours in about two months and the midnight sun then lasts for about four months, followed by a two month-long autumn. When the spring arrives and the temperature rises, large quantities of warm air are transported northwards to the Arctic from Northern Eurasia, particularly Central Europe, which usually results in some cloud formation. There is no precipitation here either. This makes the transport of air pollutants very effective and leads to very high concentrations of air pollutants in the Arctic. This phenomenon has been observed since the 1950s and is known as 'Arctic Haze'. This yellowy brown haze primarily contains particulate sulphur and soot.

During the summer, the particulate mass in the air is very low and largely only originates from local sources, as there are very few occasions when long-distance transport takes place. In addition, the deposition of particulate matter is high as a result of increased precipitation in the Arctic, which further reduces particulate concentrations in the Arctic. In the autumn, long-distance transport gradually increases and precipitation decreases, thereby resulting in an increase in concentrations in the atmosphere.

This is clearly apparent from measurements of the particulate matter and its size distribution (see Figure 3). During the winter and spring, there are many large particles. As the particulate matter is being transported over long distances, gases condense onto them, so increasing their size. During the summer, the number of particles remains approximately the same, but they are only a quarter of the size compared with the rest of the year, which results in a considerably lower particulate mass during the summer. The size difference indicates that the particulate matter is newly formed in the summer and older in the winter.
The substantial seasonal variations and the generally white land surface in the Arctic means that local climates are affected in a unique way (see Figure 4). The cloud cover during the winter insulates the ground surface by reflecting outgoing thermal radiation, which leads to higher winter temperatures.

With the Arctic Haze during the spring, the reflection of solar radiation by the cloud cover and ground surface changes. Particulate soot on the white surface of the snow has been put forward as an important factor behind increased melting. The dark particulate soot causes the sun's

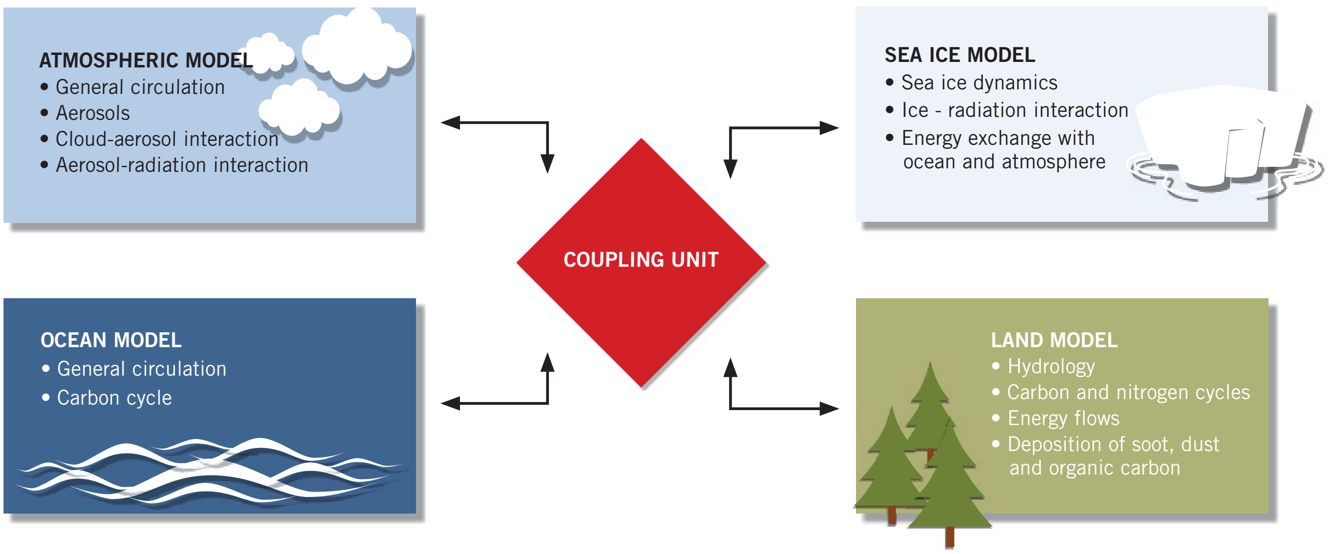

FIGURE 6. Description of the model components in the Norwegian Earth System model NorESM. Source: Kirkevåg et al., 2013.

rays to be absorbed more readily, rather than reflected.

This causes the snow and ice to melt even faster. Overall, these processes result in faster warming, with rising concentrations of particulate matter, regardless of chemical composition, during the winter, while light-dispersing particulate matter such as sulphur cause cooling, and absorbent particulate matter such as soot cause warming during the summer.

SULPHATE AND SOOT TRENDS

Arctic Haze is clearly apparent in the seasonal variation of sulphate and soot concentrations (see Figure 5). Concentrations during the spring (April-May) are almost ten times higher than during the late summer. However, sulphur concentrations during Arctic Haze have fallen by around 25 percent since 1993, although they have not changed significantly over the past decade. The latter trend also applies to soot and it is therefore unlikely that the climatic impact of the particulate matter has changed, at least not during the past ten years.

MODELS OF THE CLIMATIC IMPACT OF AIR POLLUTANTS

The specific meteorology of the Arctic and the limited number of observation sites make it difficult to model the transport and concentrations of air pollutants, and there fore how they impact on the Arctic

Modelled relationship between reduced sulphur emissions and temperature, 1980 – 2005

Measured temperature increase +2.6°C, Zeppelin station, Svalbard

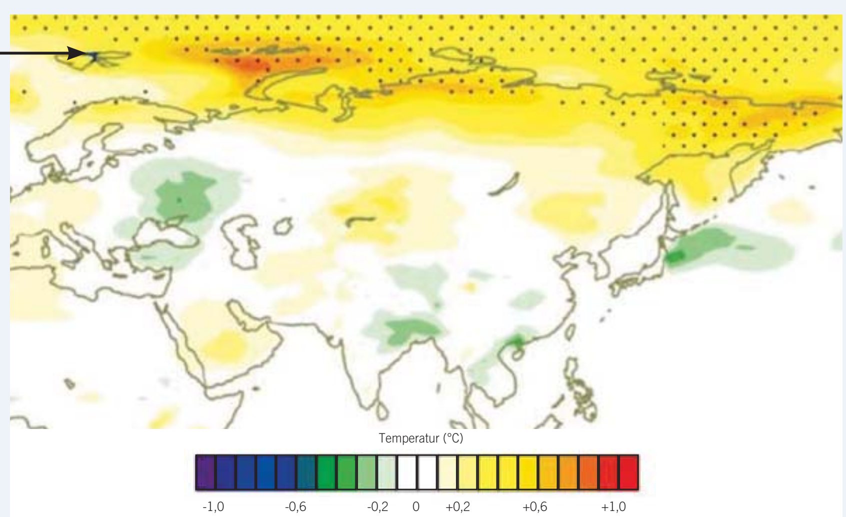

FIGURE 7. The figure shows simulations using the Earth System model NorESM of how reduced sulphur emissions have contributed to the change in temperature. The map shows the modelled temperature changes during the period 1980 – 2005. The temperature change is only significant within the dotted area. The temperature change during the same period in Ny-Ålesund-Svalbard is +2.6°C. Source: Acosta & Varma et al., 2015.

climate. The Arctic climate is also strongly dependent on the transport of heat from the south. The heat is carried on ocean and air currents, changes in which are caused by climate changes elsewhere in the northern hemisphere, which in turn can be the result of climate forcers outside the Arctic. To attempt to show how all these various processes impact on the Arctic, global 'Earth System models' are needed. These models link together the oceans, atmosphere, land and ecosystems and how they affect and are affected by climate in order to provide as complete a description of the climate system as possible (see Figure 6). The aim is a more accurate description of the climate, which will enable more accurate forecasts of future climate developments.

HISTORICAL AND FUTURE IMPACTS

Since the 1980s, sulphur emissions from Europe have fallen by about 80 percent. This development has had a substantial impact on sulphate concentrations across Europe and the Arctic. Sulphur emissions have also risen elsewhere in the world, particularly China. However, the global load of sulphur in the atmosphere has fallen by around 25 percent overall since 1980. Particulate sulphur generally has a cooling effect on the atmosphere. NorESM calculations show that the decreasing sulphur emissions have probably contributed to warming of the Arctic by about 0.5 (see Figure 7). However, as Figure 1 shows, the Arctic is warming at a much faster rate, most likely as a result of rising carbon dioxide concentrations.

Particulate soot is often considered to be a factor in to the rapid pace of climate change in the Arctic, but simulations using NorESM and other models show that the occurrence of particulate soot only has a relatively small impact compared with sulphur. These findings differ from those of previous models, but our understanding of the impact of particulate soot on the Arctic climate is still insufficient to draw any certain conclusions concerning their actual impact on the climate.

Today's models all indicate that European emissions of particulate matter have an impact on the climate, particularly in the Arctic, while the impact in the emissions area itself is relatively modest, particularly in Eastern Europe. This is probably because the air pollutants are changing the radiation balance, i.e. the sum of incoming and outgoing radiation. This process is impacting on entire weather systems, increasing the transport of heat to the Arctic, which in turn is limiting climate change in Europe. Air pollutants in Europe therefore have an indirect impact on the climate in the Arctic. A substantial global reduction in emissions through the introduction of the best possible technology in accordance with IIASA's "Maximum Feasible Reduction" scenario, entailing a reduction of around 70 – 80 percent of emissions of sulphur, particulate matter and particulate matter-forming gases, would probably result in further warming of around 1°C in the Arctic. However, it should be noted that the increase in carbon dioxide alone will result in warming equivalent to at least 3°C in the Arctic.

AIR POLLUTANTS NOT DECISIVE

Climate changes cannot be stopped by reducing air pollutants. Model simulations undoubtedly show that substantial reductions in emissions can have a significant impact on the climate in certain regions, but carbon dioxide emissions are set to completely dominate climate change in the future. This will be the case even if such emissions are limited to ensure that the 2°C target for global warming is not exceeded.

Modelling climate changes is very complicated. The monitoring of climate-changing key parameters is absolutely vital to enable the development and evaluation of the models in a way which enables future developments in the Arctic climate to be predicted with sufficient accuracy.

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Stockholm University's measurements of air pollutants in the Arctic: www.aces.su.se/zeppelin

Norwegian Institute for Air Research: www.nilu.no

Database: ebas.nilu.no

Accessibility and pressure increasing in the Arctic

The impact of climate changes is clearly apparent in the Arctic, where the ice is melting and shrinking. As the ice shrinks, it becomes easier to shipping to reach new locations for oil and mineral extraction, and new shipping routes between Europe, Asia and North America open up. The increased exploitation of the Arctic would have a further negative impact on the climate and atmosphere, particularly as a result of higher carbon dioxide emissions.

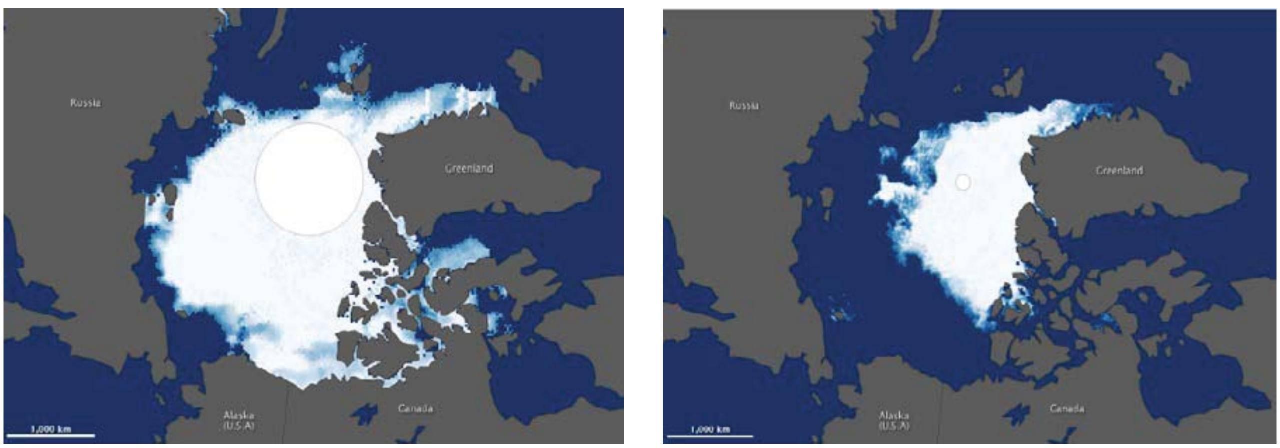


FIGURE 1. Extent of the ice in September 1984 compared with September 2014. Source: Smith & Stephenson, New Trans-Arctic shipping routes navigable by midcentury, 2013.

The Arctic is a vulnerable region and is affected by the global warming which is causing the sea ice to melt. It is the extent of the summer ice in particular which is shrinking. Photographs of the summer ice taken at 20-year intervals show a substantial reduction in the ice cover.

Since 1979, the extent of the summer ice has decreased by about 40 percent; the ice has also continually become both thinner and younger. However, the extent of the winter ice has only decreased by about 8 percent. Figure 2 shows the reductions in the winter ice (March) and summer ice (September) respectively during the period 1979 – 2014.

FUTURE EXPLOITATION A THREAT

A high proportion of the world's oil and natural gas resources can be found in the Arctic region. Ten percent of the world's oil production and 25 percent of global natural gas production already take place in the region. The majority is extracted from coastal areas in Russia and Alaska (see map). Locations far from the coast have been difficult to reach, as the sea ice not only prevents transport but is also hazardous for vessels which are carrying oil. Floating ice and ice bergs can cause substantial damage. The shrinking ice cover in the Arctic in recent years has opened up new shipping channels, making it possible to discover previously unexplored natural resources.

Together with improved technology for oil extraction, this opens up new opportunities for explorers, and many oil companies are planning to expand their operations in the Arctic over the coming years. However, falling oil prices mean that the situation is uncertain at present and many oil companies are therefore awaiting

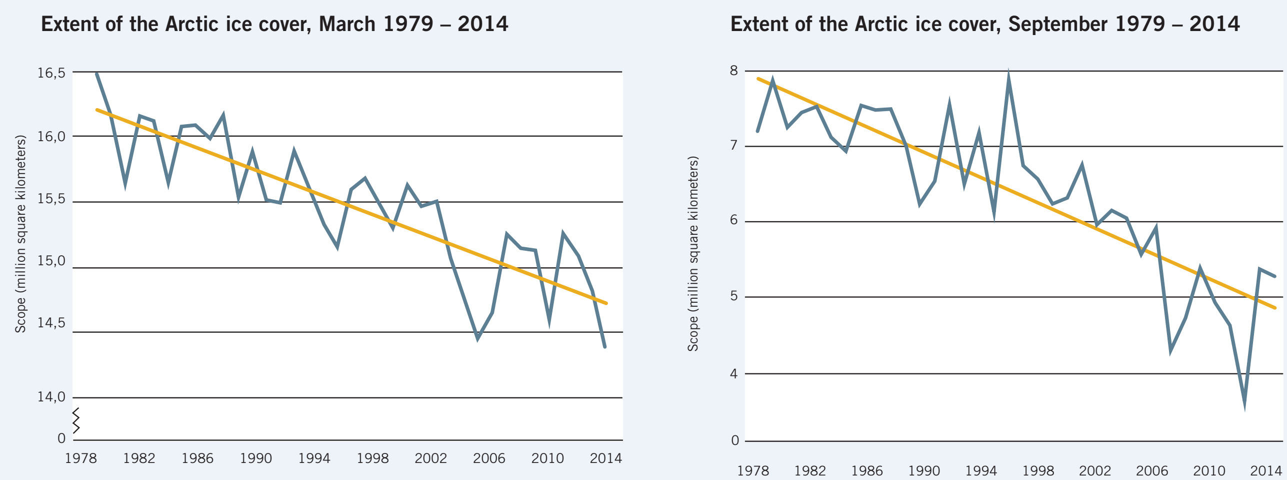
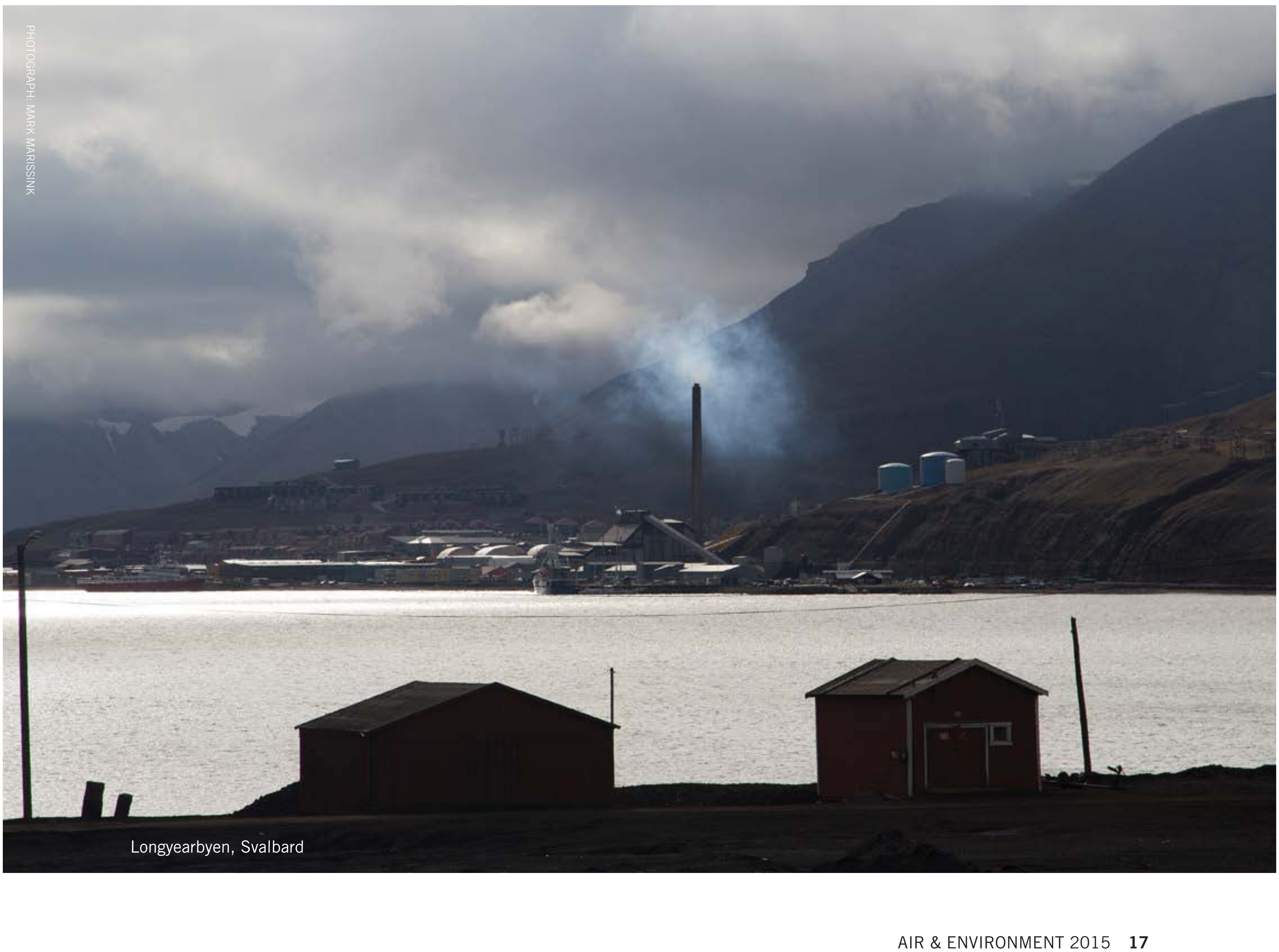


FIGURE 2. Reduction in the ice cover during the period 1979 – 2014 for March and September. Source: nsidc.org/arcticseaicenews.



