The rapidly changing Arctic environment - Implications for policy and decision makers from the NERC Arctic Research Programme 2011-16

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POLICY REPORT

The rapidly changing Arctic environment

Implications for policy and decision makers from the NERC Arctic Research Programme 2011-16

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NERC SCIENCE OF THE ENVIRONMENT

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We would further like to acknowledge the indirect inputs of all scientists and support personnel involved in the NERC Arctic Research Programme projects.

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Cover Image:
Coastal permafrost eroding into the sea, Alaska (U.S.Geological Survey)

Executive summary

- The Arctic environment is facing rapid changes as temperatures there are rising twice as fast as the global average. Trees and shrubs are spreading northward, the ice-free season is lengthening, and sea ice is rapidly diminishing in extent. These changes have strong effects on biodiversity and local communities, but also wide-ranging effects via feedbacks to climate change, sea-level rise, and therefore the future of societies globally.
- Understanding and predicting climate change in the Arctic, both from a local and global perspective, was the focus of the NERC Arctic Research Programme (ARP) which ran from 2011 to 2016. Key topics included the degree to which current effects of climate change reinforce or mitigate future change, and the identification of critical processes contributing to such changes, now and in the future. Researchers covered many Arctic habitats, including oceans, lakes, wetlands, tundra and forest.
- Research identified processes that both reinforce climate change and have neutral effects but very few mitigating processes. This suggests that many changes are likely to increase in rate and severity. Permafrost thaw and increasing temperatures are highly likely to increase greenhouse gas emissions, and coastal areas are increasingly suffering from erosion and sea-level rise. Ocean warming and the melting of sea ice are being reinforced by increased ice-free surface area which absorbs more warmth and also allows winds to stir warm water to the surface. Increased cloudiness traps warmth above sea ice and reinforces ice melt.
- Arctic Ocean currents are accelerating and ocean mixing "hot-spots" can bring ocean heat up to the surface from below. There are logical, but speculative, consequences of these two findings: accelerated and seasonally-extended sea-ice decline, and increases in mid-latitude (including the UK) extreme weather events.
- Increased freshwater flows into the Arctic and northern North Atlantic may weaken the current system (the "overturning circulation", of which the Gulf Stream is part) that brings ocean heat to northern European latitudes. The impact of global warming may be regionally reduced, with uncertain consequences for UK weather and climate.
- Increased commercial shipping activity due to diminishing sea ice will require improved short-term shipping forecasts that take into account changing ocean currents, seasons, and weather patterns, in order to minimise risk. Similar considerations are required for off-shore drilling ventures.
- Risk of methane release from the ocean is not deemed high, as most methane becomes processed into CO_2 before reaching the atmosphere. Methane hydrates, the form methane takes when trapped under water, are also unlikely to cause under-sea landslides. The largest source of greenhouse gases in the Arctic, and that most likely to increase in the future, comes from land, specifically wetlands, as well as from shelf regions due to submerged, thawing permafrost and coastal erosion.
- Future UK Arctic policy will benefit from improving communication and collaboration between scientists and policymakers, and also from further (targeted) investment in research. Researchers' suggestions include increased cooperation among national funding agencies and support of international collaborative efforts where science needs them. Archiving, digitising and disseminating existing data is a further cost-effective means of increasing Government investment in research. Given the novel investment opportunities in the Arctic, research is also needed in order to reduce uncertainty about the environmental and economic future of the region. Finally, cross-disciplinary work that involves social-science approaches is needed to place observed changes and future projections in a human context.
- The Arctic offers a unique opportunity to increase collaboration between scientists and policymakers, as science lies at the core of the UK's Arctic policy framework. Beyond providing a better understanding of the rapid changes in the Arctic, science can support the building of bridges and networks of collaborations to underpin the diplomatic relations between the UK and the Arctic states.
- Research Councils, the NERC Arctic Office and international Arctic fora have a crucial role to play in facilitating the dialogue between scientists and decision-makers. Similarly, the complexity of the Arctic requires forums to discuss issues across the worlds of NGOs, science, business and politics.
- This policy report is an example of a concrete initiative to engage with the Arctic policy community and discuss the Arctic climate research carried out in the NERC ARP. Similar initiatives, under the auspices of the Research Councils and the Government, could continue supporting the dialogue between Arctic science and policy.

Introduction

The Arctic is one of the most rapidly changing regions of the world: temperatures here are rising twice as fast as the global average, and ice cover on land and sea is rapidly diminishing.

HM Government's 2013 policy framework "Adapting to Change – UK policy towards the Arctic" recognised that the consequences of changes in the Arctic extend far beyond the Arctic region and cover a broad span of the UK's interests: societal, economic and environmental. The document also highlighted the need to devise responsible policy with full regard to the environment. UK-based Arctic science was identified as having a unique role in contributing to policy, reputation and influence.

The Arctic Research Programme (ARP), funded by the Natural Environment Research Council (NERC) ran from 2011 to 2016, and made £15 million available for research into changes in the Arctic and their possible future consequences worldwide.

This report reviews the findings of the projects funded by the NERC ARP and highlights those conclusions that might have implications for the future direction of UK Government policy over the next decades. The potential implications are not limited to changes in the Arctic alone but will affect broader regions, thus requiring the international engagement of the UK in regional strategies. Where the NERC ARP projects have contributed to a better understanding of impacts affecting the UK specifically, for example changing weather patterns or tsunamis generated by landslides in northern seas, they will be of interest to policymakers engaged in a wide range of domestic policy areas as well.

The Arctic remains one of the least well understood regions of the world for reasons of accessibility and environmental complexity. Many uncertainties still exist, and further work is required to address these (Box 1). While we here give an indication of where such uncertainties remain, we primarily highlight conclusions that can now be drawn about likely and possible future scenarios that concern the local evolution of the Arctic environment and (where appropriate) non-local consequences. This will enable consideration to be given to taking advantage of emerging opportunities as well as to possible adaptation or mitigation measures required to address future challenges.

Many links already exist between policymakers and their scientific advisers on the one hand and those involved in research on the other. Drawing on the experiences of the NERC ARP projects, this report also considers how even closer engagement between policymakers and researchers might be achieved in the future, so that their respective interests and needs are well understood at an early stage in the research cycle.