PHOTOGRAPH: MARK MARISSINK

Longyearbyen, Svalbard

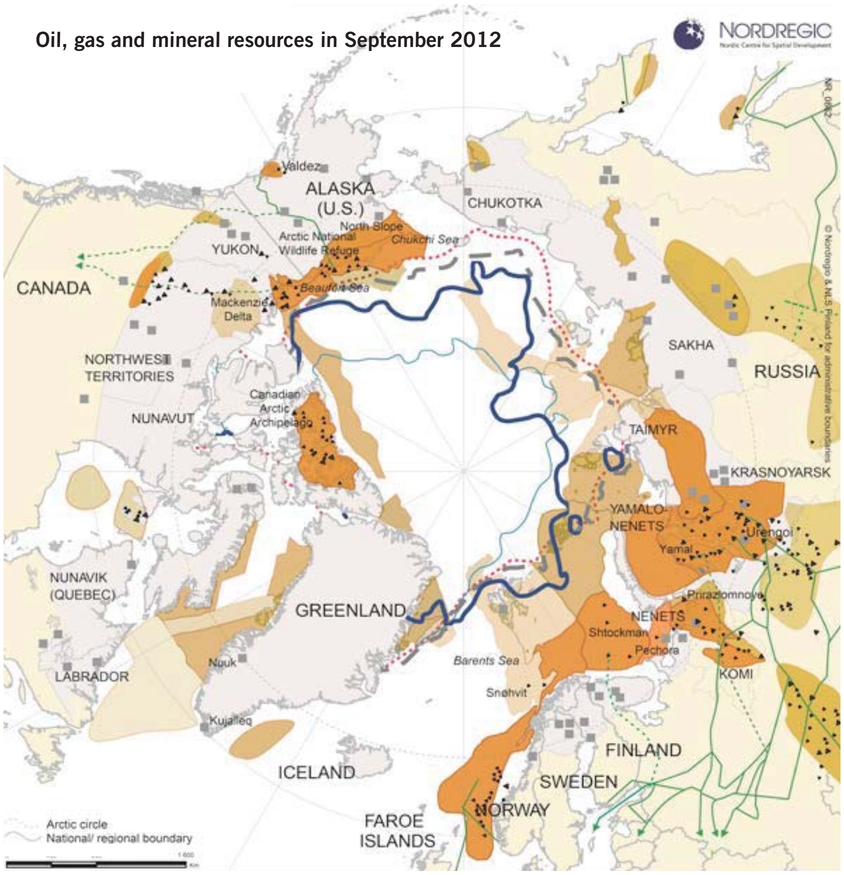


FIGURE 3. Principal locations for extraction of oil, gas and minerals, and possible development sites. Source: www.nordregio.se

further developments before acting.

It is also clear that more oil extraction in sensitive Arctic environments will have a major environmental impact on the oceans, the land and the air. There are also risks associated with oil spills which could have catastrophic consequences, as oil degrades much more slowly in the low temperatures and clean-up operations are hampered by the harsh climate.

TEMPTING MINERAL RICHES

The Arctic is also very rich in minerals and sees the extraction of 40 percent of the world's palladium, 25 percent of the world's diamonds, 15 percent of the world's platinum and 10 percent of the world's apatite and tungsten. There is also a lot of zinc, lead and chromium. Mineral extraction has become much easier because of the shrinking of the sea ice. It has also become both easier and cheaper to transport the minerals to market, which could encourage further mineral extraction.

It is not just because of developments within oil and mineral extraction that shipping in the Arctic has increased; tourism is also generating more shipping. There are strong driving forces in the region for the expansion of shipping in the waters which now remain navigable over a longer season.

NEW SHIPPING CHANNELS A REALITY

There are now two possible shipping channels in the Arctic, one via the Northeast Passage, which extends past Norway, Russia and Alaska, and one via the Northwest Passage, extends past Canada and Alaska. There is also interest in sailing directly over the North Pole, via the central Arctic Ocean route, in the future. The Northeast Passage is the most attractive route for shipping today, partly because of better ice conditions and the infrastructure left behind after the Soviet period, which includes nuclear-powered ice breakers.

The Northwest Passage has more problems with ice and inferior infrastructure for shipping, and there is also no clear political view as to how the passage should be developed.

Based on the estimated rate of shrinking of the summer ice, both the Northwest Passage and the route over the North Pole will be navigable by the middle of this century. The maps show current shipping channels and the channels which are expected to be navigable by the middle of the 21st century.

GREENHOUSE GAS EMISSIONS SET TO RISE

As mentioned previously, the increase in oil and mineral extraction and more shipping in the Arctic are

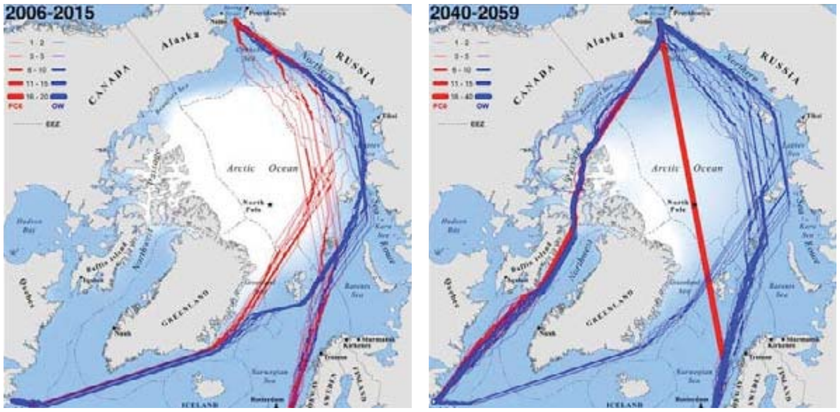


FIGURE 4. Shipping channels today compared with probable shipping channels in the mid-21st century. Source: Smith & Stephenson, New Trans-Arctic shipping routes navigable by midcentury, 2013.

having an adverse impact on the atmosphere in both the Arctic and elsewhere. Increases in the production and use of many hydrocarbon resources, such as oil and natural gas, is giving rise to more emissions of greenhouse gases and making it harder to achieve the so-called '2°C target'. This target is based on the EU's common climate policy and means that global warming will be limited to less than 2°C compared with the pre-industrial age. Since 2010, the 2°C target has been a globally agreed target. If global emissions start to fall by no later than 2020, the 2°C target can be achieved by 2050, but a high proportion of the world's fossil hydrocarbon resources will then have to be left unutilised.

THE ARCTIC ATMOSPHERE IS POLLUTED

During drilling for oil, gas is often released up through the borehole and, as such drilling often takes place far from a location where the gas could be used as fuel, it is combusted directly on-site instead. This process is called 'gas flaring' and gives rise to substantial emissions of air pollutants, such as carbon dioxide, soot and sometimes unburned methane.

Shipping traffic is also a source of pollutants. Exhaust gas emissions from vessels contain a wide variety of gases and particulate matter, which in their original form and through reactions with other substances can affect the quality of the air, and in turn both the environment and human health, in many different ways.

Carbon dioxide, nitrous oxide and methane are some of the greenhouse gases discharged during gas flaring and by shipping. Sulphur and nitrogen oxides, which are discharged by shipping in particular, form particulate matter which affects cloud formation, a phenomenon that is known to contribute to the climate changes occurring in the Arctic atmosphere. When soot (black particulate carbon) from gas flaring and exhaust fumes from vessels are deposited on the snow, they absorb more sunlight than the clean snow, so accelerating the melting process. Carbon dioxide, a long-lived greenhouse gas, allow the sun's shortwave rays to pass through, but absorbs the longwave rays. This has a strong warming effect on the atmosphere, and carbon dioxide also contributes to ocean acidification (Read more on pages 10 and 49).

ENVIRONMENTAL POLLUTANTS ARE TRANSPORTED A LONG WAY

The Arctic region is already exposed to many organic environmental pollutants and heavy metals, particularly mercury. These pollutants largely originate from the industrialised world and have reached the Arctic via long-distance transport. In the Russian part of the Arctic, there are also local industries and landfill sites which are possible sources. Many environmental pollutants are bioaccumulated in marine food webs and can reach high concentrations in

PHOTOGRAPH: SHUTTERSTOCK

PHOTOGRAPH: ISTOCK

larger fish and marine mammals. The latter are important food sources for the population in the Arctic.

The risks of exposure and health effects are therefore often higher for the population in the Arctic than in the Nordic region for example, despite the greater distance from the emission sources. (Read more about mercury and environmental pollutants in the Arctic in the articles on pages 36 and 46).

Climate change can itself affect the transport of environmental pollutants to the Arctic and the way in which they are distributed between different parts of the ecosystems, but for many substances, changes in the emissions themselves are a more important factor than climate change. Melting sea ice and glaciers and thawing permafrost can however release environmental pollutants. This can lead to further exposure for the marine ecosystems and ultimately humans.

With the greater exploitation of the Arctic, it is likely that the dispersal patterns of environmental pollutants will change and that new local sources will arise.

CHALLENGES

There is much evidence to suggest that oil and mineral extraction in the Arctic will increase. There are also arguments against such development. The international efforts being made to reduce greenhouse gas emissions are one, the high cost in terms of capital and energy is another, as is the harsh climate. The increased exploitation of the Arctic's natural resources entails substantial risks for the environment.

Exactly how and to what extent the environment will be affected is difficult to assess at present, as it is not known what effect the pollutants will have in such a cold climate. More research is needed within this area.

COLLABORATIONS TO PROTECT THE ARCTIC

The Arctic is a hot topic in the media, and many organisations are working to stop the exploitation of the Arctic's resources. The Arctic Council is an international forum in which the eight Arctic countries (Denmark, Finland, Iceland, Norway, Sweden, Canada, Russia and the USA) are working together to ensure the sustainable development of the Arctic. This work is being carried out within four main areas: environment and climate, plant and animal life, the oceans and the indigenous population. (Read more on page 54). In 2014, the IMO (International Maritime Organizationn) drew up the Polar Code for safer shipping in the waters surrounding the North and South Poles. It is also important to make the current oil production in the Arctic regions safer in order to prevent accidents. The development of renewable energy and reduced demand for fossil fuels should also make oil extraction in the Arctic of less interest.

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Ground-level ozone a growing problem in the Arctic?

Ground-level ozone is a gas which can harm health, damage plants and cultural heritage and affect the climate. Average concentrations of ground-level ozone in the Arctic are not as high as they are further south, but peaks with high ozone concentration occur during the spring. These peaks could become increasingly important if the climate changes cause the growing season in the north to start earlier in the year.

PHOTOGRAPH: DREAMSTIME

FACTS: How ozone is formed

Ozone can be formed in a number of different ways in the troposphere and stratosphere. In the stratosphere, sunlight contains energy-rich UV radiation, which can split oxygen into two free oxygen atoms (O_2 + UV-C → 2O). The free oxygen atoms can react with oxygen and form ozone ($O + O_2 \rightarrow O_3$), which leads to high concentrations of ozone in the stratosphere.

When the sunlight reaches the troposphere, the most energy-rich component of the solar radiation is filtered out. Free oxygen atoms can alternatively be formed through less energy-rich UV radiation in sunlight splitting the air pollutant nitrogen dioxide into nitrogen monoxide and a free oxygen atom (NO_2 + UV-A → NO + O), which then forms ozone in the same way as in the stratosphere through joining with an oxygen molecule.

Ozone formation in the troposphere is strongly accelerated by other air pollutants, particularly volatile organic pollutants and carbon monoxide.

PHOTOGRAPH: MATS BJÖRKMAN

Latnjajaure in the mountains of Lapland, where measurements of ground-level ozone have been taken. The station is situated approximately 1000 m above sea level.

WITHIN ENVIRONMENTAL MONITORING, research and modelling, researchers have long been studying the occurrence of ground-level ozone. However, not as much attention has been directed at the Arctic and Subarctic regions and mountainous areas. However, in recent years, both measurements and modelling have shown that ground-level ozone can be an important problem in the north.

Concentrations of ground-level ozone in northern Scandinavia show a rising trend, rather than a decreasing one. Ozone concentrations in the air at ground level during the spring (March - May) are consistently higher in the north compared with southern Sweden (see Figure 1). In the far north, at Nikkaluokta and Palovare measuring stations, monthly mean concentrations are around 100 µg/m^3 (50 ppb) during this period. To protect human health, the World Health Organization (WHO) has set a target according to which mean concentrations over a period of eight hours must not exceed 100 µg/m^3.

In the future, high ozone concentrations in the spring may also be of importance to vegetation, as the growing season in northern Sweden is starting earlier in the year due to the climate changes.

In isolated cases, ozone concentrations in the north can be very high and even approach the levels where the EU Directive states that the general public must be informed, i.e. when the hourly mean concentrations exceed 180 µg/m^3. Figure 2 shows short periods with peak ozone concentrations, known as 'ozone episodes'. In May 2006, ozone concentrations in northern Sweden and Norway rose to around 160 ug/m^3. At the time, the air with its constituent ozone-forming substances originated from large forest fires in Russia.

On this occasion, unusual leaf damage was found on bushes and trees in northern Sweden and Norway, probably as a result of the high ozone concentrations.

OZONE MODELS FOR CONCENTRATIONS IN THE NORTH

Today's large-scale atmospheric chemistry models simulate the variation of ground-level ozone concentrations in the Arctic with a maximum during the spring. Model-based research has shown that the proportion of ground-level ozone in the

Ground-level ozone, mean concentrations 2004 – 2008

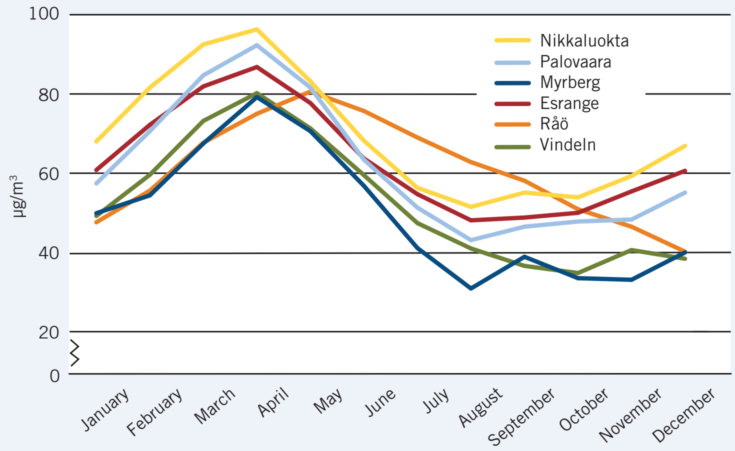

FIGURE 1. Monthly mean concentrations of groundlevel ozone broken down between the months of the year, as mean values for the period 2004-2008. The values are shown for four sites in Norrbotten County (Nikkaluokta, Palovare, Myrberg and Esrange) and one site in Västerbotten County (Vindeln), and one site by the coast in Halland County (Råö).
Source: The Swedish throughfall monitoring network for Nikkaluokta, Palovare and Myrberg. Other data from the national ozone monitoring programme.

Ground-level ozone in northern Sweden and Norway

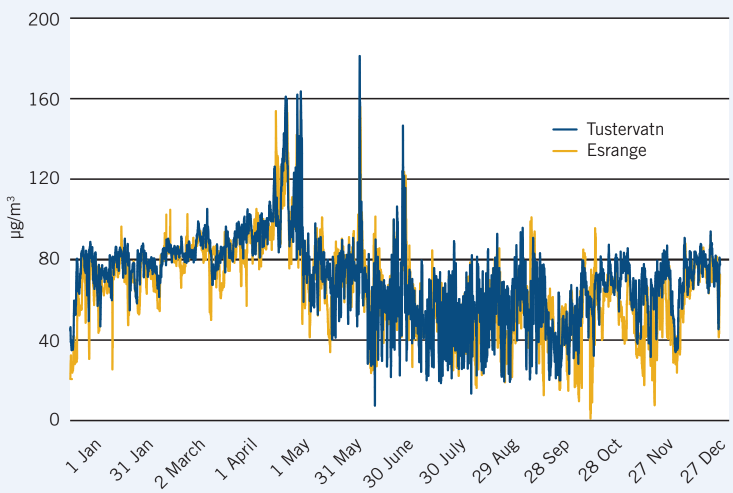

FIGURE 2. Ozone episodes in 2006 at Esrange in northern Sweden just outside Kiruna, and at Tustervatn in central Norway between Trondheim and Narvik.

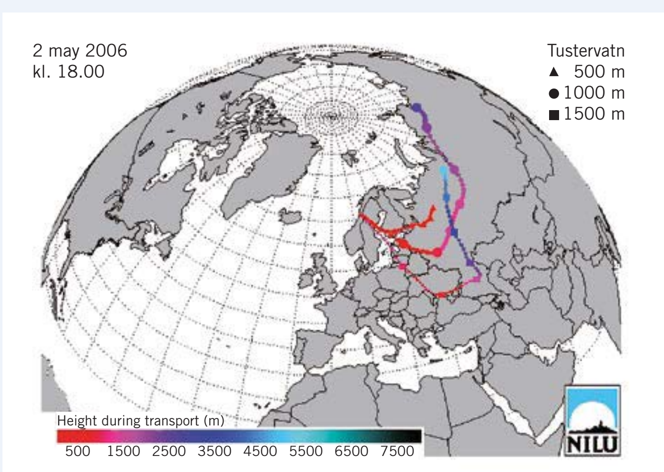

FIGURE 3. Trajectory analysis for air masses which swept in over Tustervatn in early May 2006. The trajectories, which show the path of the air masses through to a particular point, were calculated using NILU's Flextra model.

The symbols show trajectories for air masses and their altitude when they arrive at the location concerned.

The colours indicate the altitude while the air masses are being transported.

Arctic which is transported from the stratosphere is highest in the spring, sometimes up to 10 percent, whereas the contribution during the summer is small. In the stratosphere (the layer of air above the troposphere, see page 7), ozone concentrations are very high, but the air masses of the troposphere and stratosphere do not mix with each other to any great extent.

In 2014, the Swedish Meteorological and Hydrological Institute (SMHI) presented simulations of the northern hemisphere carried out using the MATCH model. The monthly mean values of ozone from the simulations for the stations at Esrange outside Kiruna and Vindeln near Umeå are shown in Figure 4. The simulations show a seasonal variation which corresponds with the measured concentrations i Figure 1, although the concentrations according to the model are generally somewhat lower. Our current understanding of how the ozone is formed and transported can to some extent explain how ozone concentrations in some parts of the Arctic vary during the year. Further model experiments are needed to establish in more detail which processes govern the seasonal variation and the high ozone concentrations during the spring in northern Sweden.