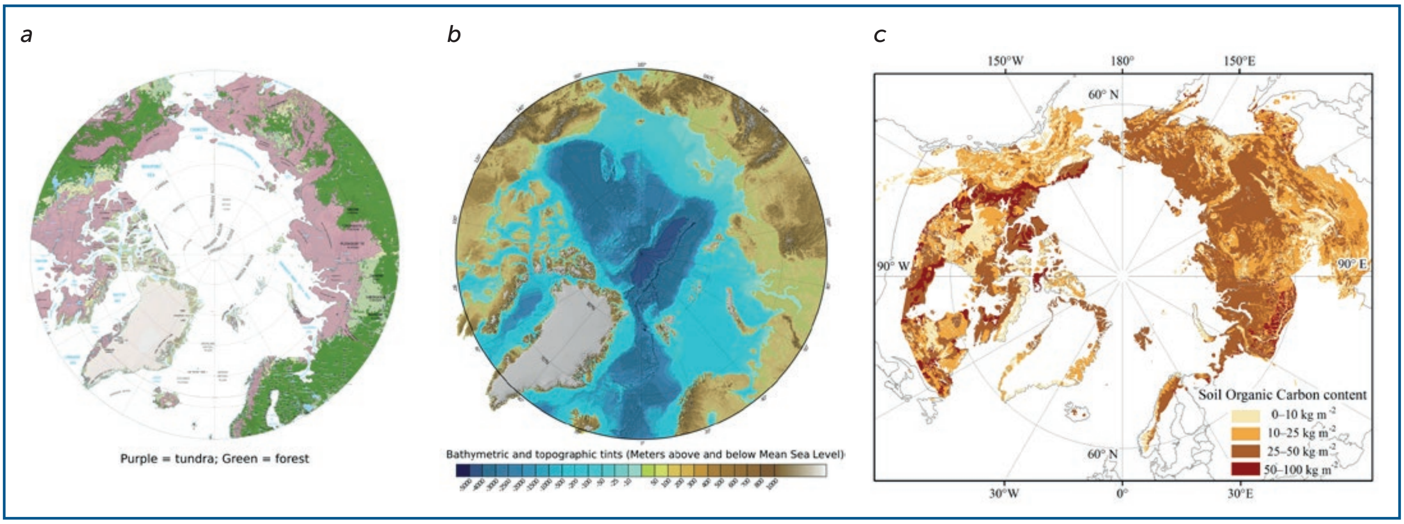


Fig. 1: a: Land cover of the Arctic and Subarctic (polar projection). Key: Dark green = forest; light green = forest-tundra (transitional); pink = tundra.
b: Topographic and bathymetric map of the Arctic and Subarctic (polar projection) Pinterest URL: https://www.pinterest.co.uk/pin/298363544038348263/.
c: The Northern Circumpolar Soil Organic Carbon Database version 2. Bolin Centre for Climate Research, Stockholm University. URL: http://bolin.su.se/data/ncscd/

Geographical areas covered by the report

"The Arctic" is hard to define in simple terms without resort to technical language and even scientists sometimes avoid giving an exact definition because of its complexity (Box 1). A climate scientist might say that the Arctic comprises the ocean and atmosphere north of their respective Polar Fronts, but on land, many criteria are possible: for example, north of the tree-line, the area occupied by tundra (or by permafrost), or the Arctic-Ocean-draining river catchments.

While no criterion can be as well expressed as latitude (Fig. 2), other criteria are useful. "The northern cryosphere" is a functional definition, where "cryosphere" is taken to mean the high latitudes which are permanently frozen or where the freeze-thaw cycle is important at the land and ocean surface. In this report, we employ the broadest and most inclusive meaning of "the northern cryosphere": where NERC ARP research was conducted and where processes and predictions identified by the scientists leading the projects apply.

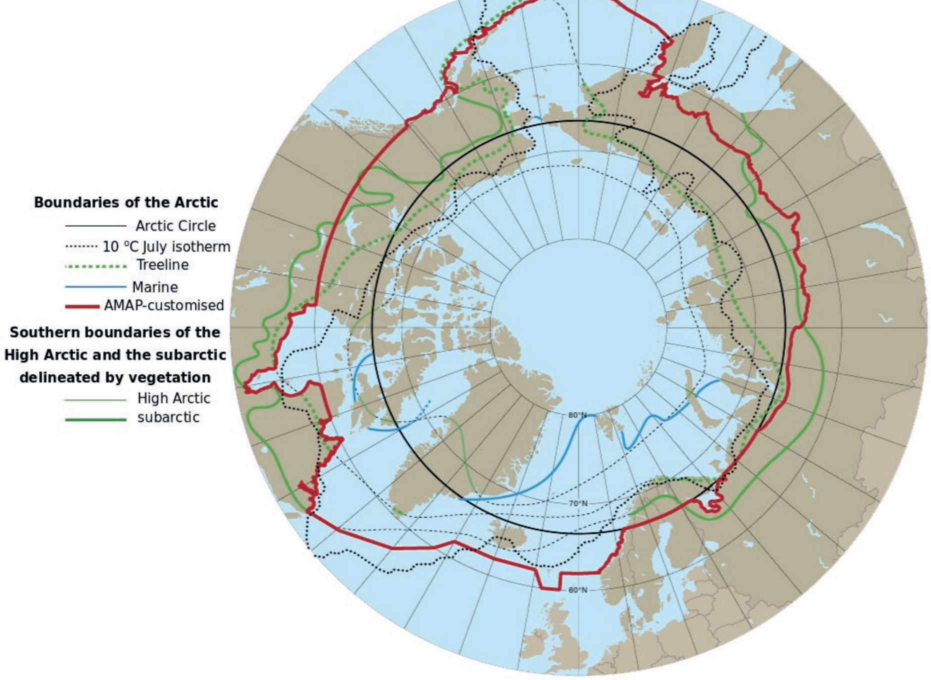
There are eight Arctic States: Canada, the Kingdom of Denmark (including Greenland and the Faroe Islands), Finland, Iceland, Norway, Russia, Sweden and the United States. These States form the Members of the Arctic Council, an intergovernmental forum. The UK is an Observer to the Arctic Council and is also the most northerly country outside the eight Members.

BOX 1: A vast and complex Arctic

The treeless Arctic alone covers 11 million km^2, an area slightly larger than Europe[1]. With the looser definition adopted in this report that includes forested areas within the Arctic Circle as well as the Subarctic (the region immediately south of the Arctic Circle), the area is even larger and more complex. It encompasses many gradients, extending from sea level to almost 4000m[1], from polar desert to wet tundra to forest, and from areas of permanent snow to those with dense vegetation and high seasonal plant growth. Understanding how the region is responding to current and future change is a challenge. Variation in the environment not only occurs across large expanses but also at small scales, for example, strong differences can exist between north and south-facing hillslopes. Furthermore, although considerable research has been devoted to understanding the Arctic, large information gaps remain, particularly in more inaccessible areas. The data available to researchers are sparse in space and time, and thus predicting spatial and temporal change is inherently challenging. Putting numbers on landscape-scale processes, such as sea-ice changes and greenhouse gas emissions, is of primary interest to both researchers and policymakers.

Example of complexity and uncertainty - Will thawing permafrost increase or decrease carbon dioxide emissions in streams and lakes? "Browning" is a term used to describe effects on streams and lakes whereby increasing temperatures thaw frozen soil and release more tea-coloured dissolved carbon into the water. This carbon may be easily converted to greenhouse gases, contributing positively to climate change. While browning has been widely reported in lower latitudes, patterns appear inconsistent in the Arctic[2]. Researchers have found that in some areas, instead of causing browning, thawing soils expose minerals that absorb carbon. The locations where each of the processes dominates over the other cannot be predicted at present; however researchers suspect that the history of the landscape may be key. For example, if thick organic soils have developed over thousands of years, more browning is likely compared to areas where the organic soil layer is thin.

Fig. 2: Various definitions of the Arctic[1]



Key findings of the NERC Arctic Research Programme

The Programme set out to address four scientific questions. Below, we summarise the main findings of each strand, emphasising new risks and opportunities arising with regard to our understanding of climate change processes and projections, and impacts on UK interests.

Question 1: What is causing the rapid changes in the Arctic at the moment?