However, the primary cause of the high ozone concentrations during the spring in northern Sweden and in the European part of the Arctic is the activation by sunlight of ozone-forming substances, particularly peroxyacyl nitrate (PAN), nitric acid and carbon monoxide, which build up over the winter. This process, combined with low deposition on surfaces covered by snow and ice and some transport of ozone-rich air from the stratosphere, is causing atmospheric concentrations of ozone to rise

A BETTER UNDERSTANDING IS NEEDED

Deposition has very little effect on the air high up in the troposphere, as the distance to the ground is so great. Other factors can also affect the amount of ozone that is available in the air at high altitude, but ozone concentrations at high altitude appear to be higher compared with those at ground level globally. In addition, our understanding of the ozone load at high altitude in mountainous areas and other upland areas at northerly latitudes remains poor. High ozone concentrations 24-hours a day, combined with long, light nights, enables virtually continuous ozone uptake and affects the life processes of plants during the summer.

Downy birch *(Betula pubsecnes ssp. czerepanovii)* with ozone-damaged, red- and brown-coloured leaves, Karasjok, Northern Norway, August 2006.

Ozone-forming substances can also be transported very long distances by winds. While ozone-forming substances in the northern hemisphere, including emissions from industry and traffic in southern and central Europe and from major fires such as in Russia, continue to be emitted, the high ozone load in the north will continue. Any future increase in shipping through the Northeast Passage will also result in an increase in

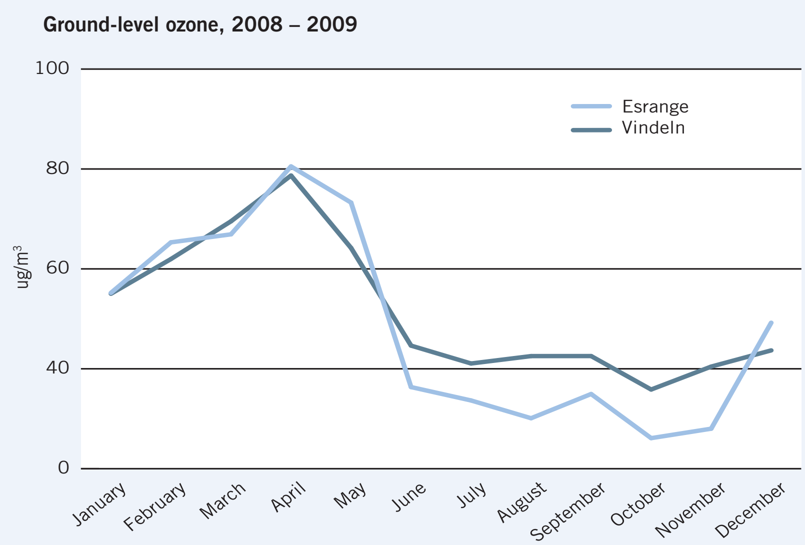

FIGURE 4. Simulated monthly mean concentrations of ozone at Esrange outside Kiruna and Vindeln in the Umeå area, as mean values for the period 2008 – 2009. Source: Data from simulations described in Monks et al. 2014.

FACTS: Ground-level ozone

The ozone that exists in the air layers closest to the ground is called 'ground-level ozone' and should not be confused with the protective ozone layer up in the stratosphere.

The concentration of ground-level ozone at a particular location depends on a number of factors. The chemical formation of the ozone is of course of decisive importance, as are the processes which consume ozone which is deposited on the Earth's surface as atmospheric deposition. For example, snow, ice and water surfaces absorb considerably less ozone than vegetation, which absorbs large quantities, particularly during the growing season in the spring and summer.

The horizontal transport of air containing high or low concentrations of ozone and ozone-forming substances, over the Earth's surface is also of major importance. This type of transport can take place over great distances.

PHOTOGRAPH: HANS TØMMERVIK, NINA TROMSØ

"Ozone uptake in leaves inhibits photosynthesis"

FACTS: Effects on plants, health and cultural heritage

Ground-level ozone (O_3) is inhaled by humans and can be taken up by the leaves and needles of plants. Ozone uptake in leaves inhibits photosynthesis and causes premature ageing of leaves, needles and maturing seeds. This can cause substantial harvest losses within agriculture and reduce timber production in the forestry sector.

Respiratory problems caused by ground-level ozone and other effects amongst humans annually result in a large number of hospital admissions and even premature deaths. The strong oxidative capacity of ozone also contributes to the weathering of house façades and stone and concrete statues, for example. It can be both difficult and expensive to restore this cultural heritage.

emissions of ozone-forming substances, which could worsen the situation.

One serious deficiency is that we currently know little about ozone load levels in mountainous areas. Measurements taken at Latnjajaure field station at around 1000 metres above sea level and elsewhere indicate that such levels may be considerably higher there than at Esrange outside Kiruna, for example. Our understanding of the large-scale atmospheric chemistry in the Arctic is also limited by a lack of regular measurements of ozone and ozone-forming substances in the Russian part of the Arctic and at high altitudes in the atmosphere.

There are many interesting research issues concerning ground-level ozone and the specific conditions which prevail in the Arctic. Some of the questions we hope to be able to answer over the next few years are: how will the high ozone concentrations in the spring increasingly impact on plants as the greenhouse effect increases in intensity? How high are the ozone concentrations at high altitude, e.g. in mountainous areas? What trends are there with regard to moderate and high ozone concentrations in the north and how can we explain any trends? The answers to these questions can provide us with a considerably better understanding of the nature of environmental risks such as ground-level ozone in the Arctic.

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PHOTOGRAPH: FREDRIK LUDVIGSSON/JOHNER

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About trajectory analysis:
www.nilu.no/projects/ccc/trajectories

Thawing permafrost tens of thousands of years old is being released along the northeastern Siberian coast.

Methane in the Arctic

Methane can be released from Arctic permafrost layers on land and in bottom sediments. Our understanding of how methane and carbon dioxide behave and interact in the Arctic is limited, but progress is particularly being made as regards our understanding of the many different sources of methane.

FACTS: Methane and methane emissions

Methane (CH_4) is a colour- and odour-less gas consisting of carbon and hydrogen, which reaches the atmosphere from a wide variety of sources and then disappears, primarily through various chemical reactions. Around 90 percent of the methane reacts with the hydroxy radical in the troposphere. As the residence time of methane in the troposphere is almost ten years, the gas is relatively well-mixed in this layer of the atmosphere.

Methane emissions can be classified on the basis of different sources: biogenic, thermogenic and pyrogenic.

Biogenic methane is produced by bacteria through the degradation of organic matter in environments with a low oxygen concentration, such as wetlands, landfill sites, rice fields and cattle farms.

Thermogenic methane is formed geologically, deep in the Earth's crust where organic matter under high pressure and temperature forms fossil reservoirs, e.g. natural gas, oil and carbon pools. These fossil fuels can then reach the atmosphere both via natural leakage or through deliberate extraction by industry, as well as through refining and transport.

Pyrogenic methane is formed through incomplete combustion, e.g. in connection with tundra fires.

In turn, all these three sources can be divided into natural and anthropogenic sources. The sum of all natural sources and the sum of all anthropogenic sources are estimated to be approximately equal. However, this estimate is associated with considerably uncertainty, particularly with regard to natural emissions.

PHOTOGRAPH: IGOR SEMILETOV

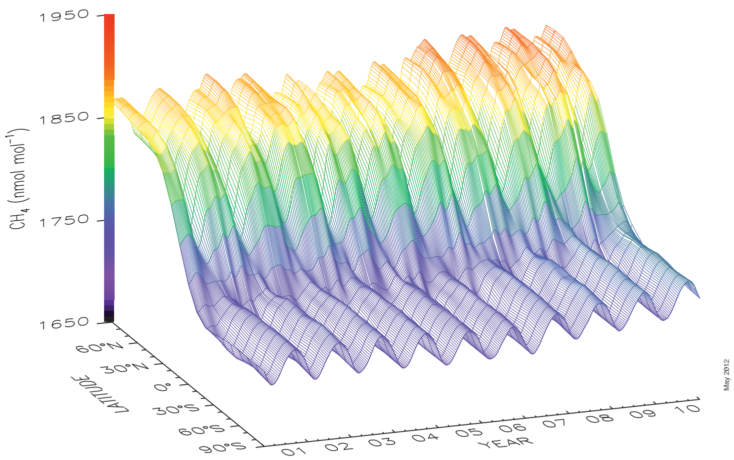

FIGURE 1. Increase in global methane concentrations during the period 2000 – 2010. The further north on the globe one goes (increasing northerly latitudes), the higher the methane concentrations and the greater the increase over time.

The highest mean concentrations anywhere in the atmosphere occur directly over the Arctic (see Figure 1). This is the result of the way in which the atmosphere is layered and local sources. Global methane concentrations in the atmosphere have more than doubled since the early 19th century, from 770 ppb to 1800 ppb, probably primarily because of emissions from human activity.

NATURAL METHANE EMISSIONS

Natural methane sources are probably dominated by emissions from wetlands, but lakes, watercourses and bogs and geological sources, known as thermogenic methane, are also sources (see facts). The emissions which mankind gives rise to, either directly or indirectly, are dominated by emissions from cattle farming, landfill sites and incomplete combustion of fossil fuels.

Sources of methane in the Arctic and its proximity, e.g. Sweden, can be found on land, in the oceans and in society. In the land areas surrounding the Arctic, particularly in Russia and Canada, there are enormous wetlands where permafrost either partially or completely dominates the landscape. Many studies of methane have focussed on these wetland systems and the uppermost layer of permafrost, which thaws every summer. These studies have included laboratory experiments, field experiments, flow measurements and long-term measurements from high towers known as "footprints", where it is possible to consider methane flows over large areas. These studies have resulted in real progress being made in our understanding of how methane behaves in wet tundra, dry tundra and lakes. However, it would be difficult to take similar large-scale measurements in the Arctic in order to predict future emissions from these systems.

Emissions of methane from marine sources in the Arctic occur from the permafrost on the seabed in the large shallow seas of eastern Siberia. This permafrost was originally situated on land, but was flooded when glaciers melted and sea levels rose at the end of the ice age. These shallow seas contain almost 80 percent of the permafrost that exists on the seabed globally. Within and beneath these permafrost layers, gas hydrates, a type of frozen water-methane complex, and natural gas are also stored. Along the continental margins of the Arctic Ocean, there are also large quantities of methane in ordinary marine gas hydrates. Over a period of many years, measurements taken by research vessels during summer

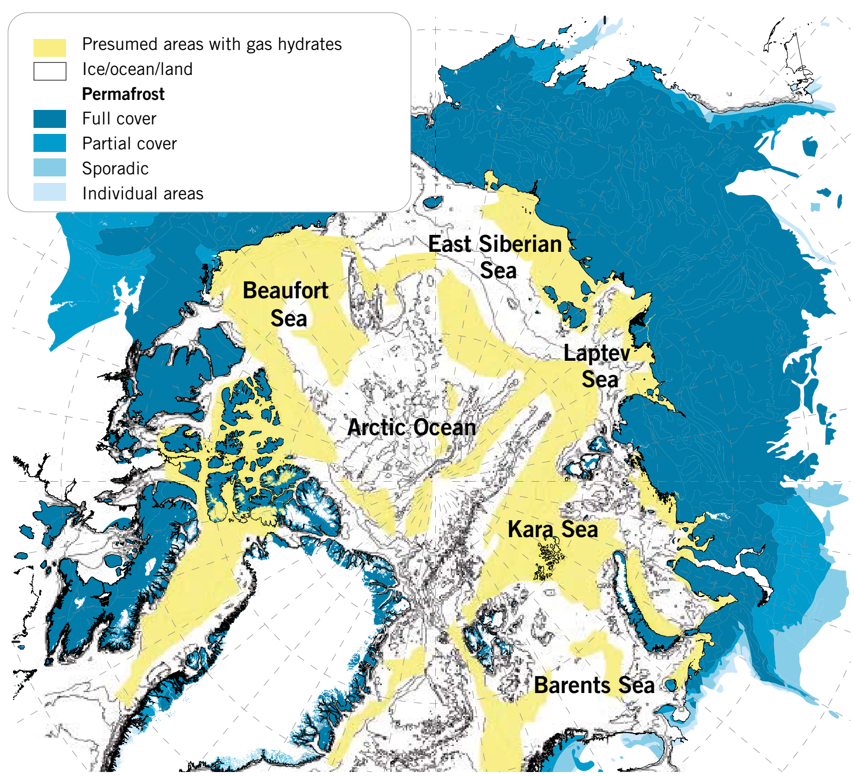

FIGURE 2. Distribution of permafrost on land and gas hydrates in the seabeds of the Arctic.

The Zeppelin research station on Svalbard. A major international collaboration concerning atmospheric monitoring is taking place here.

expeditions have revealed extremely elevated concentrations of methane in the seawater and in the air above the Arctic Ocean of eastern Siberia. Like emissions on land, these marine emissions are also difficult to quantify.

METHANE EMISSIONS CAUSED BY HUMANS

It is difficult to determine the magnitude of methane emissions from individual sources or areas using measurements of concentrations in the air. This is partly because the gas mixes rapidly in the atmosphere and partly because the measurements, particularly those taken in the Arctic, are usually taken a long way from the emission areas.

The International Institute of Applied Systems Analysis (IIASA) has prepared a scenario for future anthropogenic methane emissions. The study, which was based on assumptions concerning how much methane is released by different sectors, indicates that global emissions will rise over the coming decades. Major contributions are especially expected from coal production in China and shale gas extraction in North America. Technologies and methods are now available which can limit and recycle methane emissions from sources such as oil production, gas production and leaking gas pipes, as well as from biodegradable waste. The eight member countries in the Arctic Council account for around a fifth of global methane emissions. It would be reasonable to expect these countries to aim to reduce methane emissions as much as possible in connection with current and future oil and gas extraction in the Arctic.

LONG-TERM STUDIES AND MEASUREMENTS OF METHANE IN THE ARCTIC

Measurements of methane and carbon dioxide in the actual atmosphere, as well as on land and at sea, are vital in improving our understanding of sources, effects, long-term trends and impacts on the Arctic climate. Measurements of methane and carbon dioxide are being taken continually at three stations on Svalbard, and in Alaska and Canada. Sweden contributes indirectly to the measurements on Svalbard via the international collaboration in which the EPA is a participant. A measuring station has recently been established in northeastern Siberia (Tiksi). This station will soon start contributing the first series of measurements from a region which previously had few land-based observations. Continual measurements are also being taken in Finnish Lapland and at a number of other stations situated around the Arctic Circle. These measurements have shown that since 2007 methane concentrations in the Arctic have risen at approximately the same rate as global methane concentrations.

During the winter, the stations in the Arctic are affected by methane transport from sources at more southerly latitudes. In the summer, methane concentrations vary considerably over the course of the day, and maximum methane concentrations tend to occur in the late summer and early autumn. The reason for this trend is unclear. It may be due to emissions from either wetlands or the shallow seas of eastern Siberia.

Various isotopes of methane may be able to tell us more about the sources that it originates from. The first studies of methane occurrences in the Arctic were conducted on Svalbard in 2011, but more long-term studies of stable hydrogen isotopes and ‘natural abundance carbon14’ are also needed in order to better identify the various sources of the methane.

THAWED PERMAFROST CAN GIVE RISE TO SUBSTANTIAL EMISSIONS

Enormous quantities of organic carbon are frozen into the uppermost soil layers (1 – 3 m) and the shallow seabeds in and around the Arctic. These quantities correspond to three times as much carbon as exists in the form of carbon dioxide in the atmosphere globally and 400 times the amount of methane that can be found there. Although only a small proportion of the permafrost and/or gas hydrates thaws and is added to the atmosphere in the form of greenhouse gases; this process can impact on the climate in a relatively short period of time.

Simplified models indicate that the gradual thawing of the active layer in terrestrial permafrost can give rise to substantial emissions of greenhouse gases. If the Arctic climate were to become warmer, the carbon bound in this permafrost could cause 50 – 200 billion tonnes of methane to be released by the year 2100. This can be compared with around 800 billion tonnes of carbon in an often cited emissions scenario, which it has been calculated could be added to the atmosphere in the form of carbon dioxide from the combustion of fossil fuels over the same period.

The calculations do not take account of other rapid-release processes such as erosion, fires, thawing or permafrost collapse, as well as hydrates in the shallow seas of the Arctic. The permafrost in the seabeds of Arctic seems to have thawed faster than that on land, presumably because the seawater which flooded these areas 7000 – 15000 years ago was warmer than the air above the northernmost Siberian part of the Arctic.

It is also possible that some of the carbon which is released from the permafrost layers may not be converted to greenhouse gases, but deposited again in lakes and sea sediment as part of the carbon cycle.

FUTURE RESEARCH

The emissions currently taking place from the Arctic permafrost have no decisive impact on concentrations of carbon dioxide and methane in the global atmosphere. However, further research is needed in order to predict future emission levels of these greenhouse gases from the enormous quantities of carbon which are still frozen into the Arctic permafrost. With regard to this, an advanced monitoring programme is important and could give us a better understanding and enable us to predict future developments. International evaluations suggest that studies of thawing permafrost and collapsing methane hydrates in the Arctic should be given a high priority.

To improve our understanding of anthropogenic methane emissions in and around the Arctic and also predict how “natural” emissions in the Arctic will develop in the future, the following recommendations have been drawn up:

1) Establish more long-term measurements, particularly in the Siberian Arctic.
2) Develop the atmospheric programme with measure ments of methane isotope composition(a sort of chemical fingerprint), which reveals the origin of the methane
3) Support for process studies of permafrost and gas hydrate systems.

Finally, in order to limit global warming, it will be essential to reduce emissions of anthropogenic methane, carbon dioxide and other greenhouse gases. Limiting the warming process will also reduce the risk of additional greenhouse gases being released from natural Arctic carbon stocks, and the accelerated warming that this could cause.

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PHOTOGRAPH: PIXABAY POLAR STRATOSPHERIC CLOUD

The ozone layer over the Arctic – past, present and future

After a six-month long winter, the sun has finally returned to the Arctic. In the middle of the day, it is still low over the horizon, but it gradually climbs higher every day. High up in the stratosphere, the sun's rays are reflected by the *polar stratospheric cloud*. Feverish chemical activity will take place in this layer of the atmosphere over the next few months which will impact on the ozone layer.

Ever since the 1970s, research has suggested that anthropogenic emissions of certain substances could affect the ozone layer. However, it was not until British and Japanese researchers discovered the hole in the ozone layer over the Antarctic that doubts over whether something serious was happening in the atmosphere were finally dispelled.

This discovery led to the signing of the Vienna Convention for the protection of the ozone layer in 1985. Two years later, the Montreal Protocol was introduced. This protocol covers the elimination of ozone-depleting substances containing chlorine and bromine. Despite the conventions and protocols, the debate over whether or not mankind was affecting the ozone layer raged for more than a decade.

Gradually, our understanding of how the ozone in the atmosphere is affected by various anthropogenic substances improved. As this understanding grew, the Montreal Protocol has also been revised on several occasions. The result has been the end of the depletion of the ozone layer, and we expect the process to be reversed soon. There are also signs that it has already recovered, but this conclusion is still subject to statistical uncertainty.