Key points:

- The decline of sea ice allows more of the particles that generate clouds ("cloud condensation nuclei") to be released into the atmosphere. Low-level clouds insulate the near-surface atmosphere, thereby increasing surface warming, particularly in the autumn, when sea-ice concentration is lowest. This therefore is a positive feedback: more open water leads to more clouds, which in turn leads to more warming and more open water.
- Several mechanisms are expected to increase the input of fresh water into the Arctic Ocean. Transmission of freshened seawater into the northern North Atlantic could slow the large-scale ocean circulation that brings ocean heat via the Gulf Stream system into the North Atlantic. In the context of global warming it is however possible that regionally (meaning north-west Europe, including the UK) warming could slow as a consequence of the change in ocean circulation.
- The decline of sea ice is causing Arctic Ocean currents to accelerate, which in turn will lead to stronger turbulent ocean mixing. Stronger ocean mixing can bring heat up to the surface from below. This could cause further ice melt and local (Arctic) atmospheric warming, which in turn may change mid-latitude (including UK) weather and extremes.
- New shipping routes will open as a result of the reduction in arctic sea-ice cover and after 2050, very little sea ice will be left in summer. While the NERC ARP projections represent trends in sea-ice cover in an average year, variability from year to year is likely to be significant, so reliable forecasts for each season will be needed to allow operators to plan ahead.
- Shipping in the Arctic is unlikely to contribute significant amounts of black carbon when compared with atmospheric transport from sources such as vehicles and industry elsewhere in the world. Therefore, regulation of the Arctic shipping industry is likely to be an insufficient control on the warming effect of black carbon deposition.

The Arctic climate is governed by complex interactions between atmosphere, ocean, sea ice and land areas. Some may involve feedbacks, when changes in one part of the system reinforce (or mitigate) changes in another. One of the best known examples of reinforcement is the so-called ice-albedo feedback. Here, the melting of sea ice leads to a greater extent of open water, which absorbs more heat from the sun than ice because it is less reflective. The extra heat in turn warms the ocean, leading to still more ice melt. The ice-albedo feedback contributes to the doubling of the global rate of warming in the Arctic, known as "Arctic amplification".

Clouds and climate

The largest single uncertainty in modelling the Arctic climate is a poor understanding of clouds and the processes that lead to their formation. The effect that clouds have on climate is complex and depends on several factors, including their thickness and altitude in the atmosphere. Thick clouds in the lower atmosphere help to keep the Earth's surface cool by reflecting away solar radiation that would otherwise cause surface warming. In the Arctic, however, this cooling effect is less important in areas where sea ice remains, because the ice is itself reflective (Box 2) and it is outweighed by the clouds' role as an insulating blanket, holding in heat at the surface and preventing it from being radiated away into space.

In order to form, a cloud needs both a source of water vapour and a source of liquid droplets or particles on which the water vapour can condense. It has been suggested that a feedback mechanism might exist: more open water results from increased sea-ice melt. This allows more particles to move from the ocean into the atmosphere, where they can generate clouds, hence causing increased surface warming.

NERC ARP researchers investigated the conditions that lead to cloud formation using specialist research aircraft and ships. In coastal areas, they discovered evidence of iodine particles, which can contribute to cloud formation, and it is suspected that these come from seaweed, which is able to grow where sea ice has broken up[2]. This might also be an important feedback mechanism.

In another study, researchers developed a computer model to look at whether increased amounts of sea-salt and dimethyl sulphide (a chemical released by algae) projected into the atmosphere from the newly exposed ocean might increase cloud formation. They found that the concentration of particles was not as great as expected, perhaps because they are removed from the atmosphere by rain[3].

The insights that the researchers have gained from their measurements have contributed to a better representation of clouds and their formation in climate models. At the time of writing, analysis of new predictions from the models is continuing.

BOX 2: Black carbon in the Arctic

One potential source of Arctic warming is black carbon, or soot particles. If these settle on the surface of ice, they absorb more of the sun's energy than the ice alone because they are darker and less reflective. Researchers investigated whether deposition of black carbon generated by increasing shipping traffic in the Arctic (Box 3) might contribute to faster ice melt. They concluded that shipping in the Arctic was unlikely to contribute significant amounts of black carbon when compared with atmospheric transport from sources such as vehicles and industry elsewhere in the world. Therefore, regulation of the Arctic shipping industry was likely to be an insufficient control on the warming effect of black carbon deposition[3,4].

The effect of melting sea ice on the ocean and atmosphere

The progressive loss of Arctic sea ice through the 21st century (Fig. 3) is likely to have consequences both for local (Arctic) and remote (mid-latitude, including the UK) weather and climate. This, in turn, will influence international investment in new Arctic shipping routes (Box 3).

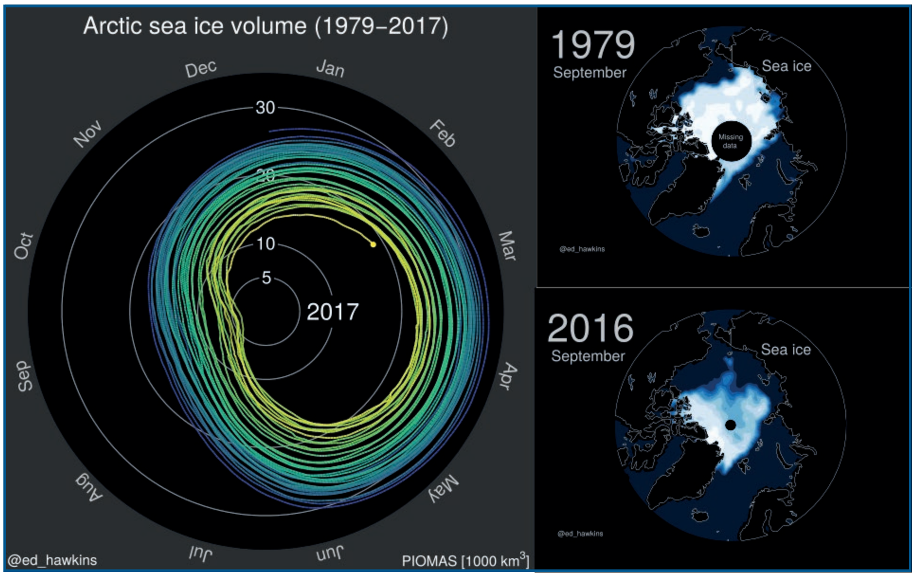


Fig. 3: Sea-ice decline from the 1970s to recent years. The line traces ice volume through time (greatest Mar-May; least Aug-Oct). The most recent years (yellow) show diminishing values compared with the 1980s URL: https://www.climate-lab-book.ac.uk/spirals/

Weakening of overturning Ocean circulation

Considering climate first, there is a well-recognised mechanism, called the Atlantic Meridional Overturning Circulation (AMOC) that is responsible for the UK's mild climate. The AMOC brings warm ocean surface water northwards through what is commonly known (in the North Atlantic) as the "Gulf Stream System". Westerly winds blow across this warm water and pull heat from it, so the system acts like a "fan-assisted storage heater". When this warm Atlantic seawater reaches much higher northern latitudes, it becomes much colder and denser, so it sinks and returns southwards at great depth – hence "overturning circulation".

The AMOC possesses an Achilles heel, however. If the Atlantic waters are capped by a layer of lighter, fresher water, the loss of heat to the atmosphere can be inhibited, so the overturning circulation slows, and the delivery of ocean heat to our latitudes is slowed. There are a number of ways in which this cap of fresher seawater could appear: sea ice melting, increased river runoff into the Arctic Ocean, release of fresher seawater presently held in the Arctic Ocean, and also by increased melting of the Greenland ice cap. In the context of global warming, it is possible that regionally (meaning north-west Europe, including the UK) warming could slow.

Faster sea-ice decline

In the Arctic Ocean, the vertical pattern of water temperature is unusual. Warm, salty water flows into the Arctic from the Atlantic Ocean. In the Arctic Ocean, this Atlantic seawater lies mostly about 200 metres below the surface because it is denser than the layer of cold, fresher Arctic-sourced seawater that covers it like a lid. While the warm water is isolated from the surface in this way, the heat that it contains cannot contribute to melting of the sea ice at the surface. However, if the boundary between cold and warm water is disturbed for any reason, the rate of sea-ice loss might increase. This process of "disturbance" in the ocean is called turbulent mixing and it causes stirring together of adjacent layers of seawater. If the cold waters near the surface can mix with the deeper, warmer seawater, then the resulting mixture of the two will have a temperature between the two. As a result, temperatures near the surface would increase.

In an important series of field expeditions, UK researchers measured turbulent mixing rates all around the Arctic Ocean: some measurements were over the continental slope under sea ice, others were over the continental slope in open water, and still more in the deep ocean. They found that the strength of the mixing was much greater over the continental slope than in the central Arctic, and they suggest it is caused (at present) by tidal currents passing over the rough sea floor[4] (akin to the atmospheric turbulence generated when winds blow over mountains, a phenomenon routinely experienced by air travellers). This generates localised "hot-spots" of surface heating from below by mixing upwards some of the heat contained in the deep-lying Atlantic-sourced seawater.

Now for this turbulent mixing process to affect the rate of sea-ice decline, it would need to become much more geographically widespread, around the Arctic Ocean. At present, the mixing is driven by tidal currents, but they will not change in the future. However, it is possible that the Arctic Ocean circulation itself - the system of currents that controls the horizontal movement of seawater around the Arctic - will change. At present, the Arctic Ocean circulation is notably sluggish, with currents typically 2 cm/s, compared with the rest of the world ocean, where currents are over ten times faster. Slow currents mean that mixing rates are presently weak, excepting the "hot-spots", where fast but local tides provide strong currents to generate turbulence. So the question is: might the Arctic Ocean currents accelerate in the future?

UK scientists have found that the answer to this question is yes, and Arctic Ocean currents are actually accelerating now. Satellite observations show that in the Canada Basin, in a wind-driven circulation pattern called the Beaufort Gyre[5], currents have doubled or trebled in speed because broken-up (or "unconsolidated") sea-ice floes transfer the force of the wind to the ocean more efficiently than the fully ice-covered ocean surface can do. This process of acceleration of ocean currents is called "spin-up" and scientists expect the Arctic Ocean currents to spin up more in coming years as a result of the action of the wind on greater areas of wholly or partially ice-free water. With stronger currents comes more vigorous mixing, which can transfer more heat from the deep warm layer to the surface. This may cause the presently localised hot-spots to expand all around the Arctic.

This may have significant consequences for the rate of decline of sea ice, because increased turbulent mixing can bring heat up to the surface all year round, so that the melt season would no longer depend solely on the spring-time arrival of heat from the sun. The melt season would extend forwards into early spring and late winter, and back into late autumn and early winter. An extreme possibility is that zero sea ice – confidently predicted to happen in late summer later this century – might ultimately happen all year round.

BOX 3: New shipping routes open up

A reduction in summer ice cover in the Arctic Ocean could open the door to new shipping routes between Europe and Asia, saving time and fuel and reducing greenhouse gas emissions and pollutants (Fig. 4). NERC ARP researchers have modelled changes in accessibility and likely transit times along different routes across the Arctic Ocean over the next century. Transit will always be easiest in September, when ice cover is at a minimum, but to become viable, Arctic routes will need to be open for a longer season. The researchers conclude that after 2050, very little sea ice will be left in summer and the route via the North Pole should be accessible even by ships with minimal ice strengthening. The journey time between Europe and Asia on this route is projected to be about 10 days shorter than the route via the Suez Canal.

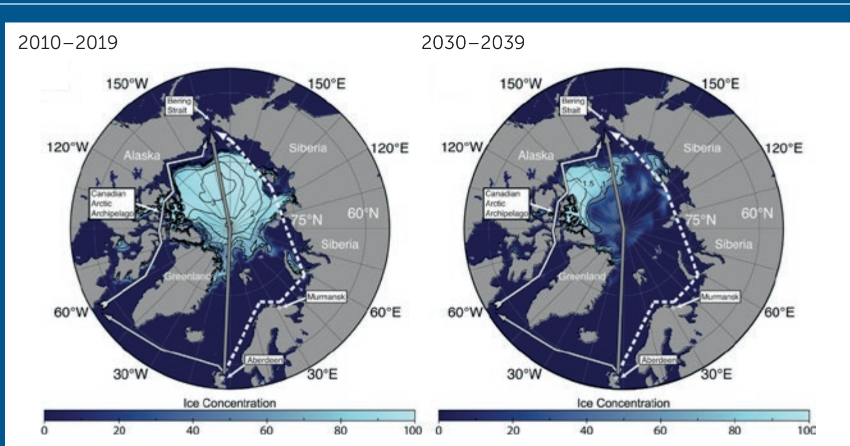


Fig. 4: Model outputs for 2010–2019 and 2030–2039 sea ice concentration (%, shades of blue) and thickness (labeled contours) during the navigation period (June–October). The Arctic shipping routes are shown schematically: the Northern Sea Route (NSR) (dashed arrow), the North Pole Route (NPR) (dark-grey arrow) and the Northwest Passage (NWP) and Arctic Bridge (AB) (light-grey arrow). (Image credit: Yevgeny Aksenov)

While these projections represent trends in sea ice cover in an average year, variability from year to year is likely to be significant, so reliable forecasts for each season will be needed to allow operators to plan ahead. Ships will also need access to short term forecasts of weather conditions such as fog to complete their journeys safely. The insights from the NERC ARP studies should help operators to make a rounded appraisal of the potential benefits of Arctic shipping routes, alongside factors such as relative fuel costs and the additional costs of ice-strengthened vessels and ice-breaker escorts if required[5].

Mid-latitude weather and extremes

It is already known that the Arctic is warming twice as fast as the rest of the world through "Arctic amplification" (see key points). Research over the last few years[6] is beginning to show how Arctic amplification is affecting weather and extremes outside the Arctic, in the northern hemisphere mid-latitudes, including the UK. Faster Arctic warming means that the surface temperature difference between the Arctic and mid-latitudes is slowly decreasing. This decreasing temperature difference impacts mid-latitude weather, by causing weather systems (depressions) to move more slowly across the Atlantic and even to make them prone to "stalling". In parallel, continental high pressure systems are harder to push away. The outcome is more persistent spells of extreme weather, including floods, snowfall, heatwaves, droughts and poor air quality – and these phenomena have been seen variously in recent years in e.g. the US, UK and China.

In summary, scientists found during NERC's Arctic Research Programme (i) that Arctic Ocean currents are accelerating and also (ii) that mixing "hot-spots" can bring ocean heat up to the surface from below. We have described logical, but necessarily speculative, consequences of these two findings: accelerated and seasonally-extended sea-ice decline and increases in extreme mid-latitude weather events. While speculative, these potential consequences provide powerful motivation for future research directions.