SWEDEN STARTING TO MEASURE OZONE

In Sweden, the EPA was given responsibility for protecting the ozone layer, which included initiating the elimination of ozone-depleting substances and also monitoring of the development of the ozone layer. SMHI was tasked with carrying out what are known as 'total ozone measurements' as part of the national environmental monitoring programme. These measurements began in Norrköping in 1988 and were expanded through the addition of a station at Vindeln in 1991.

The thickness of the ozone layer is measured at this station in Vindeln. The station has two ozone spectrophotometers, an older one which is operated manually and a new, automatic one.

PHOTOGRAPH: PERNILLA LÖFVENIUS

Well into the 1990s, there was still concern that the thickness of the ozone layer would continue to decrease substantially. The measurements of total ozone thus formed the basis of a warning system in the event of holes developing in the ozone layer and the resultant increase in UV radiation from the sun. SMHI developed a simple model to calculate the amount of harmful UV radiation on behalf of the former Swedish Radiation Protection Authority, now the Swedish Radiation Safety Authority. This is now known as the 'UV index' and is directly available to anyone with a computer or a smartphone.

SATELLITE MEASUREMENTS

Satellite-based measuring techniques were gradually developed which offered good coverage. Ground-based instruments can be kept operational for a very long time, whereas those in satellites often have a limited life. The combination of satellite instruments and ground instruments means that we now have a good global monitoring system in place

FACTS: The ozone layer

The ozone layer sits at an altitude of 10 – 40 km above the Earth's surface. However, the concentrations of ozone are low, of the order of 100 ppb. Despite these modest concentrations, the ozone plays an incredibly important role in protecting flora and fauna against harmful UV radiation from the sun.

Ozone is both formed and destroyed through photochemical processes. The effectiveness of the processes depends on a number of factors, such as which gases and particulate matter are present in the atmosphere.

Ozone is a reactive gas which is readily degraded and new ozone gas must continually be formed in the atmosphere in order to replace the gas that is lost. As solar radiation is an important factor in the production of ozone, most of the ozone in the atmosphere is formed at high altitude over the tropics. From there, it is transported by winds to higher latitudes. The ozone layer over Antarctica and the Arctic is therefore strongly dependent on the circulation in the atmosphere. This also means that the thickness of the ozone layer varies more over the polar regions than it does over the tropics.

for the ozone layer, which was not the case a few decades ago.

SUBSTANTIAL VARIATIONS

The Montreal Protocol meant that depletion of the ozone layer over Europe stopped at around 5%. However, there is considerable variation in the thickness, and week-long episodes with substantial reductions have occurred, sometimes amounting to reductions of several tens of percent compared with the long-term mean. SMHI's measurements also show that the ozone layer over our latitudes varies greatly from day to day and also from year to year. These relatively large natural variations make it harder to detect small, long-term changes.


PHOTOGRAPH: IBL BILDBYRÅ

Sending up measuring instruments attached to a balloon enables important information to be obtained about the vertical distribution of the ozone layer in the atmosphere.

PARTICULATE MATTER AND POLAR VORTEXES AFFECT THE OZONE LAYER

Today, the threat of a globally thinned ozone layer has almost been averted, yet some ozone-depleting substances still exist which must be eliminated. The ozone measurements being taken today are therefore needed not as a warning indicator, but as a check to ensure that the trend is continuing in a positive direction. However, another threat has quickly emerged where these ozone measurements could contribute, namely climate change caused by the increasing greenhouse effect.

Ozone is an important greenhouse gas, and there are therefore links between the ozone issue and climate change. As the greenhouse gases trap a high proportion of the Earth's outgoing thermal radiation, the lower atmosphere (the troposphere) becomes warmer while the upper atmosphere (the stratosphere), which contains the ozone layer, becomes colder. The falling temperatures, combined with the occurrence of a Polar Vortex (see facts) favour the occurrence of particulate matter, which in turn gives rise to polar stratospheric clouds. These clouds occur over both the Arctic and the Antarctic during the winter and contribute to the occurrence of ozone holes because the particulate matter in the cloud accelerates the depletion of ozone. However, this process does not begin until the early spring, when the sun starts to warm and activate the chlorine and bromine molecules which accumulate over the Arctic during the long winter. The molecules are quickly broken down into free atoms by the sun's rays. These are chemically more aggressive and can then degrade the ozone molecules which offer protection against harmful UV radiation. In the late spring and summer, this rapid ozone depletion stops.

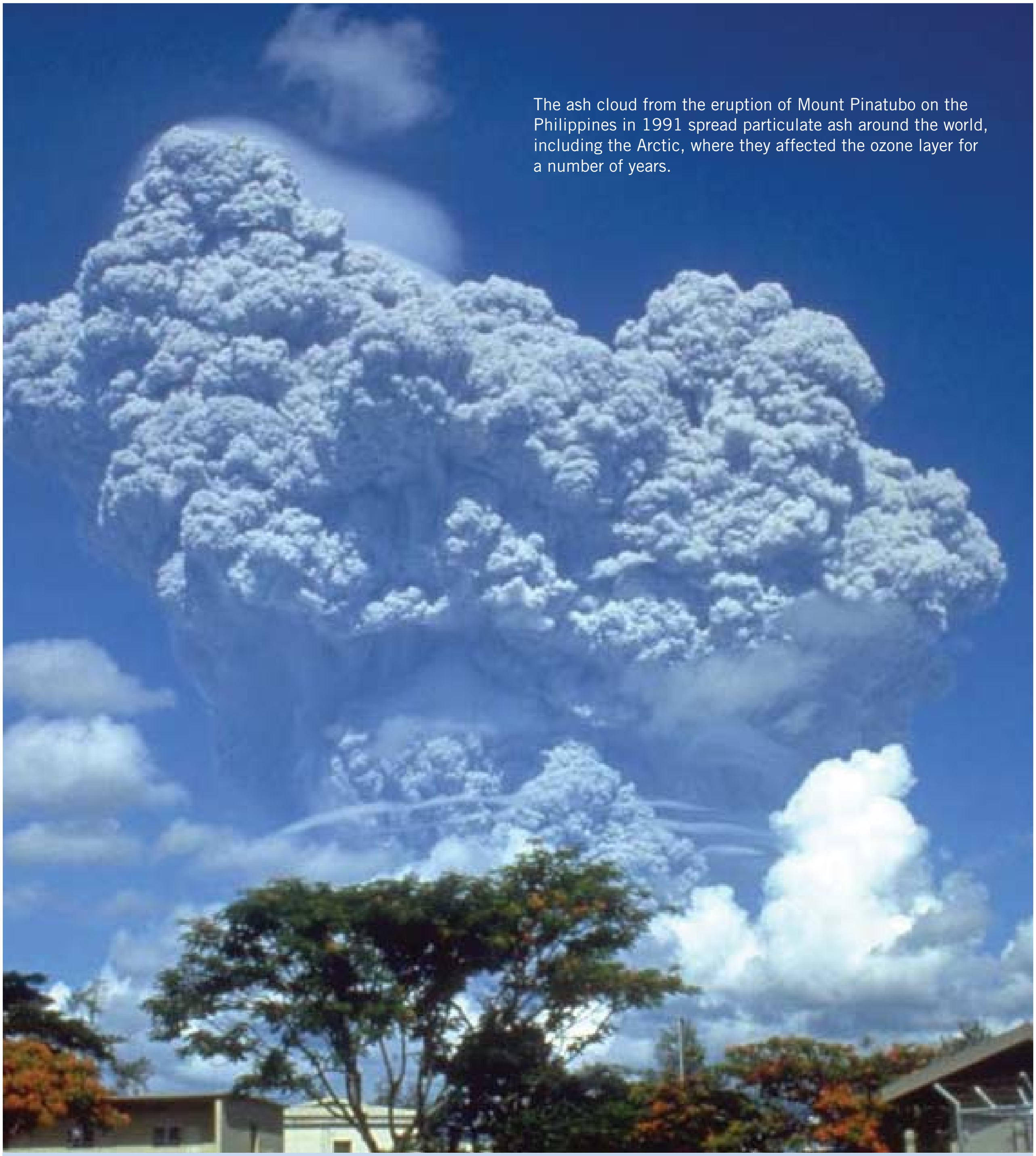
In some years, ozone hole-like episodes can occur in the Arctic which last for one or more weeks during the spring. These occur during extreme but naturally cold Arctic winters, and may become more common as the upper atmosphere becomes

FACTS: Polar Vortex

During the winter months, the polar night prevails over the Arctic. At this time, a polar vortex occurs in the stratosphere, caused by a combination of atmospheric circulation and cooling via outgoing radiation towards space. The vortex, which moves across different parts of the Arctic, effectively separates the air within from that outside. Inside the vortex, temperatures can drop below -90°C across large areas during the winter.

The stratosphere is very dry, and ordinary clouds therefore very rarely form at such a high altitude. However, when the temperature drops, nitric acid and sulphuric acid, which occur naturally at that altitude and freeze at very low temperatures, can form clouds. The ice crystals in the cloud act like catalysts where inactive forms of chlorine can be converted into active forms faster than they would otherwise have been. Active chlorine compounds can then attack the ozone molecules when the spring sun starts to shine. The process is reinforced further by the fact that the nitrogen, which can normally convert the chlorine to inactive forms, is bound as nitric acid as the cloud forms.

PHOTOGRAPH: RICHARD P. HOBLITT/ U.S. GEOLOGICAL SURVEY



The ash cloud from the eruption of Mount Pinatubo on the Philippines in 1991 spread particulate ash around the world, including the Arctic, where they affected the ozone layer for a number of years.

FACTS: The atmospheric path length of solar radiation

The atmospheric path length of solar radiation through the atmosphere is usually compared with the atmospheric path length that applies when the sun is at its zenith (=1). Atmospheric path length is the distance that the sun's rays pass through as they travel through the atmosphere. The lower the sun in the sky, the longer the path length. At mid-day in the summer in southern Sweden, the relative atmospheric path length is approximately 1.3, whereas at mid-day in mid-winter in southern Sweden, it is around 6. In northern Sweden, the corresponding atmospheric path lengths are around 1.4 and above 10. This indicates that the height of the sun is the most important factor in determining how the UV radiation varies over the course of the day, and how it can vary at different latitudes.

colder. Once the vortex has dissipated when the spring warmth arrives, air masses with ozone-depleted air can move southwards to Sweden for example and thus affect the ozone layer there. This occurred in spring 2011. At the time, depletion of the ozone layer of more than 30 percent was observed over a period of several days at several measuring stations in Scandinavia. One consequence of this was that the UV radiation in the middle of the day more than doubled compared with the normal level for the time of the year. The Arctic vortex is also more mobile than its Antarctic counterpart. This could have consequences, as the thinned ozone could affect densely populated areas to a much greater extent.

VOLCANIC ERUPTIONS CAN CAUSE DEPLETION

Another type of particulate matter which could affect the ozone layer is volcanic in origin. When major volcanic eruptions occur, such as the eruptions of El Chichon in 1982 and Pinatubo in 1991, enormous quantities of dust and gases can end up in the atmosphere. Although these eruptions took place in Mexico and the Philippines respectively, the particulate matter reached the Arctic within just a few months and affected the photochemistry of the ozone there for a couple of years. The consequence was a global depletion of the ozone layer by a few percent.

UV RADIATION IN THE ARCTIC

The ultraviolet solar radiation (UV) generally decreases substantially during its journey through the Earth's atmosphere. There are two main processes which reduce UV radiation: absorption and scattering at atomic or molecular level. The thicker the ozone layer, the more UV radiation is absorbed, and the longer the path length of the solar radiation through the atmosphere, the more it is scattered. The latter means that a low sun will result in less UV radiation than a high sun.

In addition to the height of the sun, the thickness of the ozone layer and the amount of particulate matter in the atmosphere, the amount of UV radiation also depends on the reflectivity of the ground surface and the thickness of the cloud cover.

The special conditions of the Arctic, with its extensive snow and ice, mean that if the UV radiation encounters an extensive area of snow, a high proportion of it will be reflected back up into the atmosphere, and then be reflected back down again towards the Earth's surface. This process is repeated several times and is known as 'multiple reflection'. This increases the amount of UV radiation by as much as 20 – 40 percent compared with the situation where the radiation encounters snow-free ground or forest. In extreme polar environments, the increase can be almost twice as great.

Much of the Arctic consists of marine areas. When the sea is covered by ice, virtually no UV radiation penetrates down into the sea, but during the summer months, under more ice-free conditions, a reasonable proportion of the UV radiation can penetrate down to depths of several metres. During the winter, the amount of UV radiation is practically zero, but in the summer, the increased UV radiation can affect the ecosystem in the Arctic Ocean and melting polar ice can accelerate this process.

KNOWLEDGE PRIOR TO IMPORTANT DECISIONS

On many levels, the threat to the ozone layer became a happy story to take great pleasure from, yet it is also something to draw lessons from. This is particularly true as regards the value of researchers seeking and applying knowledge and then disseminating their findings, however complex and unwelcome they may be, to decision-makers. For the latter, it is a question of having the ability to strive to understand and ignore short-term gains, ongoing conflicts and, in particular, to reach agreement with decision-makers in other countries, even though the underlying knowledge is not always complete.

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Mercury is being transported to the Arctic

There are no known sources of mercury in the Arctic. Despite this, mercury concentrations in the atmosphere are often just as high as those in background air at more southerly latitudes. The explanation for this is air transport, but mercury also often follows marine currents. Coastal areas also receive substantial inputs of mercury from the erosion of sedimentary layers and via rivers from the land masses surrounding the Arctic.

With the aid of model calculations, it is estimated that around 100 tonnes of mercury are transported to the Arctic Ocean every year via the atmosphere, which is about as much as all the other flows combined. Mercury via air transport thus represents the single biggest contributor to mercury in the region. It is deposited on land and water as inorganic mercury via rain and snow, as well as via the deposition of mercury bound to particulate matter. Because of a special phenomenon known as "AMDE", large quantities of oxidised mercury are also deposited in the Arctic region during the spring (see facts).

Mercury concentrations in humans and animals

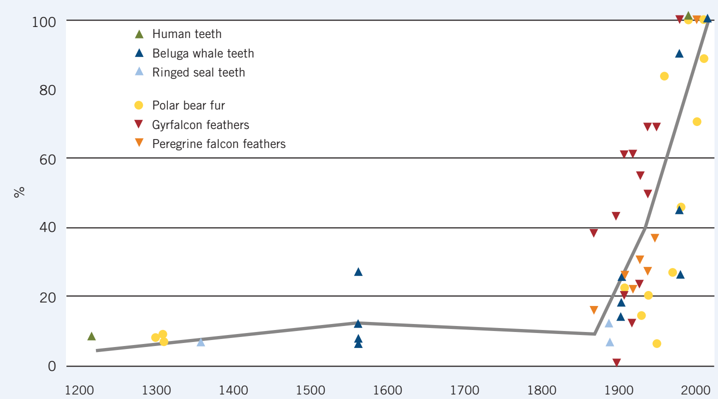


FIGURE 1. Mercury concentrations in material from humans and animals which lived in the Arctic, expressed as a percentage of present-day concentrations. The material studied originates from museums. Source: AMAP, 2011.

HOW ANIMALS AND HUMANS IN THE ARCTIC ARE AFFECTED

High concentrations of mercury in humans and animals affect reproductive capacity, the immune system and the cardiovascular and nervous systems. Mercury can harm the development of children's brains, particularly those of unborn children.

Figure 1 shows mercury concentrations in human and animal remains in the Arctic from the 13th century through to the present day. There is a shortage of material dating from before 1850, but the rise in mercury concentrations appears to coincide with industrialisation in Europe and the USA.

Exposure to mercury has been measured through many analyses of mercury in hair, blood, liver, kidney and brain samples. Various species of fish, whales, birds, seals and polar bears have also been studied. Mercury in the brains of beluga whales and other toothed whales has been found in such high concentra tions that the possibility of effects on the nervous system cannot be excluded. As some methylmercury is stored in the fur, fur-bearing animals such as polar bears and seals shed some of the mercury when they moult. This is probably the reason why polar bears and seals have lower mercury concentrations in their brains than toothed whales. Changes in the liver and kidney which have probably been caused by mercury have been found in polar bears off eastern Greenland, in beluga whale, bowhead whale and ringed seal in Alaska. Pilot whales off the Faroe Islands have such high mercury concentrations that they are at risk of suffering liver damage. Despite the studies that have been carried out, we still do not have an overall picture of how Arctic fauna is affected by mercury.

COMBINATION EFFECTS

Arctic fauna is also affected by other environmental pollutants such as cadmium and persistent organic environmental pollutants. The combined effect of several environmental pollutants and climate changes can be of decisive importance. This is a very complex issue and much research remains to be done within the field.

DIET A RISK

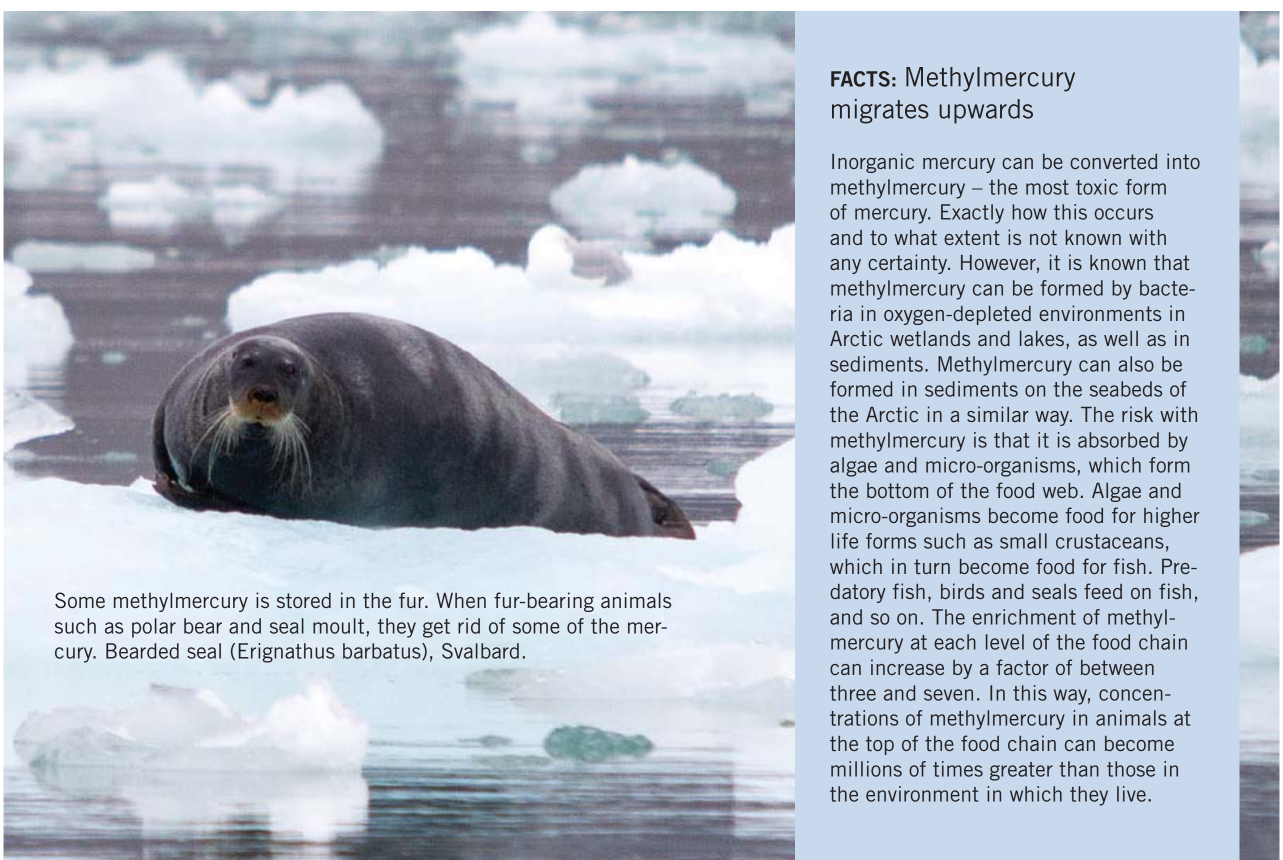
As the traditional diet of many ethnic groups in the Arctic, such as the Inuit, consists of fish, seal and whale meat, as well as the internal organs of seal and whale, they are particularly exposed to mercury and other environmental pollutants. Attention was drawn to this problem at an early stage and the public authorities in the countries concerned have disseminated information on the risks and provided advice concerning what and how often one can eat a traditional diet, as methylmercury from the mother can be passed to the foetus via the blood. Pregnant women and women of child-bearing age are recommended to completely refrain from eating food containing high mercury concentrations, as mercury been shown to cause direct harm to foetuses and breastfed children.

The Faroe Isles are a very special case, where pilot whales have been an important food. Concentrations of mercury in pilot whales are very high, and studies from the 1980s and 1990s showed that children breastfed by mothers who ate pilot whale meat suffered from minor, but very distinct, development disorders in the form of language learning skills and memory capacity, as well as visual and hearing impairments. The authorities then recommended that women of child-bearing age refrain from eating pilot whale meat completely. This advice was followed and since then mercury concentrations in the blood of this group of women have fallen by almost 90 percent.

Studies now show that mercury concentrations in the blood of women of child-bearing age are falling across the whole of the Arctic. Despite this, there are still mothers and young women amongst these ethnic groups in the Arctic who are taking in mercury via their food in quantities well above the recommended intake.

MERCURY IS DISPERSED IN THE ENVIRONMENT

Because of human activity, mercury concentrations in the air, water and land have risen sharply. For thousands of years, the mercuric mineral cinnabar has been used as a pigment in dyes and for extracting pure, metallic mercury. In turn, metallic mercury has for example been used in gold extraction, again for many thousands of years. However, the biggest increase occurred during the 20th century when industrialisation really took hold.



Some methylmercury is stored in the fur. When fur-bearing animals such as polar bear and seal moult, they get rid of some of the mercury. Bearded seal (Erignathus barbatus), Svalbard.

PHOTOGRAPH: MARK MARISSINK

FACTS: Methylmercury migrates upwards

Inorganic mercury can be converted into methylmercury – the most toxic form of mercury. Exactly how this occurs and to what extent is not known with any certainty. However, it is known that methylmercury can be formed by bacteria in oxygen-depleted environments in Arctic wetlands and lakes, as well as in sediments. Methylmercury can also be formed in sediments on the seabeds of the Arctic in a similar way. The risk with methylmercury is that it is absorbed by algae and micro-organisms, which form the bottom of the food web. Algae and micro-organisms become food for higher life forms such as small crustaceans, which in turn become food for fish. Predatory fish, birds and seals feed on fish, and so on. The enrichment of methylmercury at each level of the food chain can increase by a factor of between three and seven. In this way, concentrations of methylmercury in animals at the top of the food chain can become millions of times greater than those in the environment in which they live.

PHOTOGRAPH: MARK MARISSINK

Inhabitant of Aksarka, Yamalo-Nenets Autonomous Okrug, Tiumen Oblast, western Sibiria.

In drill cores from glaciers, the deposition of air pollutants from previous years accumulates in different layers. If the mercury content of these layers is analysed, it is possible to see how the deposition has changed over time. Drill cores from a glacier in the Rocky Mountains in the USA show how the quantity of mercury in the atmosphere has varied from the early 18th century through to the present day (Figure 2). Early variations in mercury concentrations in glacier ice could be linked to major volcanic eruptions, but during the latter part of the 19th century through to the present day, the distribution is completely dominated by human activity.

Current anthropogenic emissions of mercury into the atmosphere are estimated at around 2000 tonnes of mercury per year. Figure 3 shows the breakdown of the emissions between different activities. The largest contribution comes from small-scale gold extraction, which accounts for 37 percent of total emissions. Other important sources are the combustion of coal, various types of metal processing and cement production. New technology at coal-fired power stations and other activities have reduced mercury emissions in Europe and North America in recent decades, but they are increasing in developing countries both in Asia and elsewhere.

THE NATURAL MERCURY CYCLE

All mercury originates from bedrock. Before man began to exploit discoveries of coal, metals and other resources, the mercury in the air, land and oceans had only natural sources. The mercury in the oceans and on land is slowly returned to the mineral kingdom when it becomes bound in soils on land and in sediments in lakes and on seabeds. This is a very slow process which has been going on for thousands of years. In the past, there was probably some sort of balance

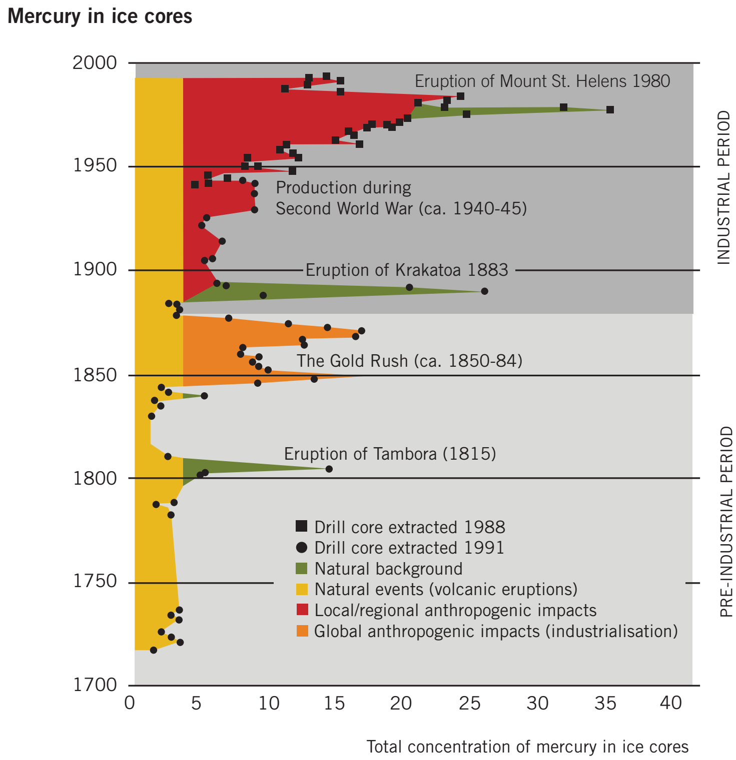


FIGURE 2. Analysis of mercury in ice cores from the Upper Fremont Glacier in the Rocky Mountains, USA (1 ng = 1 billionth of a gram). Source: Schuster et al. 2002.

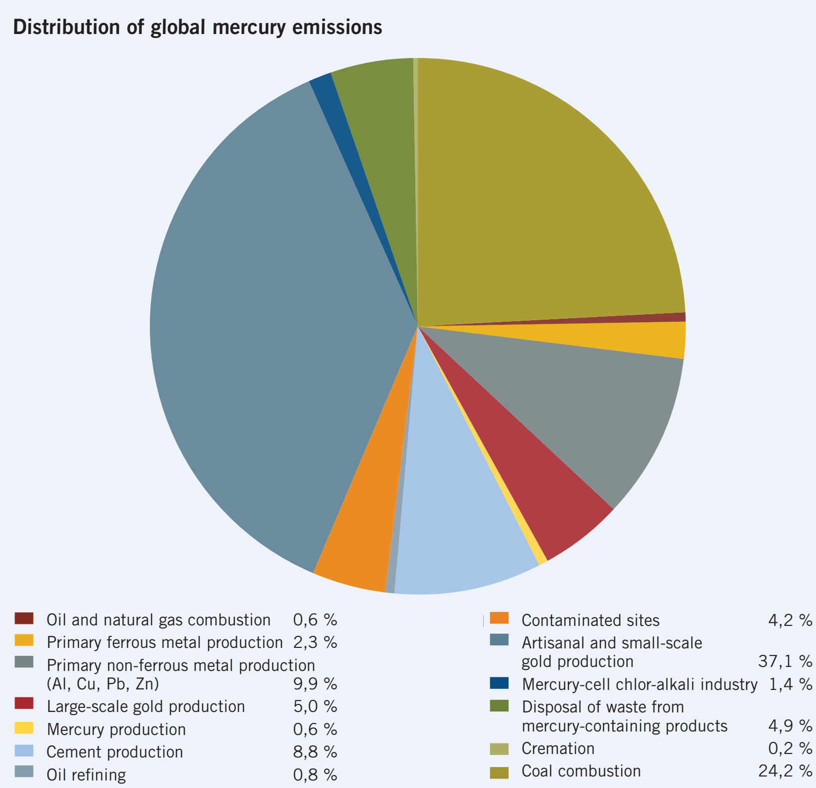


FIGURE 3. Global atmospheric emissions of mercury broken down between different sectors of society Source: AMAP report 2013.

FIGURE 4. Mercury has a complicated natural cycle and the figure shows a simplified illustration of this cycle. Mercury deposited on land and marine areas can be returned to the atmosphere. This extends the residence time of mercury in the environment.

FACTS: Mercury

Mercury (Hg) is a poisonous heavy metal which occurs in the Earth's crust at low concentrations, primarily in the form of the mineral cinnabar (HgS, i.e. mercury sulphide). The metal is unique in many ways as it has a lower melting point (-39°C) and a lower boiling point (357°C) than any other metal. This means that mercury is volatile at room temperature and can occur in gaseous form, i.e. as Hg atoms (Hg^0), in the atmosphere. Other than the noble gases, mercury is the only element which occurs as an atomic gas at normal temperatures. Mercury can also be found in inorganic and organic chemical pollutants. Airborne mercury largely consists of atomic mercury (> 98 percent) and small quantities of oxidised gaseous mercury, as well as mercury bound to particulate matter. Mercury atoms are relatively stable in air, which means that they have a long residence time in the atmosphere (about a year) and can be dispersed globally before they are oxidised and leave the atmosphere via wet or dry deposition. In other words, via deposition in connection with precipitation or in the form of dry particulate matter deposition. Oxidised mercury (Hg^{2+}) can be converted to methylmercury in damp and oxygen-depleted environments via natural biological processes. Methylmercury is the most toxic form of mercury in nature and is readily taken up and enriched in living organisms.

between the mercury that was being added to the atmosphere via volcanic eruptions and that which was being returned via sedimentation and conversion to bedrock. As a result of the release of large quantities of mercury in a relatively short period of time, this balance has been disturbed and mercury concentrations in the atmosphere are estimated to have risen by a factor of between three and seven compared with concentrations several thousand years ago. Mercury concentrations on land and in the oceans have risen correspondingly.

Mercury has a complicated cycle in nature. The largest dispersal takes place via the atmosphere in the form of gaseous mercury atoms. The metal can also occur on particulate matter in the air and there are also oxidised forms of mercury which are gaseous. Atomic mercury has a long residence time in the atmosphere, which means that it can readily be dispersed globally before it is oxidised and deposited on land and marine surfaces. The residence time is also prolonged through the fact that mercury can be reduced back to atomic form, which returns to the atmosphere in the gaseous state. It has been estimated the release of mercury from land and marine areas is equal to or greater than the direct emissions of mercury caused by man.

INTERNATIONAL WORK TO REDUCE EMISSIONS

Within the UNEP (United Nations Environment Programme), important efforts are being made to reduce global emissions of mercury. The Minamata Convention is an international agreement to reduce all use and emissions of mercury by man in order to protect humans and the environment. By March 2015, 128 countries had signed the convention and ten countries, including the USA, had ratified it, i.e. undertaken to follow the international agreement and introduced legislation to make this possible. The Minamata Convention is a major step forward in the right direction to reduce the occurrence of mercury in nature, but much work remains to be done.

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PHOTOGRAPH: HÅKAN RODHE

FACTS: AMDE

Atmospheric Mercury Depletion Events are cases where mercury in its basic form (Hg^0) is oxidised and deposited on snow and ice. The phenomenon occurs in the Arctic after the spring equinox. The process only takes a few hours and sometimes occurs from the end of March through to the beginning of May. The entire process is believed to be due to atmospheric reactions driven by sunlight and halogens, particularly bromine compounds, which occur naturally in the oceans and the ice. The phenomenon also leads to other gases such as hydrocarbons and ground-level ozone being oxidised. The amount of mercury transported to the Arctic via AMDE is not known with any certainty, but model calculations suggest that it could be up to 40 tonnes a year. This can be compared with the total annual transport of mercury to the Arctic, which has been estimated at around 200 tonnes. Some of this mercury can be converted to methylmercury and taken up in the Arctic food chain. This occurs late in the spring when the ice and snow melt. It is however unclear what effect AMDE has on the input of mercury to the Arctic, because as much as 80 percent of deposited oxidised mercury can be reduced back to Hg^0 in just a few days. It will then become biologically unavailable, and it may also be transported away from the Arctic.

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AMAP, 2011. Arctic Pollution 2011. *Artic Monitoring and Assessment Programme* (AMAP)
ISBN – 13 978-82-7971-066-0

AMAP/UNEP Technical Background report for the *Global Mercury Assessment* 2013. www.amap.no

Helen M. Amos, Daniel J. Jacob, David G. Streets, Elsie M. Sunderland. 2013. *Legacy impacts of all-time anthropogenic emissions on the global mercury cycle.* GLOBAL BIOGEOCHEMICAL CYCLES, VOL. 27, 410 – 421, doi:10.1002/gbc.20040

Paul F. Schuster et al. 2002. Atmospheric mercury deposition during the last 270 years: *A glacial ice core record of natural and anthropogenic sources.* Environ. Sci. Technol. Vol. 36, 2303-2310.

FACTS: Taiga

The Swedish pine forest environment forms part of the boreal taiga. This term is usually used to refer to Siberian pine and primaeval forest, but it is also used as a general term for the pine forest belt in the northern hemisphere. The taiga is one of the largest forest areas, with the majority of the Earth's pine trees, and accounts for around 29 percent of the total forest area on the planet. After the tundra, the taiga is the plant and animal community which has the lowest annual mean temperatures.

Mercury transport and deposition in Sweden

The pine forests of Sweden form part of the boreal taiga. Pollutants such as mercury are transported from the industrialised world and deposited in areas a long way from the sources, such as the taiga. Mercury is very toxic and has a complicated natural cycle. The transport of mercury in the ecosystem is affected by forestry, climate changes and other factors. The impact of forestry has attracted considerable attention, but research shows that it can have everything from a limited to a major impact on how mercury behaves. The climate changes can alter flows because of changes in precipitation patterns.

Mercury concentrations in precipitation have been measured since the 1980s in Sweden, initially as part of a research programme and since 1994 as part of the national environmental monitoring programme. Since 2000, measurements have been taken as a result of the EU's air quality directive. The number of measuring stations has fluctuated and currently covers five stations from Skåne to northern Finland (Figure 1). The deposition of mercury today is of the order of 2 – 8 µg/m^2, i.e. around two to three times lower than during the 1980s.

Measurements of mercury deposition clearly show two trends. Firstly, there is a geographic gradient with higher values in the south than in the north, clearly indicating the effect of sources in Europe. Secondly, deposition has also decreased sharply over time, particularly as a result of

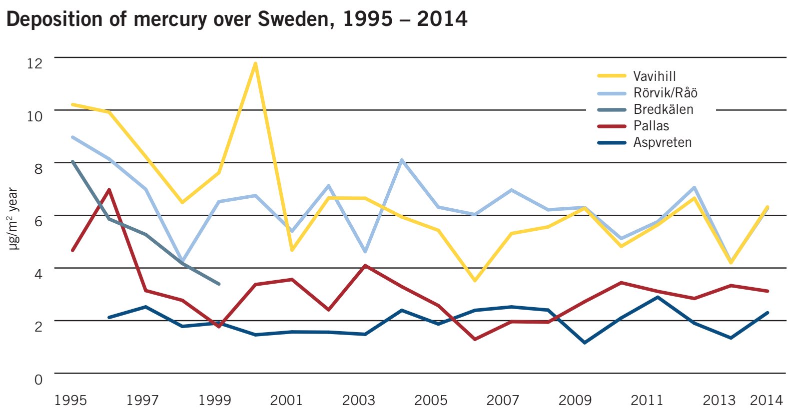

FIGURE 1. Deposition of mercury at some monitoring stations. The deposition is higher in southern Sweden (Vavihill, Råö/Rörvik) than in the northern part of the country (Bredkälen, Pallas (Finland)). Deposition has deceased in recent decades, particularly in southern Sweden. Source: Swedish Environmental Protection Agency's data host.

substantial reductions in emissions in Europe during the 1990s, and to a lesser extent during the 2000s. Emissions from Swedish sources are now low and have a relatively small impact on deposition in Sweden. Emissions in Europe have continued to fall during the 2000s, but deposition in Sweden is also affected by the global transport of mercury and emissions in China, for example, have risen over the same period that European emissions have decreased. The deposition has only been affected to a very limited extent in recent years. Leaching from forestry land to surface water

The mercury cycle in the environment is complicated and affected by both chemical and biological conversion processes. Transport between different parts of ecosystems can take place in the air and in water. Mercury binds relatively strongly to organic matter, with the result that substantial quantities of mercury have been stored on forestry land together with humus. The leaching of mercury from forestry land to surface water is an important source of the load in lakes and watercourses, in some cases greater than atmospheric deposition. Under certain circumstances, the leaching of methylmercury can also be considerable.

EFFECTS OF FORESTRY

The transport of mercury from forestry land to surface water accounts for only a fraction of the amount of mercury which is stored in the ground, but can still be an important source for lakes and watercourses.