Question 2: What are the processes influencing the release of greenhouse gases such as methane and carbon dioxide – and how much of these gases could enter the atmosphere in future?

Key points:

- A huge reserve for potential greenhouse gas emissions exists in the Arctic in the form of permafrost soils, peat, lake sediments and vegetation. If all Arctic permafrost thawed, exposing previously frozen carbon to decomposition, atmospheric CO_2 concentrations could double according to some estimates[8].
- Even with partial permafrost thaw, there is a risk of climate change accelerating due to increased release of greenhouse gases from Arctic and Subarctic areas that are becoming warmer, moister and more densely vegetated.
- There is a risk of positive feedbacks to climate change due to increasing greenhouse gas emissions in shelf regions, where carbon-processing hotspots are created by increases in carbon supply from thawing permafrost under the sea and coastal erosion enhanced by current climate change.
- The High Arctic is likely to be an exception to the expected self-reinforcing nature of climate change in the Arctic, having an increased likelihood of future CO_2 and methane uptake with warming.
- The risk of increase in atmospheric greenhouse gases due to the release of methane from deep-sea methane hydrates is assessed as small.
- Beyond the trends observed in NERC ARP projects, uncertainty exists about the quantities of greenhouse gas emitted now and in the future, owing to landscape complexity and scarcity of observational data.

Currently, the Arctic is a methane source, emitting more CH_4 than it takes up. According to some estimates, high latitudes contribute approximately 12% of global methane emissions, the highest sources still being tropical wetlands and ruminants[7]. However, there is still uncertainty about how much methane the Arctic emits or will emit, owing to landscape complexity and scarcity of observational data. Importantly, we know even less of carbon dioxide - we cannot even be certain of whether or not the Arctic is a carbon dioxide sink or source. A huge carbon reserve for potential greenhouse gas emissions exists in form of permafrost, peat, lake sediments and vegetation.

The land

Climate change is resulting in many changes in the Arctic. These include a northward advance of trees into areas currently under shrub tundra and the advance of shrub tundra into areas with currently low-growing tundra vegetation, a process called "greening". Other changes include the thawing of permafrost and increasing precipitation, especially in autumn[9]. All these processes impact the function of greenhouse gas "sinks" and "sources", i.e. areas that on balance either take up or emit greenhouse gases. It is currently uncertain how much these changes will affect the overall status of greenhouse gases in the Arctic (Box 1 & 4). One of the main uncertainties to date has been what effect thawing permafrost is having and will have on the Arctic and thence the global carbon cycle[10]. Increasing greenhouse gas emissions from wetlands are expected, but they may be offset by carbon dioxide (CO_2) uptake by larger and more rapidly growing plants.

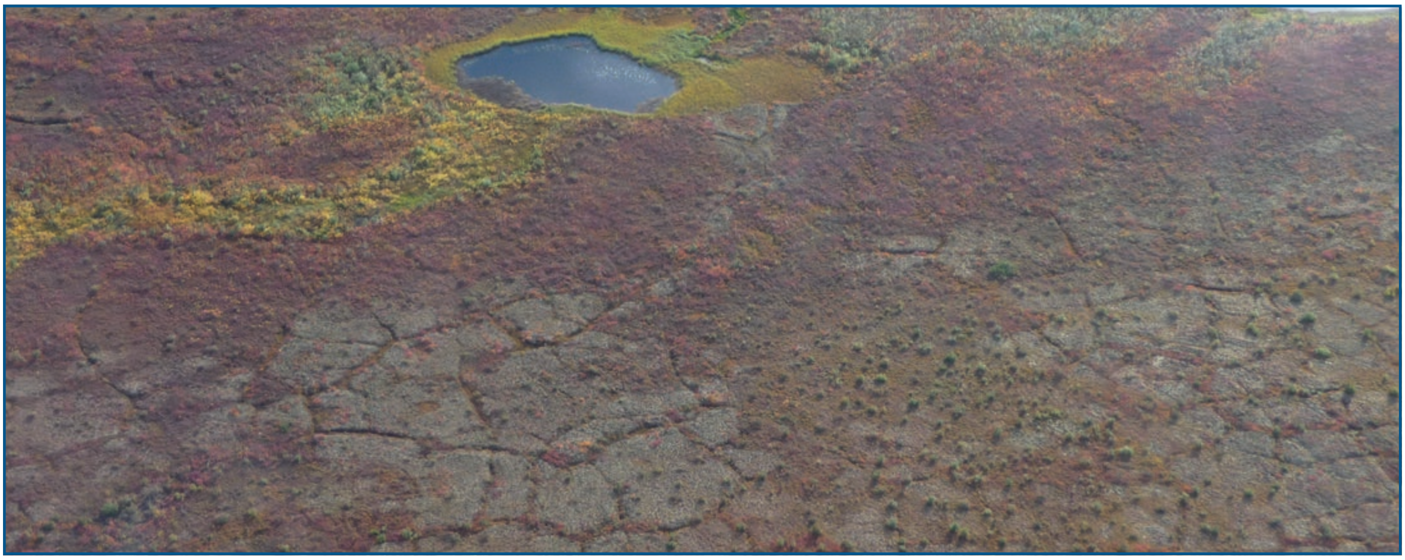


Fig. 5: Areas with ice wedge polygons may become drier with climate change as ice melts and channels between hummocks drain; in this photograph, from the Mackenzie Uplands between Inuvik and Tuktoyaktuk (Northwest Territories, Canada) drainage and drying of polygons is evident, as well as shrub encroachment, especially on polygon margins (photo credit: Philip Wookey)

Several NERC ARP projects focused on improving our understanding of carbon processes and feedbacks. Disconcertingly, evidence points towards self-reinforcing climate change:

Rainfall is predicted to increase with climate change. It enhances thawing of permafrost because it decreases the insulation capacity of the soil regardless of the nature of the dominant vegetation (e.g. forest, tundra)[11]. Thawing permafrost activates carbon stored in the soil for centuries or millennia. This carbon becomes processed by microbes into greenhouse gases, again becoming a positive climate change feedback.

Greening in the form of northward spread of birch and willow shrubs surprised researchers by its release of CO_2 from soil carbon stocks, offsetting the carbon uptake by the shrubs themselves. It is suspected that the magnitude of CO_2 release vs. capture depends on the history of the soil—how much soil and carbon has accumulated over millennia—and therefore on how much excess carbon is decomposed by soil microbes.

Hydrology is key in predicting the balance between CO_2 and methane (CH_4) emissions (Box 4). However, hydrological change itself is difficult to predict. In some areas, thawing permafrost has resulted in the formation of new pools and lakes, whereas in others lakes and pools have emptied and left the landscape dry[12,13] (Fig. 5).

"Wetting" is most likely to occur in lowland depressions and coastal areas where rising sea levels are causing water tables to rise. In more complex landscapes, both wetting and drying may occur. Methane release in wetting areas will, in terms of greenhouse gas forcing, offset CO_2 uptake in drying areas. It is probable that Arctic methane contributions will increase in the future and therefore be a positive feedback to climate change.

These conclusions are supported by many in the international research community, who have jointly emphasised that warming-related greenhouse gas emissions may offset the uptake of these gases by greening[14].