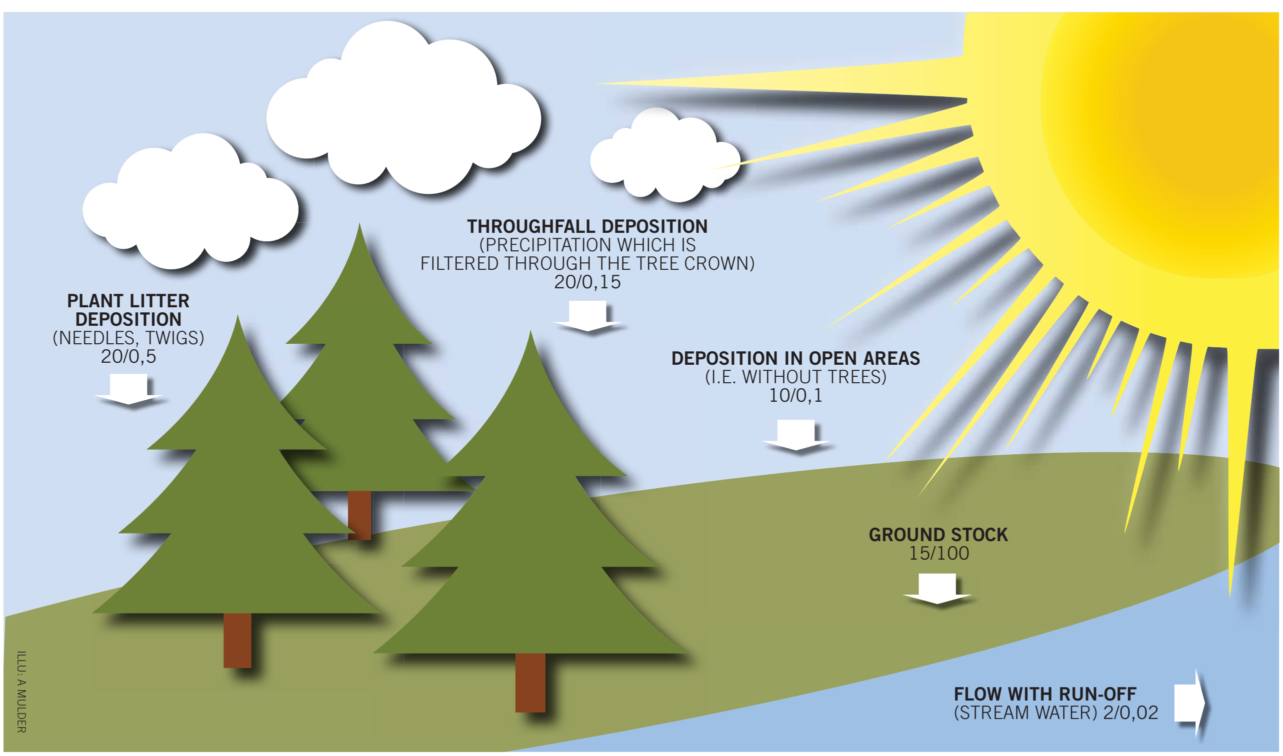

FIGURE 2. Stocks and flows of mercury or methylmercury in forest ecosystems based on measurements taken during the 1990s. Typical flows and stocks of mercury in a forest ecosystem. Figures on the left – total mercury (µg/m²). Figures on the right – methylmercury (µg/m²). Ground stocks are specified in g/m² for total mercury and µg/m² for methylmercury.

Relatively minor changes in leaching can therefore also cause a substantial increase in the load. The factors that determine how mercury binds to and leaches from forestry land are as yet unclear to some extent. Substantial variations occur between catchment areas, but the leaching of mercury has for example been shown to correlate closely with the leaching of organic matter. Catchment areas with a high proportion of wetland leach methylmercury more readily to the surroundings than podzol soils, for example.

The impact of forestry on the leaching of mercury, particularly methylmercury, has attracted considerable attention since it was first discovered about ten years ago. The flow of mercury is partly affected by the fact that deforestation changes the water balance of the land, but damage caused by forestry machinery is the main factor. Studies of the effects of forestry show variable results, covering everything from zero effect to a major effect, but in summary the impact is greatest in areas which had low levels of leaching before the land was damaged. Areas which already had high leaching levels before felling took place are however affected to a lesser extent.

CHANGING CLIMATE HAS AN IMPACT

Climate changes can impact on leaching from forestry land, primarily through the resultant increase or decrease in precipitation and changes to flows which can alter the water balance of the land. Higher temperatures can also accelerate the degradation of organic carbon, which would otherwise bind mercury in the ground, and speed up the production of methylmercury.

At present, there is unfortunately very little information available concerning the impact of climate change on mercury leaching. In a study conducted in the Gårdsjö area, 50 km north of Gothenburg, involving experimental watering of a small catchment area corresponding to a 50 percent increase in precipitation, mercury and methylmercury leaching increased sharply, but it is difficult to generalise the findings from this experiment.

FACTS: Methylmercury

All forms of mercury are poisonous to humans, but methylmercury is the only form which occurs in the environment in concentrations which can harm people, even though it only accounts for a very small proportion overall. This is because methylmercury is readily taken up by organisms and accumulated in food webs in our lakes and watercourses. Today, around half of the country's lakes contain mercury concentrations above the international standards which have been set for protecting the most vulnerable individuals, which in this case is foetuses. Pregnant women should therefore not eat certain forms of freshwater fish, as there is a risk of foetal damage.

www.livsmedelsverket.se (Swedish National Food Agency)

CLEO PROCESSES NATIONAL DATA

The CLEO research programme collates and processes statistical national data concerning mercury in run-off water together with information concerning climate, catchment area characteristics, etc. The results have been used to calculate and scale up the impact that forestry may have at national level. Preliminary analyses show that intensive new forestry on 15 percent of Sweden's forested land would cause the mercury load on surface water to increase from the current 347 kg/year to 413 kg/year. The corresponding figures for methylmercury are an increase from 25 to 36 kg/year.

FISH CAN BE AFFECTED FURTHER

The increased load on surface water might be expected to impact on mercury concentrations in fish, but by how much is difficult to assess. Mercury in fish in Swedish lakes often exceeds the EU's thresholds and the recovery process is slow, despite the reduction in deposition. Even minor changes in the load can prolong the future recovery of fish.

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FACTS:

Mercury in the environment

Mercury is an element which occurs everywhere in our ecosystems. During the industrialisation, mercury emissions from industry and the combustion of coal, among other things, increased. This has resulted in higher concentrations in the air, soil and water. Mercury has often been used in many industrial processes and products, with mercury thermometers being perhaps the best known application. The presence of mercury compounds in the country's lakes and watercourses is the result of historical national emissions and the long-distance transport of mercury from emission sources in Europe and globally.

Mercury's properties, mobility and harmful effects vary depending on its chemical form. Elementary, metallic mercury is a liquid metal which is also volatile, which means that it can evaporate into the air and be transported over long distances. In precipitation, lakes and the oceans, mercury mostly occurs in its oxidised, water-soluble state, while on forested land and sediments it is bound to organic matter. A very small proportion of the total amount of mercury in the environment consists of organic mercury, known as methylmercury.

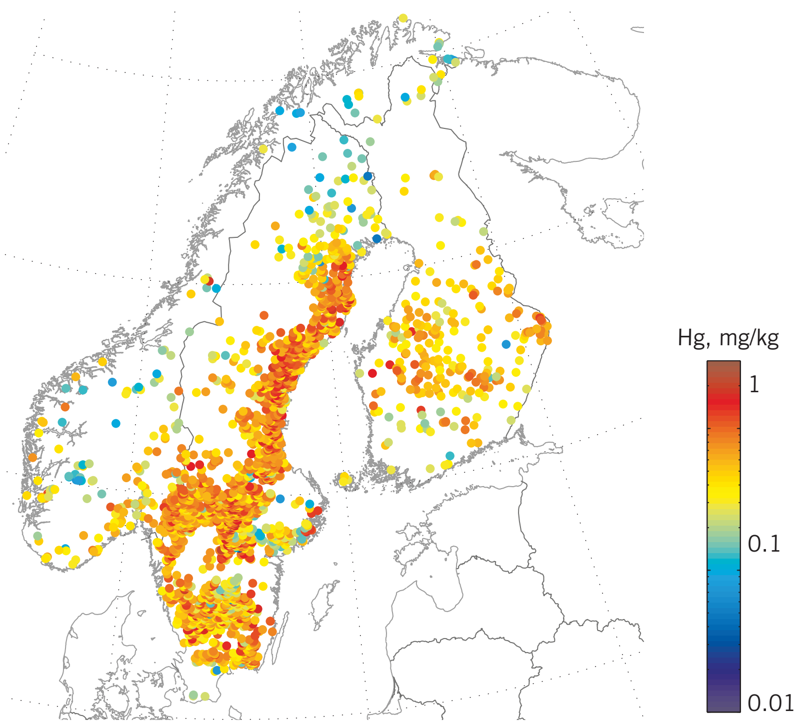

FIGURE 3. Mercury in pike (1 kg) in Nordic lakes. The figure is based on data collected during the period 1965 to 2004. Red values above the threshold of 1.0 mg/kg (measured in muscle) mean that the fish cannot be sold as food under EU rules. Source: Swedish Environmental Protection Agency's data host.

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PHOTOGRAPH: CINDY MILLER HOPKINS/DANITA DELIMONT

FACTS:
Stockholm Convention

The aim of the UNEP Stockholm Convention is to protect human health and the environment from persistent organic pollutants (POPs). This is to be achieved by prohibiting and limiting production, use, trade and storage, and by minimising or where possible eliminating emissions of unintentionally formed POPs. The long-distance transport and occurrence of organic substances in the Arctic environment are important parameters for the regulation of substances under the Stockholm Convention.

Environmental pollutants are being transported to the Arctic via the atmosphere

Persistent organic pollutants, known as POPs, occur in the Arctic environment even though they have never been used or released there. They are primarily transported there via the atmosphere from sources in Europe, for example. Once there, they can pollute both aquatic and terrestrial ecosystems via atmospheric deposition, e.g. in the form of rain or snow.

A GROUP OF SUBSTANCES WHICH commonly occurs in Arctic regions is polychlorinated biphenyls, PCB. These industrial chemicals are harmful to health and the environment, and they are still present in the environment even though they have been banned since the 1970s. They are stored in sediments, animals and plants, for example. PCBs are one of the most studied environmental pollutants and are therefore often used as indicators to describe how pollutants with similar properties can be transported in the environment. Many chlorinated pesticides which are prohibited today also occur in the Arctic environment. Examples of such pesticides are hexachlorocyclohexanes (HCHs), which have been used worldwide in the past.

LONG-DISTANCE TRANSPORT

The way in which chemicals move and are distributed in the environment depends on the physical and chemical properties of the substance and where and how they were released. Many POPs belong to the "semivolatile" group of organic substances, i.e. they occur in the air both in the gaseous phase and bound to particulate matter. The form in which a substance occurs in the atmosphere is important for its further dispersal in the environment.

The airborne transport of persistent, i.e. long-lived, organic substances from the regions where the substances are used and released to the Arctic takes place through a number of climatic zones. This can be described as what is known as 'global fractioning' – the repeated evaporation and deposition of the substances, which partly depends on the air temperature and the physio-chemical properties of the substances concerned. When persistent organic substances are transported from warmer to colder regions in accordance with this principle, it is called the 'grasshopper effect'.

Many organic environmental pollutants have been found in the air, water, ground, plants and animals in the Arctic. Persistent substances which reach the Arctic can bioaccumulate in food webs. Animals and humans are exposed via food and it is amongst these top consumers that they accumulate in the highest concentrations.

MEASUREMENTS IN THE AIR

Within the framework of the EPA's air monitoring programme, measurements are taken of concentrations of organic environmental pollutants and atmospheric deposition at a subarctic station in northern Finland (Pallas) and on Sweden's west coast (Råö) and east coast (Aspvreten). These measurements will tell us more about the sources and dispersal paths which may exist, as well as the importance of long-distance airborne transport. The subprogramme began in the mid-1990s, making it possible today to analyse temporal trends in concentrations in both air and deposition. The measurements are a part of both the European (EMEP) and the Arctic (AMAP) measurement programmes.

That PCBs can be transported over long distances is apparent from the fact that they occur in background air both in the Arctic and in northern Finland. PCB concentrations at Pallas in 2013 were at the same level or somewhat higher than the corresponding concentrations at the Zeppelin Arctic research station on Svalbard (see Figure 1). PCB concentrations have generally been higher in southern Scandinavia, since it is closer to the sources, than in northern Finland.

Concentrations of PCBs at Pallas have declined since the measurements began, but interannual variations with higher concentrations do occur (see Figure 2). Trend calculations show that PCB concentrations at Pallas and Råö have decreased by between two and five percent per year during the measurement period. The reduction in PCB concentrations is slow, indicating that PCBs have accumulated in both society and the ecosystem.

Atmospheric concentrations of PCBs at Pallas vary between the seasons. They are highest in the summer and lowest in the winter. This indicates that PCBs are returned to the atmosphere from

Sum of PCBs in the atmosphere at monitoring stations, 2013

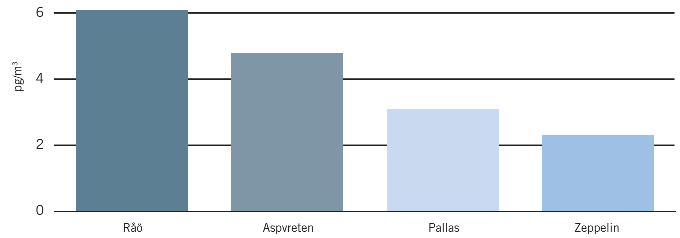

FIGURE 1. Concentrations of sum PCB 7 (the sum of seven congeners – variants of PCB) in the atmosphere at Råö, Aspvreten, Pallas and Zeppelin (Svalbard). Annual mean values 2013. Source: EBAS database and the Swedish Environmental Protection Agency's data host.

Sum PCB 7 in the atmosphere, Pallas 1996 – 2013

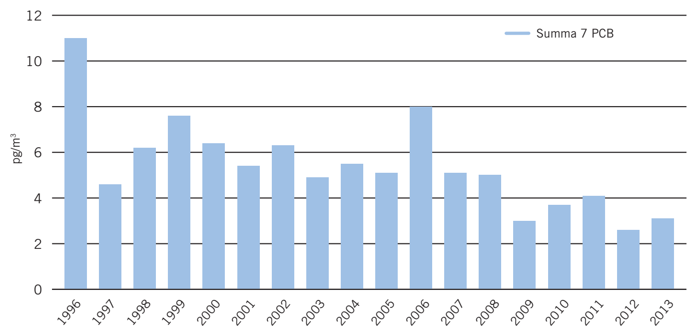

FIGURE 2. Concentrations of sum PCB 7 in the atmosphere at Pallas. Annual mean values. Source: Swedish Environmental Protection Agency's data host.

HCHs in the atmosphere at the monitoring stations, 2013

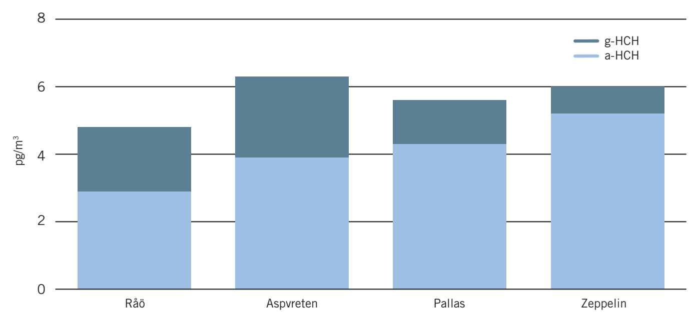

FIGURE 3. Concentrations of alpha- and gamma-HCHs in the atmosphere at Råö, Aspvreten, Pallas and Zeppelin (Svalbard). Annual mean values for 2013. Source: EBAS database and the Swedish Environmental Protection Agency's data host.

HCH in the atmosphere, Pallas, 1996 – 2013

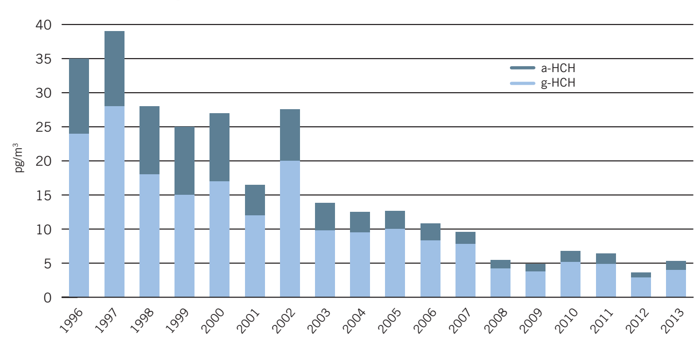

FIGURE 4. Concentrations of HCHs in the atmosphere at Pallas, annual mean values. Source: Swedish Environmental Protection Agency's data host.

PHOTOGRAPH: HÅKAN RODHE

Measuring station, Adventdalen, Svalbard.

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AMAP, Arctic Monitoring and Assessment Program: www.amap.no

EBAS database: www.nilu.no.

Environmental pollutant effects on biota in the Arctic: www.ArcRisk.eu

Swedish Environmental Protection Agency's data host www.ivl.se/datavard-luft

aquatic and terrestrial environments when temperatures rise because of increased evaporation (see "grasshopper effect" above). It is therefore not new sources which are giving rise to the higher PCB concentrations during the summer. Figure 3 shows the concentrations of alpha and gamma HCHs. Unlike PCBs, concentrations of HCHs are at about the same level in the north and the south. HCHs are more volatile than PCBs and occur in the atmosphere in the gaseous phase.

HCH concentrations in the atmosphere have fallen markedly since measurements began in the mid-1990s. This reduction reached a peak during the early years of the measurements and levels have since stabilised (Figure 4). Trend calculations show that HCHs have decreased by an average of around six percent per year. Both alpha- and gamma-HCHs are listed in the Stockholm Convention and the use of these substances is prohibited or heavily restricted.

NEW SUBSTANCES AND NEW THREATS

The monitoring of concentrations of different substances in the air, water, ground, plants and animals represents a powerful tool and help us to understand changes and trends in different pollutants. The long-term monitoring of persistent organic pollutants in the atmosphere which takes place in Scandinavia and the Arctic regions is important in order to assess trends over time and follow up different measures, national environmental quality objectives and international legislation. The measurements taken at Pallas and the other Swedish stations are of considerable value in mapping the dispersal and concentrations of different chemicals in the atmosphere and in Arctic regions.

In addition to the above mentioned pollutants, the Swedish national air monitoring programme covers a large number of other substances. This includes environmental pollutants which are now prohibited, unintentionally formed substances and 'new' chemical substances which have been released onto the market – known as substances of 'emerging concern'. Under the EPA's screening programme, a large number of new chemicals and their occurrence in the environment have been mapped. Examples of chemicals which have been found in Arctic regions are brominated flame retardants such as polybromiated diphenyl ethers (PBDE) and pesticides such as endosulfan. These are now included in the atmospheric monitoring programme at Pallas.

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FACTS: AMAP

Arctic Monitoring and Assessment Program, AMAP, is a working group under the Arctic Council which provides information on the status of and threats to the Arctic environment. The working group also provides scientific advice and supports the Arctic governments in their efforts to implement corrective and preventive measures relating to pollutants and their adverse effects. Data from Swedish atmospheric monitoring stations such as Pallas is used in AMAP's evaluations.

How ocean acidification affects the Arctic

Around 30 percent of our atmospheric carbon dioxide emissions to date have been taken up by the oceans globally, a process which is still continuing today. Without the oceans, the greenhouse effect would therefore have been much stronger than it is. When carbon dioxide is dissolved in the oceans, it causes the pH to drop. How are the oceans around the Arctic affected when the pH drops?

The combustion of fossil fuels has increased carbon dioxide concentrations in the atmosphere dramatically since the end of the 19th century. Today, concentrations are typically around 400 ppm, compared with approximately 280 ppm in 1750 before the industrial revolution.

The pH of the oceans globally has dropped by between 0.1 and 0.2 pH units. This might seem a small decrease, but as pH is a logarithmic scale, the drop is actually quite considerable. Relatively reliable forecasts for pH change indicate that the pH of the oceans is likely to drop by around 0.4 units by the year 2100. There is no evidence to suggest that such rapid changes in the acidity of marine waters have ever occurred in the past. Water with a pH of 7 is considered to be neutral. The term 'ocean acidification' is used, although from a chemical perspective, the oceans are still basic rather than acidic.

However, they are becoming increasingly acidic. In the cold Arctic Ocean, the pH is lower than in warm oceans, as the carbon dioxide dissolves more readily in the cold water. Modelling of the ocean currents around the Arctic and the exchange of carbon dioxide between the atmosphere and the oceans indicates that the pH will drop at a faster rate here than further south. At certain times of the year, the pH of the surface water in the Arctic will probably be so low that aragonite, a form of calcium carbonate which occurs in mussel shells and corals for example, could dissolve.

ORGANIC MATTER HAS AN IMPACT

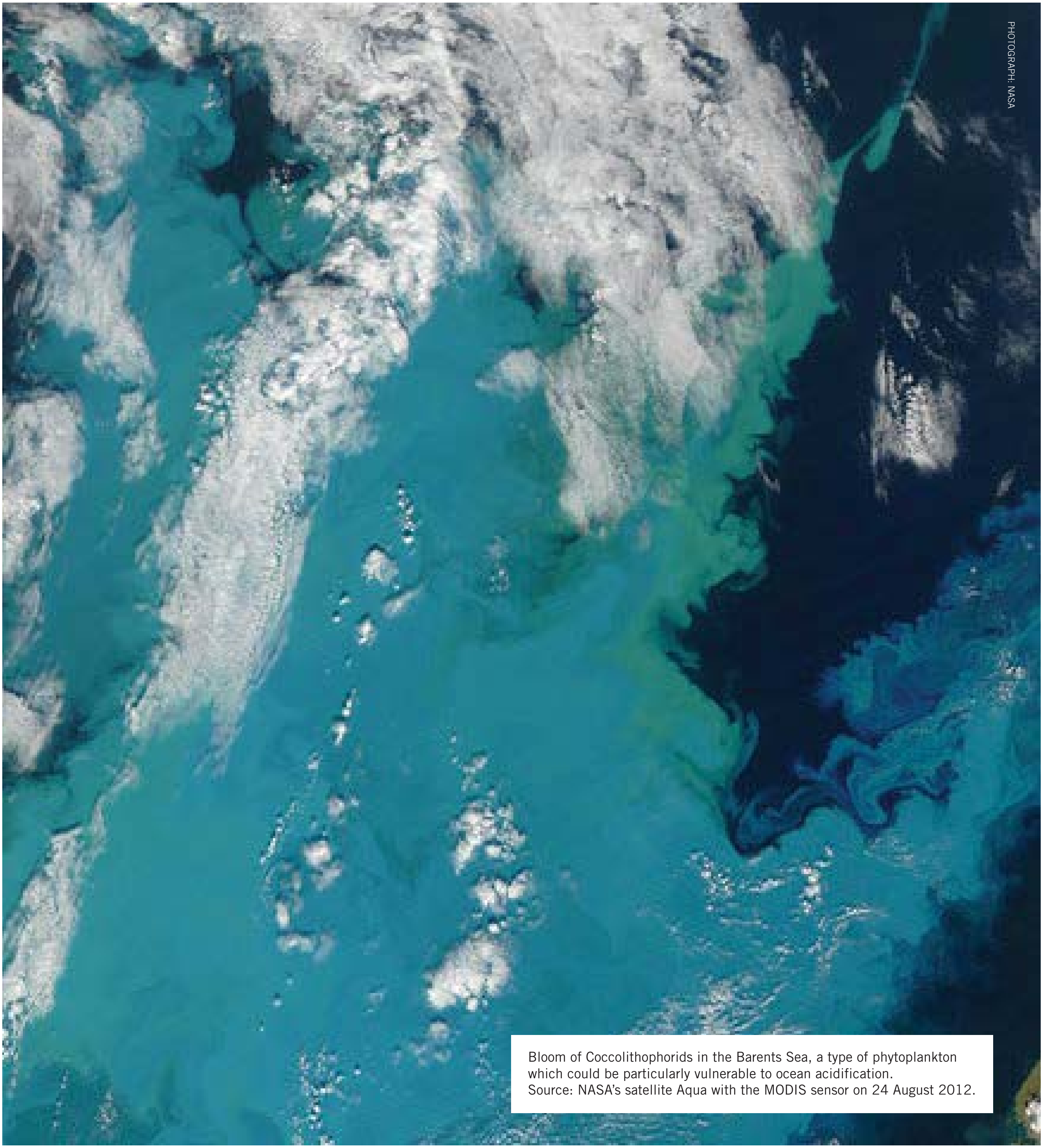
An increase in run-off from rivers in the Arctic into the oceans complicates the issue. One effect which has been observed in recent years is that large quantities of organic matter are being supplied to coastal waters from land. These quantities are likely to increase further if the permafrost thaws. When organic matter is degraded, oxygen is consumed, at the same time as carbon dioxide is formed and the pH drops. Other more short-term effects on pH include algal blooms, which increase the pH as the phytoplankton absorb carbon dioxide as they grow with the aid of photosynthesis.

PHYTOPLANKTON REACT DIFFERENTLY

What might ocean acidification mean for the Arctic Ocean and other oceans in the Arctic? The entire ecosystem will probably be affected, but it is difficult to know exactly how, as acidification is taking place alongside other changes. Questions which must be asked include: how is the layering of the water affected by higher water temperatures and changes in run-off?

However, some processes are worth highlighting. The growth of phytoplankton may be favoured generally as carbon dioxide becomes more readily available in the oceans. This could result in more algal blooms. Studies have shown that phytoplankton species can react in different ways. In an experiment conducted on Svalbard, large plastic bags were filled with seawater. The pH of the water was then adjusted

PHOTOGRAPH: PETER PROKOSCH



Bloom of Coccolithophorids in the Barents Sea, a type of phytoplankton which could be particularly vulnerable to ocean acidification.
Source: NASA's satellite Aqua with the MODIS sensor on 24 August 2012.

and the subsequent impact on the phytoplankton community studied. It was apparent that small phytoplankton were favoured over larger ones when the pH fell. Other experiments have shown that phytoplankton covered by mats of calcium carbonate are adversely affected by a lower pH. These phytoplankton are called Coccolithophorids and can produce blooms in the Arctic which are so large that they are clearly visible on satellite images (see photo). Recent studies also indicate that Coccolithophorids can adapt to changes in pH, which could even enable them to thrive at a lower pH.

PHOTOGRAPH: ISTOCK

There is a risk that mussels in the oceans will be increasingly replaced by sea urchins.

SEA SQUIRTS INSTEAD OF MUSSELS

Animals which have a calcareous skeleton, such as mussels, shells, sea urchins and some cold-water corals, may also be particularly vulnerable to ocean acidification. Experiments looking at this issue have also shown that there is considerable variation between species. Some appear to cope well with the acidification, whereas others are more vulnerable. Larval stages are probably more sensitive to a drop in pH compared with adult individuals. If organisms with a calcareous skeleton are disadvantaged relative to other organisms, major changes in the ecosystem might occur. There is a risk that mussels could be replaced by sea urchins to some extent. The changes will also affect the so-called ecosystem services in the oceans, including fisheries.

CHALLENGES FOR THE MONITORING PROGRAMME

Changes linked to ocean acidification and other climate changes are imposing new demands on environmental monitoring in the Arctic. It is important to establish sampling locations with frequent and long-term measurements of marine biological, chemical and physical parameters. Automatic measuring systems can be used to some extent, but sampling from research vessels and marine biological stations form the heart of a monitoring station. There are also measuring systems onboard cargo vessels in the region, e.g. between northern Norway and Svalbard. In the Baltic and North Sea region, it is common for ferries and cargo vessels to carry what are known as Ferry-Box systems onboard. These systems are used to automatically measure various parameters such as carbon dioxide concentrations in the water and air. Automatic water sampling also takes place in order to collect samples for laboratory analysis. As the ice cover in the Arctic shrinks, cargo shipping traffic increases. This enables more cargo vessels to be used as environmental monitoring platforms. Remote analysis can also provide information on algal blooms under cloudless conditions and could ultimately reveal more about changes linked to the greenhouse effect and ocean acidification.

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The effects of Arctic climate change on the weather in Sweden

PHOTOGRAPH: PER ERIKSSON/JOHNÉR

The Arctic climate has changed rapidly over the past thirty years. Observations indicate that the temperature in the region has risen more than twice as fast as the global mean temperature. The climate changes are affecting the Arctic, but how will these changes affect the weather systems further south?

The extent of the sea ice, particularly during the summer and autumn, has decreased by over 30 percent, and the thickness of the ice cover has reduced by even more. Snow on the Arctic land masses is melting earlier in the spring. Less ice and snow is leading to stronger exchange processes between the relatively warm ocean and the colder atmosphere. This is having a major impact on the local climate and resulting in much higher temperatures, less stable temperature layering in the atmosphere and more precipitation.

An amplified warming in the Arctic leads also to a decreased temperature gradient between the Arctic and lower latitudes, particularly in autumn and winter. This temperature difference is one of the key drivers of the large-scale atmospheric circulation over land areas south of the Arctic, including Sweden.

A WARM ARCTIC MEANS A RISK OF COLD WINTERS FOR US

Whereas the Arctic regions have become increasingly warm, several cold temperature spells and heavy snow events have occurred in Europe, Asia and North America in recent years. The trend of warmer winter temperatures in these regions has been significantly smaller than the global mean warming trend. Many recent winters show what is known as a 'warm Arctic – colder further south' pattern. In Sweden too – after a long period of predominantly mild winters between 1990 and 2005 – we have experienced three cold winters in recent years.

Many climate studies investigated this possible linkage between the ice reduction in the Arctic and winter weather patterns in Europe and Asia. These studies have involved both data analysis and simulations using climate models . The results are not entirely conclusive, but many studies point to a link between less ice and fewer low pressure systems over the North Atlantic. Fewer low pressure systems over the Atlantic mean weaker westerly winds in Sweden and

Winter temperatures, trend 1982 – 2013

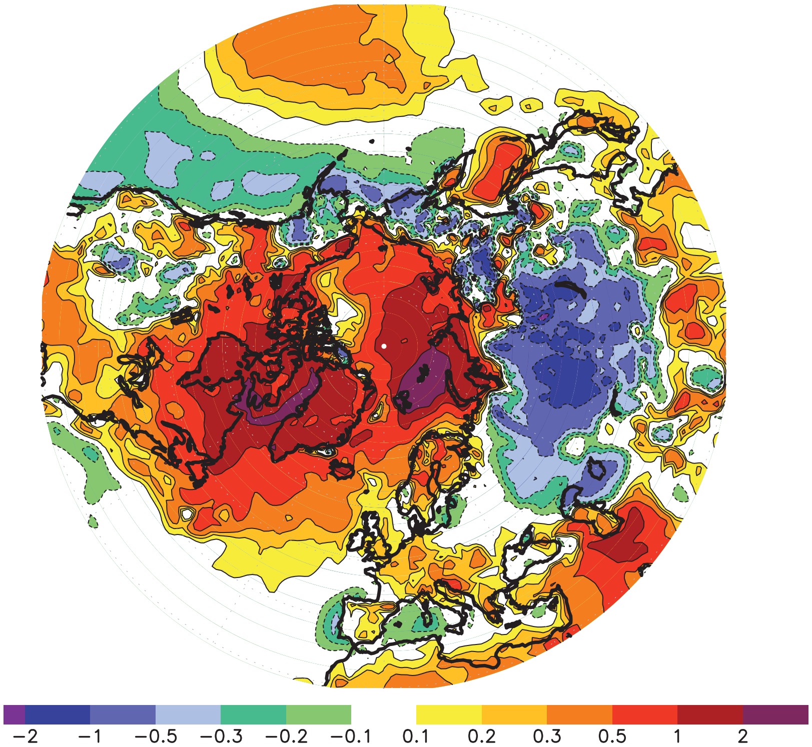

FIGURE 1. Temperature trend during the winter, measured during the period 1982 – 2013. The figure shows temperature changes in °C per 10 years. The largest change occurs in the Barents Sea and Baffin Bay, over 2°C in ten years. This is because the sea ice has shrunk in these areas. In Eastern Europe and Asia, it will become that much colder as a result of changes in winds.

an overall tendency towards colder winters.

Some studies also suggest a stronger north-south component of the large-scale wind systems, as well as longer spells with the same weather conditions. For Sweden, this could not only mean longer cold spells, but also longer periods with warm southerly winds. Although we had three cold winters in 2008 – 2009, 2009 – 2010 and 2012 – 2013, the winters of 2007 – 2008, 2013 – 2014 and 2014 – 2015 saw record high temperatures in some parts of Sweden.

RISK OF MORE HEATWAVES

The reduction in ice in the Arctic has the biggest impact on atmospheric circulation in the winter because of much stronger changes in heat flows between the oceans and ice at this time. This results in larger changes in the temperature difference between the Arctic and the mid-latitudes (the area between 40°N and 60°N) than during the summer. However, there are indications that even summer weather may be affected by the shrinking ice cover. Studies also show a trend with fewer westerly winds during the summer. The consequence of this could be increasing risk for heatwaves in the future, as well as more periods of continuous rain in Sweden. However, the link between summer trends in Europe and the shrinking of the Arctic ice is still very uncertain.

SHORT TIME SERIES

Climate change studies involving the sea ice are based on relatively short time series. No reliable observations of the Arctic ice from satellite data were available before 1978. This is leading to some uncertainty as to whether the link between the ice cover and atmospheric currents during the winter is real or random. It is also unclear whether the link is dependent on how much the ice shrank and in which area it shrank the most. Accelerated sea ice reduction in the Arctic could also lead to more warming south of the Arctic, e.g. in Russia and Eastern Europe, as northerly winds carry less cold air southwards when the Arctic continues to warm up. At the same time, this would also lead to fewer extreme cold spells, a development also indicated by the climate models.

Further research is needed to determine how Arctic climate changes will impact on the weather in Sweden. Research is also required to better understand the processes which link the Arctic climate to the prevailing climate at more southerly latitudes.

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SUGGESTED READING:

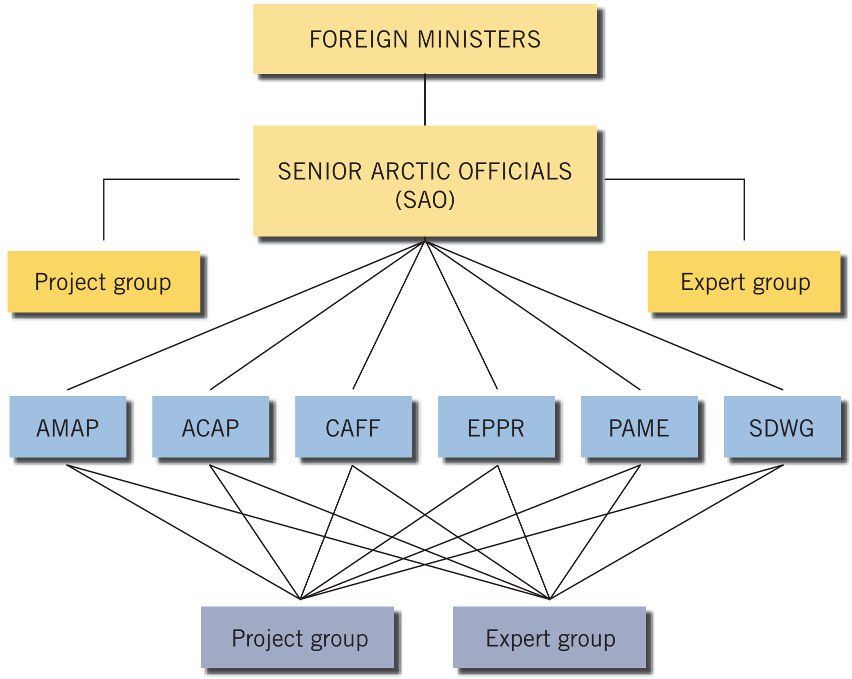
Coumou, D., J. Lehmann & J. Beckmann, 2015. *The weakening summer circulation in the Northern Hemisphere mid-latitudes.* Science, doi: 10.1126/science.1261768.

Overland, J.E., J.A. Francis, E. Hanna & M. Wang, 2012 *The recent shift in early summer Arctic atmospheric circulation.* Geophys. Res. Lett. 39, doi:10.1029/2012GL053268.

Vihma, T, 2014. *Effects of Arctic Sea Ice Decline on Weather and Climate: A Review.* Surv Geophys 35: 1175-1214, doi: 10.1007/

The Arctic Council

The Arctic Council is the Arctic States' collaborative forum to promote responsible development in the region. It is the only political collaborative body for Arctic issues to involve all countries in the region north of the Arctic circle. This work has been under way for almost twenty years and the challenges being faced are not decreasing in number.



AMAP: Arctic Monitoring and Assessment Programme **ACAP:** Arctic Contaminants Action Programme **CAFF:** Conservation of Arctic Flora and Fauna **EPPR:** Emergency Prevention Preparedness and Respons **PAME:** Protection of the Arctic Marine Environment **SDWG:** Sustainable Develeopment Working Group.

The main aim of the Arctic Council is to protect the Arctic environment and to promote the sustainable development of the region. These efforts are aimed at improving the economic, social and cultural well-being of those living in the Arctic.

The Council is not based on any legally binding agreement, but has its origins in a collaboration between the environmental ministers of the Arctic States, known as the Rovaniemi Process. This collaboration led to a declaration to protect the Arctic environment. In recent years, other issues have also been added to the agenda, including issues which concern the interests of trade and industry. The Arctic Council has a mandate to consider all issues, except for military security.

POLITICAL RECOMMENDATIONS

The Council is chaired by the foreign ministers of the member countries and meets every other year. After each meeting, the Arctic Council publishes a ministerial declaration. The recommendations set out in this declaration are aimed at the member countries and the intention is for them to be implemented nationally in each country. Although the recommendations are not legally binding, they are politically binding. The chairmanship rotates between the countries and lasts for two years. Between the ministers' meetings, the work is led by a committee of Senior Arctic Officials (SAO), which meets at least twice a year. The formal decisions of the Arctic Council are taken at the ministers' meetings through a consensus.

FACTS: Members of the Arctic Council

The Arctic Council was established in 1996 in Ottawa following an Arctic meeting of environment ministers.

The member countries are the eight Arctic States of Denmark, Finland, Iceland, Canada, Norway, Russia, Sweden and the United States. The Council is one of the few international collaborative bodies with representatives of indigenous peoples with permanent participant status. In addition to the member countries and the permanent participants, there are also observers; twelve countries and non-profit and international organisations.

THE CHAIRMANSHIP DETERMINES THE PRIORITIES

Canada's chairmanship ended in April 2015 and the USA have now taken over. Through its chairmanship programme, the country which chairs the Arctic Council has considerable influence over the issues which the Council will consider over the following two years.

The USA will place the emphasis on the Arctic Ocean during its chairmanship. The issues considered will include maritime safety, acidification, scientific understanding and the negotiation of a regional marine programme. Better living conditions and underlying economic conditions for the indigenous peoples will also be prioritised. The impact of climate changes on the Arctic is another priority issue.