BOX 4: Methane vs carbon dioxide

The two main greenhouse gases emitted in the Arctic, carbon dioxide (CO_2) and methane (CH_4), tend to be produced under different circumstances. In terms of greenhouse gas forcing of temperature, CH_4 is approximately 30 times stronger than CO_2. As the Arctic climate changes, will more or less greenhouse forcing occur as a function of the changing balances between production and uptake of CH_4 and CO_2?

Carbon processing in many landscapes is dominated by photosynthesis, by which plants take up CO_2 from the atmosphere, and by respiration (including decomposition), which releases CO_2. Carbon dioxide is produced by all respiring organisms when oxygen is present. Interestingly, new research in Greenland has found these processes to be balanced - warm years lead to similar increases in both photosynthesis and respiration unless disturbances such as pest outbreaks destroy vegetation.

Methane, on the other hand, is produced under circumstances in which oxygen is severely restricted or lacking, such as underwater locations, which can include areas close to ocean floors where currents are slow, sediments of lakes and ponds, and waterlogged soil. Methane production, like CO_2 production, also increases with warming. Therefore, in areas that become wetter and warmer, CH_4 production will increase in the future, and offset the potential reduction in CO_2.

Arctic lakes and carbon

Lakes cover almost 6% of the land surface of the Arctic, a high proportion compared with most latitudes[15], and they have more intensive carbon cycling than most land areas. One NERC ARP project specifically focused on lakes, with the aim of understanding how their ecology and productivity changed with climate warming since the end of the last ice age. In ecology, productivity refers to the growth and reproduction of biomass in an ecosystem (e.g. plants such as algae). All else being equal, increases in productivity generally make lakes more likely to act as greenhouse-gas sinks, i.e. they use more carbon than they release. Based on the properties of lake sediments and associated fossils (Box 5), it appears that, just as on land, warming leads to increased plant growth within the lake and at the water's edge (Fig. 6).

The productivity of lake plants, including algae, is also controlled by the vegetation surrounding the lake. The spread of conifer forest and presence of deep, carbon-rich soils can decrease productivity, while, on the other hand, spread of alder, a shrub that leaks nitrogen into waterways, fertilizes lakes, thus increasing productivity. As on land, we observe contrasting processes and it is their balance that will determine whether lakes will increase their net release of greenhouse gases with further warming. In modern studies, researchers have shown most Arctic lakes to be greenhouse gas sources. It is therefore a key question whether increases in productivity can offset the extra carbon now being released into aquatic systems in the Arctic.

Fig. 6: A lake in Sisimiut, SW Greenland, in a typical landscape for the area (photo credit: Madeline Giles)

Arctic research has tended to focus on carbon-rich areas of the Low Arctic. The High Arctic, in contrast, has carbon-poor soils and low productivity, because of the low temperatures and low precipitation and because water is frozen most of the year. Overall, less carbon is buried in high-arctic lake sediments than in low-arctic lakes and little, if any, is released as greenhouse gases[16]. Carbon-poor areas are expected to become CH_4 and CO_2 sinks as temperatures increase and soils develop. Consequently, the High Arctic and its lakes have the potential to remain a greenhouse gas sink as a result of future warming[17].

Climate change effects on lakes will also have repercussions on local communities. Increasingly early ice-out on lakes across the Arctic, revealed by satellite data analysis, impacts the use of frozen lakes and wetlands as winter transport routes. Users of such routes need to be aware of this in order to avoid accidents and accommodate seasonal trends when planning both transport logistics and new roads.

BOX 5: Dating sediments: palaeolimnology

Sediments from lake bottoms can be sliced and dated using radioactive forms of carbon (radiocarbon dating). Multiple analyses can be undertaken on the slices to reconstruct the history of a lake. Combined, these analyses give us information of past temperatures, precipitation, carbon accumulation, and the biology of both aquatic and terrestrial environments.

The information helps us understand how climate change in the past has influenced biodiversity, greenhouse gas emissions, and the landscape.

This information provides baselines and conditions for comparison and describes previous responses to change, all of which can inform current understanding and projections of future change.

Fig. 7: A sediment core being retrieved from a lake in Greenland (photo credit: Mark Stevenson)

The oceans

Ocean warming has led to fears that methane might be released through the collapse of methane hydrate, which is a crystalline form of methane that occurs in the seabed below the deep ocean under conditions of low temperature and high pressure. NERC ARP researchers investigated whether methane released from hydrate might make its way to the atmosphere and contribute to global warming now and in the future.

Researchers examined data collected west of Svalbard, an area chosen because warming waters flowing in from the Atlantic meet the seafloor there, making the release of methane more likely than in other Arctic regions. They found signs of methane release but observed that nearly all of the gas was transformed into carbon dioxide and dissolved in the seawater before it could be released to the atmosphere[18]. Such dissolution will contribute to ocean acidification, but the effect is small.

After analysing the measurements taken on site and running computer models, the researchers concluded that the contribution to the carbon dioxide content of seawater from the steady breakdown of hydrates is likely to be less than 1% of the ocean uptake of carbon from anthropogenic sources over the 21st century[19]. Further, new estimates of atmospheric methane sources indicate that only ca 1% of global methane emissions result from hydrates[20].

A different situation occurs in shelf regions such as the East Siberian Arctic Shelf (ESAS), where the ocean abuts large land masses. Here, new findings suggest an important role for greenhouse gas contributions from shelf areas. On the ESAS, the water is shallower and carbon is received from rivers, streams and eroding land. Furthermore, vast amounts of submerged permafrost are stored within shelves, which can thaw, with considerable release of methane[21]. The coastal erosion is of particular importance. ESAS is already under stress due to combined effects of climate change: increasing wave action, rising sea levels and the sinking of land as permafrost thaws — all consequences of warming — together result in ever increasing coastal erosion rates[22] (see cover image). ARP research shows the process of coastal erosion potentially transports more carbon to the East Siberian Shelf than all rivers in this area combined, much more than previously thought. All of these processes create potential hotspots for greenhouse gas emissions. Much of the carbon can be, and has been, converted to CO_2. It has already resulted in acidification in excess of levels projected in this region for 2100[23].

Question 3: How can we improve our predictions of what will happen to the climate in the Arctic and the amounts of greenhouse gases released in the future?

Key points:

- Satellite data are becoming increasingly important in helping scientists acquire enough data to construct predictive models. Researchers found that most of the variation in the capacity of ecosystems in the Arctic to act as CO_2 sinks could be predicted using simple and available measures such as light available to plants, air temperature and the way vegetation reflects radiation. This means that rough predictions of productivity can be made despite spatial variation in vegetation.
- Technical improvements have also been made in using available data. Greenhouse gas estimates for remote and inaccessible areas could improve in the near future.
- Improvements in the models have also enabled researchers to identify the sources of methane-rich air masses. Tracing sources of methane will be invaluable in improving greenhouse gas source maps as well as predicting future emission hotspots.
- The predictions of Arctic sea ice cover that underpin global climate models encompass the entire area of the Arctic Ocean. Less effort has hitherto been put into developing models which can produce the detailed regional forecasts that will be of most use for shipping and for indigenous populations. NERC ARP researchers have found that predicting sea ice is most difficult in areas closest to the coast, which is where the forecasts are likely to be of most value.
- There is still scope to improve model predictions of Arctic climate and sea ice cover, but some technical challenges remain to be addressed. Better observations of sea ice and more observations in the terrestrial Arctic (both in time and space) are required. At the same time, traditional on-location and long-term monitoring remains an important basis for predictive models (Fig. 8).