ORGANISATION OF THE COUNCIL

The work is primarily carried out by six working groups consisting of experts from ministries, public agencies and research institutions. These working groups have different orientations and deal with issues such as climate changes and other environmental impacts in the Arctic region, environmental monitoring, environmental protection issues, biodiversity, marine issues and issues concerning the indigenous peoples. The working groups establish and work in projects, programmes and expert groups as determined by the committee of Senior Arctic Officials.

The results of the working groups' efforts are often presented in scientific reports, which have often attracted considerable attention on the international stage. Based on these reports, the Arctic Council submits recommendations to the member countries, which should then follow up and implement them.

PHOTOGRAPH: HÅKAN RODHE

RECENT INITIATIVES

Biodiversity, marine issues and climate are issues which are accorded a high priority by the Arctic Council.

- The efforts to reduce climate forcers have resulted in an 'Arctic Council Framework for Action on Enhanced Black Carbon and Methane Emissions Reductions'. This framework focuses on ambitious national and collective activities and was approved at the meeting of foreign ministers in April 2015.
- The report entitled 'Arctic Ocean Acidification' and associated follow-up. The first report to consider ocean acidification from an Arctic perspective.
- The report entitled 'Arctic Biodiversity Assessment' and the follow-up of its recommendations. This report evaluate the status and trends of Arctic biodiversity. The report has provided a basis for global and regional evaluation and will continue to guide the Arctic Council with regard to issues concerning biodiversity.
- 'Arctic Search and Rescue Agreement' has been adopted and the work within this area is ongoing.
- A new 'Arctic Marine Strategic Plan' for 2015 – 2025 has been drawn up and was approved at the meeting of foreign ministers in April 2015.
- An overarching collaboration with indigenous peoples has also been given a high priority and is now included in the programmes of all working groups.

SWEDEN AND THE ARCTIC COUNCIL

On behalf of Sweden, the Ministry of Foreign Affairs holds the formal posts in the Arctic Council, handles negotiations and takes decisions under the leadership of the Minister for Foreign Affairs. The issues are prepared at national level, together with the relevant ministries and public agencies.

The Ministry of the Environment and Energy plays an important role in the Arctic Council, as most issues considered by the Council relate to the environment. Sweden is active in all six working groups and the EPA participates as Sweden's representative in three of them. ACAP (Arctic Contaminant Action Program), AMAP (Arctic Monitoring and Assessment Programme, see fact box) and CAFF (Conservation of Arctic Flora and Fauna). The overarching objectives for the EPA's participation in the Arctic Council are to:

- contribute to attainment of national environmental objectives,
- contribute to ensuring that Swedish priorities are reflected in the analyses and investigations of international organisations.
- contribute to ensuring that Swedish experiences and knowledge are safeguarded in underlying material and analyses,
- develop environmental efforts in line with EU directives and international conventions,
- contribute to the dissemination of knowledge in Sweden concerning underlying scientific information and reports, and
- contribute to the follow-up of guidelines in Sweden's Arctic strategy.

During the Swedish chairmanship between 2011 and 2013, the Swedish government adopted the first national strategy for the Arctic. The aim of this strategy for the Arctic region is to set out, in an international perspective, Sweden's approach to the Arctic, our priorities and the way in which Swedish policy concerning the Arctic should be developed. The strategy has three thematic areas: Climate and environment, Economic development and The human dimension.

From Sweden's strategy for the Arctic Region:
'The Arctic region is in a process of far-reaching change. Climate change is creating new challenges, but also opportunities, on which Sweden must take a position and exert an influence. New conditions are emerging for shipping, hunting, fishing, trade and energy extraction, and alongside this new needs are arising for an efficient infrastructure. New types of crossborder flows will develop. This will lead state and commercial actors to increase their presence, which will result in new relationships. Moreover, deeper Nordic and European cooperation means that Sweden is increasingly affected by other countries' policies and priorities in the Arctic. It is in Sweden's interest that new emerging activities are governed by common and robust regulatory frameworks and above all that they focus on environmental sustainability'.

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SUGGESTED READING:

The Swedish National Audit Office's reports concerning the Arctic Council, including: *Sverige i Arktiska rådet - effektivt utbyte av medlemskapet?* Riksrevisionen RIR 2013:9. These reports can be found at: www.riksrevisionen.se; search for the Arctic Council (Arktiska rådet).

Sweden's strategy for the Arctic Region. www.regeringen.se, search for the title

Arktiska rådet – Arctic council: www.arctic-council.org

PHOTOGRAPH: MARK MARISSINK

Liefdefjorden, Svalbard.

FACTS: AMAP

The task of the AMAP (Arctic Monitoring and Assessment Programme) working group is to monitor and evaluate the status of the Arctic environment. This group works extensively on climate issues and various types of environmental pollutants, and within its remit produces both scientific and popular science reports as well as recommendations for measures. Under AMAP are a number of expert groups, and it is usually these expert groups which write the scientific reports. For atmosphere- and climate-related issues, there are expert groups for climate, climate forcers, marine acidification, persistent organic pollutants, mercury, radioactivity and human health. There are Swedish researchers in most of these expert groups. Reports from AMAP can be downloaded from www.amap.no. Sweden is represented on AMAP by Tove Lundeberg of the Swedish Environmental Protection Agency.

Sweden’s 16 environmental quality objectives

The environmental quality objectives are followed up once a year. Through this follow-up, an assessment is made of trends in the status of the environment and whether approved instruments and the measures being implemented have improved the prospects of achieving the objectives. Every four years, a more detailed evaluation is carried out of the opportunities for achieving the environmental quality objectives and the ‘generational goal’, which is to hand over to the next generation a society in which the major environmental problems have been solved, without causing increased environmental or health problems outside Sweden’s borders. The conclusions drawn from the annual detailed evaluations form the basis for the priorities and directions that are set out in environmental policy. Through this, the environmental monitoring programme has a very important role to play, as it is a prerequisite if the environmental quality objectives are to be evaluated.

The primary environmental quality objectives which are concerned as regards the link to the atmosphere and climate in the Arctic are: ***Clean air, A Protective Ozone Layer, Reduced Climate Impact, A Non-Toxic Environment and Natural Acidification Only.***

FACTS: The environmental quality objectives

Sweden’s Parliament has adopted 16 environmental quality objectives which, together with specifications of the respective objectives, describe the status of the Swedish environment that is to be achieved. The environmental quality objectives are intended to serve as guiding principles for the environmental efforts of the whole of society, public agencies, county councils and municipalities, as well as trade and industry and other stakeholders.

www.miljomal.se and www.naturvardsverket.se/miljomal

National air monitoring programme – national monitoring of the atmosphere

The national air monitoring programme studies concentrations and deposition of air pollutants which can harm health, the environment and cultural objects and contribute to climate changes, ozone depletion, acidification and eutrophication. The monitoring programme for air includes twelve sub-programmes.

NATIONAL AIR MONITORING PROGRAMME:
Monitoring primarily takes place through measurements and sampling, but model calculations are also performed. The results contribute to the follow-up of requirements laid down in legislation and conventions, and represents an important aspect of the basis for international reporting, official statistics concerning the status of the environment and follow-up of the national environmental quality objectives.

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ACIDIFYING AND EUTROPHYING SUBSTANCES IN AIR AND PRECIPITATION
Aims to monitor trends in acidifying and eutrophying substances. The programme is split into two subprogrammes. The EMEP network and the Air and precipitation chemistry monitoring network. The EMEP (European Monitoring and Evaluation Programme) stations represent four of around 100 measuring sites in Europe at which concentrations of sulphur and nitrogen pollutants, etc. are measured in air and precipitation (Vavihill, Råö, Aspvreten and Bredkälen). In the Air and precipitation chemistry monitoring network (LNKN), many corresponding airborne pollutants in precipitation are currently being measured at sixteen stations and as concentrations in the air at nine stations. The subprogramme contributes to the follow-up of the environmental quality standards and, among other things, the environmental quality objectives *Clean air and Natural Acidification Only*.

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SWEDISH THROUGHFALL MONITORING NETWORK
Measurements are being taken in the Free crown depositions network in collaboration with the county administrative boards and are primarily intended to contribute underlying information for the follow-up of the environmental quality objective *Natural Acidification Only*. Under the programme, which encompasses sixteen stations, the deposition of sulphur, nitrogen and other pollutants is measured, as throughfall, on open land, as soil water and to some extent also as dry deposition. The Swedish EPA funds analyses of measurements on open land at 18 stations and measurements of dry deposition at ten stations.

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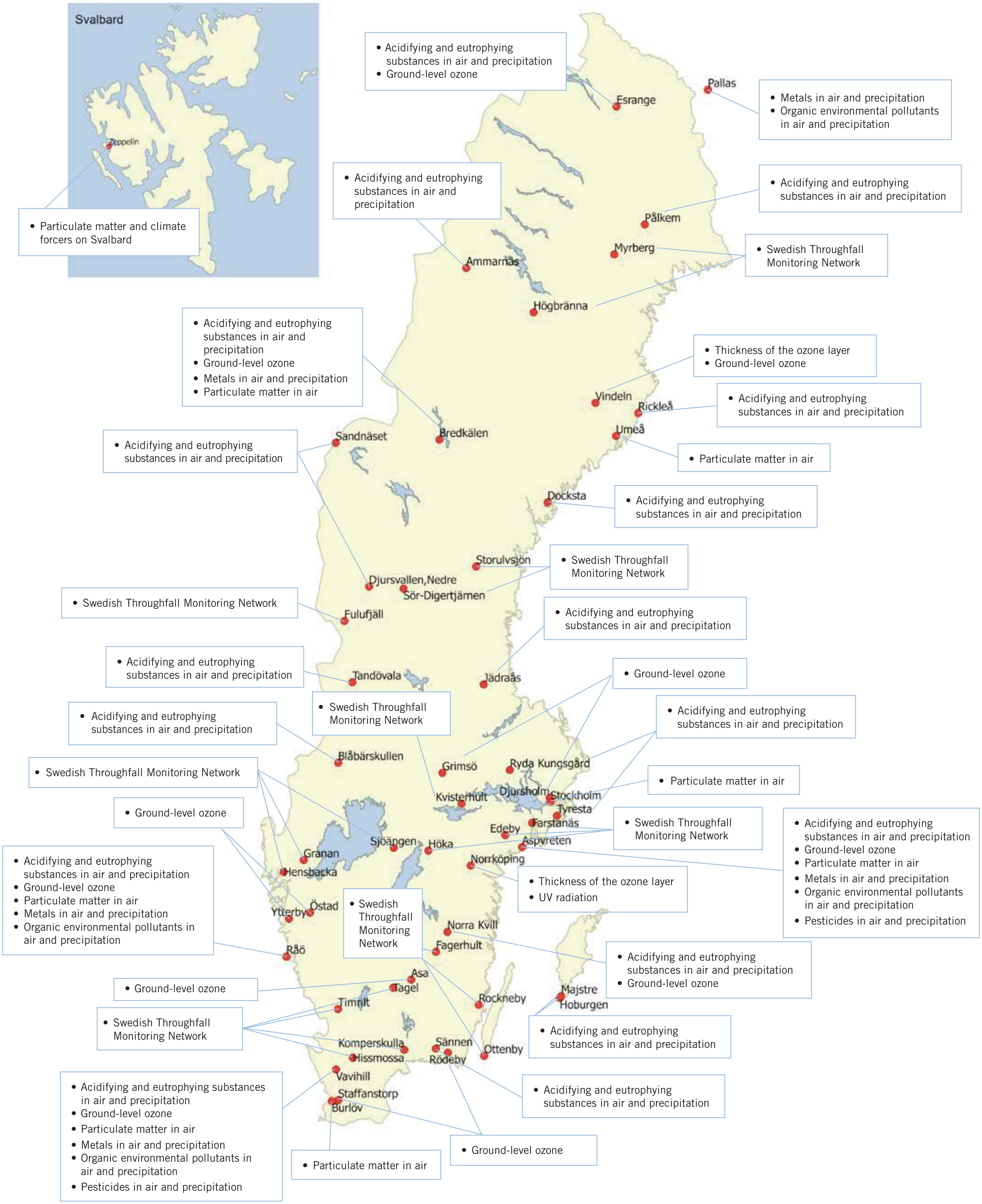
ALL NATIONAL MEASURING STATIONS AND THEIR SUBPROGRAMMES



PARTICULATE MATTER IN AIR

Under the particulate matter subprogramme, measurements of PM10, PM2.5 and soot are taken at the four EMEP stations in accordance with the Air Quality Directive and the Convention on Long-range Trans boundary Air Pollution.

At two of the stations, light dispersal, particulate matter size distribution and elementary and organic carbon are measured. At a further three stations situated in an urban background in Burlöv, Stockholm and Umeå, the so-called exposure reduction targets for PM2.5 are followed up. The subprogramme contributes to the follow-up of the environmental quality standards and the environmental quality objective *Clean Air*.

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GROUND-LEVEL OZONE

Ground-level ozone is measured at the four EMEP stations and at a further ten stations in regional and suburban backgrounds in accordance with the requirements of the Air Quality Directive. The results contribute to the follow-up of the environmental quality standards and the environmental quality objective *Clean Air*. The monitoring also includes a warning service for particularly high concentrations. In the event of such high concentrations, information is distributed to the relevant local radio stations.

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METALS IN AIR AND PRECIPITATION

Heavy metals are measured at the four EMEP stations in Sweden in accordance with the Convention on Long-range Transboundary Air Pollution and in order to follow up the requirements of the Directive on metals and PAH. Mercury is measured at three of the stations and at one station in Pallas, northern Finland. The subprogramme contributes to the follow-up of the environmental quality standards and the environmental quality objective *A Non-Toxic Environment*.

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METALS IN MOSSES

Metal concentrations in mosses are being measured at five-yearly intervals in accordance with the Directive on metals and PAH and ICP Vegetation in the Convention on Long-range Transboundary Air. As part of this mapping, about ten heavy metals are measured at around 600 sites across the country. The subprogramme contributes to the follow-up of the environmental quality objective *A Non-Toxic Environment*.

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ORGANIC ENVIRONMENTAL POLLUTANTS IN AIR AND PRECIPITATION

Under this subprogramme, PAH, PCB, HCB, dioxins/furans, pesticides, brominated flame retardants and PFAS are being measured at four stations, including Pallas. VOC is measured at one station in urban background in Gothenburg. These measurements are being conducted in accordance with the Directive on metals and PAH, the Air Quality Directive and international conventions, such as the Stockholm Convention. The subprogramme contributes to the follow-up of the environmental quality standards and the environmental quality objectives *A Non-Toxic Environment* and *Clean Air*.

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PESTICIDES IN AIR AND PRECIPITATION

The monitoring of pesticides (plant protection products) is carried out at two stations in the country during the summer (April - October). The programme currently covers around 130 substances in precipitation and around 65 substances in the air. The list encompasses all prioritised pesticides in accordance with the EU's Directive as regards priority substances in the field of water policy. The subprogramme contributes to the follow-up of the environmental quality standards and the environmental quality objectives *A Non-Toxic Environment*. and *A Varied Agricultural Landscape*.

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DISPERSAL CALCULATIONS USING THE MATCH MODEL

The MATCH model shows the geographic distribution of concentrations and deposition for acidifying and eutrophying substances such as sulphur and nitrogen. The results are contributing background information for the follow-up of a number


PHOTOGRAPH: ISTOCK

of environmental quality objectives, such as *Clean Air* and *Natural Acidification Only*

Conducted by: Swedish Meteorological and Hydrological Institute (SMHI)
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STRÅNG – UV RADIATION

STRÅNG is a model which produces data on a daily basis concerning global radiation, photosynthetically active radiation, UV radiation, direct radiation and sunshine duration. The subprogramme follows the measures in the Vienna Convention and contributes to the follow-up of the environmental quality objectives *A Protective Ozone Layer, Reduced Climate Impact* and *A Safe Radition Environment*.

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THICKNESS OF THE OZONE LAYER

The thickness of the ozone layer is being measured at two sites in Sweden, Norrköping and Vindeln, in accordance with the Vienna Convention and the Montreal Protocol. The subprogramme contributes to the follow-up of the environmental quality objectives *A Protective Ozone Layer* and *A Safe Radiation Environment*.

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PARTICULATE MATTER AND CLIMATE FORCERS ON SVALBARD

In addition to environmental monitoring within Sweden's borders, the EPA contributes to the funding of monitoring on Svalbard, in some cases in collaboration with Norway. The monitoring takes places on Zeppelin Mountain and contributes to the study of particulate matter and climate forcers, and the effects that these pollutants can have on the climate globally, particularly in the northern hemisphere. The measurements cover carbon dioxide and particulate matter, among other things. The subprogramme contributes to the follow-up of the environmental quality objectives *Reduced Climatic Impact* and *Clean Air*.

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SUGGESTED READING:
www.naturvardsverket.se/programomradeluft


FOTO: AYSUNBK-ISTOCK


PHOTOGRAPH: NATURE PICTURE LIBRARY


PHOTOGRAPH: ISTOCK

Other thematic reports from the Environmental monitoring programme

The report entitled 'Havet' [The Ocean] discusses the latest developments concerning the environment status of Sweden's marine areas. It is published jointly by the Swedish Agency for Marine and Water Management, the Swedish Institute for the Marine Environment and the Swedish Environmental Protection Agency. The next Havet report will be published in 2016.

The report entitled Sötvatten [Freshwater] discusses the latest research concerning Sweden's lakes and watercourses. It is published by the Swedish Agency for Marine and Water Management. The next edition of 'Sötvatten' will be published in autumn 2015.

The report entitled 'Skog & mark' [Forest & Land] discusses the status of Sweden's land environments. It is published by the Swedish Environmental Protection Agency. The latest version of the report, with the theme 'Mountains', was published in October 2015.

The results of the Swedish environmental monitoring programme are needed in order to describe the status, identify changes and assess threats in the environment. The results of the systematic studies also form the basis for decisions concerning measures. The Swedish Environmental Protection Agency and the Swedish Agency for Marine and Water Management coordinate and carry out the national environmental monitoring programme.

naturvardsverket.se/publikationer

2015

ENVIRON-
MENTAL
MONITORING

ENVIRONMENTAL MONITORING FOR THE ENVIRONMENTAL OBJECTIVES

The results of the national monitoring programme show the status of the environment and are used to assess whether we are achieving Sweden's environmental quality objectives. The 16 objectives were adopted by the Swedish Parliament and describe the desired status of the environment.

More about the environmental monitoring programme
naturvardsverket.se/miljoovervakning

More about the environmental quality objectives
miljömal.se

"Air & Environment Arctic 2015" follows the path taken by air pollutants to the Arctic and shows the impacts that they have on the air and climate in the Arctic and, as a result of this, also globally. Read about everything from ocean acidification to how the ozone layer and weather patterns in Sweden are affected, about the opening up of new shipping channels and increased exploitation, about the impact of air pollutants on health and the environment both in the Arctic and far away from the Arctic, and also about what is being done to improve the status of the environment.

SWEDISH ENVIRONMENTAL MONITORING

The results of the Swedish environmental monitoring programme are needed in order to describe the status, identify changes and assess threats in the environment. The results of the systematic studies also form the basis for decisions concerning measures. The Swedish EPA coordinates and carries out the national air monitoring programme within the national environmental monitoring programme.

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