Fig. 8: Picnic, Canadian style. On reconnaissance at Trail Valley Creek, Northwest Territories, Canada; August 2012. (photo credit: Philip Wookey)

Accurate predictions of the future Arctic climate over different timescales are valuable for a number of reasons. Longer-term predictions allow policymakers in the Arctic and indigenous groups to plan for future change, but, given the influence of the Arctic on the atmosphere and oceans in the rest of the world, they are also important in informing predictions of global climate. As Arctic sea ice cover diminishes, shorter-term forecasts looking a few weeks or months ahead will allow shipping companies to make informed decisions about likely access to shipping routes, for example.

Greenhouse gas predictions

The NERC ARP has much improved our understanding of how the processes producing greenhouse gases in the Arctic are changing in response to warming, increases in rainfall, and the northward spread of shrubs and trees. NERC ARP results and other recent research suggest increasing self-reinforcing warming in the Arctic (see previous section).

However, large uncertainties exist in our capability to predict not only in time, but also spatially. Arctic data are sparse and balancing greenhouse gas fluxes across landscapes requires extrapolation. Therefore, models that work on simple principles that can be measured remotely (e.g. via satellites) are ideal. Encouragingly, researchers found that most of the variation in ecosystem productivity (i.e. potential CO_2 uptake), regardless of vegetation cover type, could be predicted using simple and available measures such as light available to plants, air temperature and the way vegetation reflects radiation. This means that rough predictions of productivity can be made despite spatial variation in vegetation[24]. However, microbial processes in soils cannot be measured remotely, which leaves a gap in estimating net greenhouse gas fluxes.

Technical improvements have also been made in using available data. Methane fluxes estimated by satellite data appear promising based on comparisons with empirical measurements. Thus, greenhouse gas estimates for remote and inaccessible areas could improve in the near future. Further, improvements in models have enabled identification of the sources of methane-rich air masses. For example, some high values measured over the sea between mainland Norway and Svalbard were traced to originate not from the sea, but from wetlands in Russia[25]. Tracing sources of methane will be invaluable in improving greenhouse gas source maps as well as predicting future emission hotspots.

Sea ice predictions

Researchers compared the predictions of sea ice cover made by different computer models to determine what factors influence the accuracy of predictions. No model can produce completely accurate predictions because of the underlying chaotic nature of the climate system, but the researchers concluded that improvements in the models are still possible, although there are some challenges to be addressed[26].

Models do not run completely independently of observations. They need data from observations to be incorporated to provide their starting conditions. Newer models also incorporate observations to improve accuracy as they run. For accurate predictions to be made of sea ice cover some months ahead, the researchers found that it was most important to have good observations of sea ice thickness. These come from satellite measurements, but there is a technical challenge involved in making these as accurate as possible because the satellites' sensors are confused by pools of water forming on the surface of the ice floes as they begin to melt. Further work will be required to address this challenge.

The predictions of Arctic sea ice cover that underpin global climate models encompass the entire area of the Arctic Ocean. Less effort has hitherto been put into developing models which can produce the detailed regional forecasts that will be of most use for commercial purposes. NERC ARP researchers have found that predicting sea ice is most difficult in areas closest to the coast, which is where the forecasts are likely to be of most value[27]. This is another area where further work to improve model predictions is likely to be fruitful.

Fig. 9: RRS James Clark Ross in sea ice (photo credit: British Antarctic Survey)

Question 4: Are the risks of natural hazards in the Arctic region increasing as a result of regional warming and what are the threats posed to the UK?

Key points:

- Sea-level rise in the Arctic has two major consequences: coastal erosion and rising water tables. This might exacerbate some of the positive climate feedbacks identified by NERC ARP scientists, i.e. through methane emissions. Rising sea levels combined with longer ice-free seasons and increased storminess are also threatening local communities.
- Submarine landslides have occurred more frequently than previously thought and they are now likely to be included in the UK National Risk Register. However, they are unlikely to be triggered by collapse of methane hydrates. Instead, risk appears most likely associated with the speed and amount of sediment accumulating on the seabed at particular locations.
- The risk of offshore fossil fuel drilling acting as a trigger for submarine landslides is poorly researched and currently unknown.

Sea-level rise

Sea-level rise has two major effects on land masses. First, coastal erosion may increase as wave fronts hit higher on the coastline. The effects are already being felt, as sea-level rise combined with longer ice-off seasons and increasing storminess are threatening coastal communities[28,29]. Secondly, sea-level rise may exacerbate some of the positive climate feedbacks identified by NERC ARP scientists. Methane emissions are projected to rise in areas becoming wetter due to climate change, in particular lowlands, many of which border coastlines, which will experience rising water tables. Furthermore, some of the water may become saline, with unknown consequences on the biogeochemistry and therefore greenhouse gas emissions of these areas.

Under-sea landslides and tsunamis

The highest uncertainties in current understanding of under-sea (submarine) landslides relates to the frequency at which catastrophic, societally damaging landslide-triggered tsunamis occur and the role that methane hydrates play in triggering landslides. The latter process especially has been hotly debated as there is a possibility that hydrates will collapse in response to ocean warming (see above). This could result in potentially catastrophic tsunamis. Such tsunamis have historically occurred most frequently in latitudes at or below the Subarctic. One of the largest known to date originated ca 8000 years ago at Storegga (65°N, 4°E) in the Norwegian Sea, an area studied by NERC ARP scientists.

The researchers discovered that landslides have occurred more frequently than previously thought, qualifying them for inclusion in the UK's National Risk Register (< 100,000yr) as a potential tsunami risk. For example, a more recent and severe landslide at the Storegga site was discovered during field sampling, highlighting the importance of developing recurrence intervals/risks of landslides at particular locations. Whether and how to designate landslide-related tsunamis as a formal risk is currently under discussion.

Evidence does not support the idea that methane hydrates cause landslides. Instead, risk appears most likely associated with the speed and amount of sediment accumulating on the seabed at particular locations.

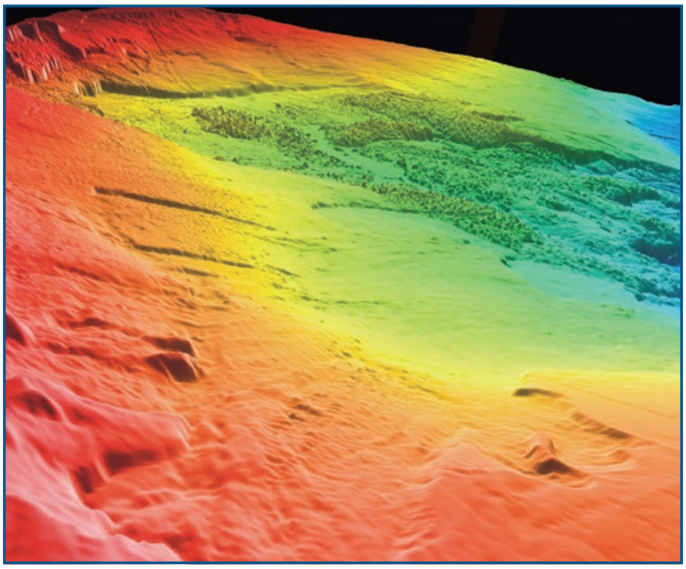


Fig. 10: Sea-floor view (looking south) of the Storegga Slide area (blue/green colours). The slide affected several hundred km of the Norwegian continental shelf about 8000 years ago. Image: Christian Berndt, GEOMAR. URL: http://www.geomar.de/en/news/article/meeresboden-in-bewegung-ge-faehrdete-kuesten/

Risks to offshore gas and oil extraction

As there is only weak evidence for landslides being caused by methane hydrates, locations of methane hydrates may not reliably highlight hotspots for future landslide events. However, the risk of methane hydrate collapse with rising sea temperatures cannot be discounted. It should be considered in the planning of Arctic gas and oil extraction.

Implications for future UK policy

The Government compiled an up-to-date Climate Change Risk Assessment in 2016[30]. It highlighted several changes occurring at alarming speed globally and in the Arctic. For example, fourteen of the sixteen warmest years on record have occurred since 2000, with 2015 confirmed as the warmest year recorded globally[30]. Further, new observations show faster polar ice loss than reported in recent IPCC assessments[30,31].

Specifically in the Arctic, sea ice extent has reduced significantly over the last few decades (Fig. 3), at a minimum being 49% below the 1979 – 2000 average[30]. The NERC ARP identified multiple self-reinforcing climate change feedbacks which increase the risk of accelerating climate change in the region and globally. Below, we summarise the main policy implications arising from the NERC ARP research, ranging from climate change policy to opportunities for increasing engagement between researchers and Government.

Arctic-linked climate change policy

The current UK Arctic policy framework states that the UK is a "global leader" as regards both pushing for reduced emissions of greenhouse gases and tackling the rapid changes facing the Arctic[32]. Self-reinforcing climate change in the Arctic that has global effects (e.g. sea-level rise, increasing greenhouse gas concentrations, impacts on mid-latitude weather) is extremely likely. This report supports retaining current policy towards the Arctic, investing in both research and in concrete efforts to reduce greenhouse gas emissions, and advocating the global importance of the Arctic environment. The possibility of increasing frequency of weather extremes in coming years and decades has implications for UK Government policy across many areas, including health, water, food, energy security and transport. Key Government Departments with an interest include the FCO, Cabinet Office (Civil Contingencies Secretariat), DEFRA, Department of Health, BEIS and Department for Transport, amongst others.

Investment in future Arctic research

NERC ARP Principal Investigators were credited advisors on the Lloyd's of London & Chatham House report "Arctic Opening: Opportunity and Risk in the High North" published in 2012[33]. In the report's Foreword, the CEO of Lloyd's, Martin Ward, notes that "the pace of environmental transformation currently taking place in the Arctic is unprecedented". The opportunities concern business sectors such as energy and mineral extraction, shipping, fisheries and tourism. But Ward observes that the level of uncertainty about the environmental and economic future of the Arctic is significant and he states that "there is a clear need for sustained investment in Arctic research".

A strong theme echoed by many scientists is the need for internationalisation: cooperation among national funding agencies, provision of support of international collaborative efforts where the science is needed. On land, this is particularly the case for Russia, which administers large portions of the Arctic and sub-Arctic landmass and for which there is a striking paucity of data. The advent of stronger UK-Russia scientific relations in 2017 is a promising development and should be capitalised upon.

Another strong theme raised by scientists is the need for regular monitoring of the Arctic. Monitoring programmes often fall foul of the short-term science funding cycle, but they have a critical function in tracking change. The UK is active in the European Space Agency and UK institutions have expertise in satellite-based remote-sensing. Two projects used satellite-derived data for remote assessments of properties of the Arctic land surface. Promotion of space-based observation is a key route to overcoming the inaccessibility of the Arctic region.

People live in the Arctic and their lifeways are changing due to the changes occurring in the environment. As was reiterated at the last Arctic Science Summit, local populations must have a voice in research and their needs must be factored into Arctic policy decisions. While the UK does not have jurisdiction over communities in the Arctic, its science and policy nevertheless affect those populations. Cross-disciplinary work that involves social science approaches is needed to place observed changes and future projections in a human context. So far, this context has been lacking from the Arctic programme, as it remains discipline-specific.

Biodiversity, ecology and human subsistence

The UK Government's 2013 Arctic policy report emphasised biodiversity changes as a key issue in Arctic policy. The majority of projects in the NERC ARP were physical and did not specifically address biodiversity or subsistence issues. However, several land-based projects contributed new knowledge about how changes in the landscape, primarily driven by the loss of permafrost, drive changes in vegetation cover and degree of waterlogging, etc.

Thawing permafrost alters landscape drainage and wetness, in turn affecting the navigation of the Arctic landscape by humans and animals. This in turn affects the distribution and health of animal species and thus the lives of subsistence herders and hunters. Changing weather patterns also affect animals. For example, mass starvation and death of deer has occurred in areas where climate change has resulted in late autumn rains. Once the rain freezes, it forms a layer that the animals cannot break to access food[34].

The Arctic contains a vast number of fresh-water bodies: rivers, lakes and ponds. Their physical properties, such as length of the season of solid ice cover, are changing and affecting human and animal movements. Changing vegetation cover ("greening") affects nutrient loads in rivers and lakes, which in turn is likely to alter the ecology and biodiversity of aquatic systems, which are critical to the ecology of numerous migratory bird species and locally important sources of fish for human populations. We can expect major changes in biodiversity and ecosystem function in Arctic lakes and waterways that may be as great as the changes associated with planetary warming at the end of the last ice age.

Opportunities for engagement between Government and researchers

Science diplomacy

The undertaking of Arctic research and subsequent use of the results obtained underpins the UK's policy engagement in the Arctic and contributes directly to its good relations with Arctic States. As an Observer to the Arctic Council, the UK's contribution to the sustainable development and environmental management of the Arctic is largely based on scientific cooperation with Arctic States and the wider Arctic science community.

Beyond providing a better understanding of the rapid changes in the Arctic, science can support the building of bridges and networks of collaborations to underpin the diplomatic relations between the UK and the Arctic states. Scientific research and collaborations are strongly interwoven with sustainable development and political stability in the Arctic. Supporting the one will generally lead to strengthening the other.

Reciprocally, diplomacy can facilitate international scientific cooperation. It is therefore crucial for the quality of UK Arctic science that the UK continues to support international science cooperation and multilateral large-scale research infrastructures in the Arctic, for example through active membership of, and engagement with, IASC (the International Arctic Science Committee).

Making Government data accessible for science

The Arctic is a difficult environment in which to gather data because access is limited both by sea ice and complex terrain and because satellite coverage is currently limited. Due to these limitations, researchers lack observational data to calibrate and validate models, especially predictive models, such as sea ice and climate cycle predictions. As the accuracy of model predictions is currently limited by data availability more than by computing power, more data are needed if models are to realise their potential to make reliable predictions.

The UK Government can play a crucial role, not only through funding for further research and data collection, but through an increased effort to facilitate access to existing data both in the UK and internationally through collaboration with Arctic States. Declassifying data, such as in the SEATS project that analyses Ministry of Defence submarine data, is an excellent example of successful use of government-held data (Box 6). More should be done to allow access for scientists to measurements held by the UK Government and its agencies.

Beyond making data accessible, more attention should be given to "data rescue". For example, large amounts of historical data, such as ship data, are held in the National Archives. Gaining access to extensive historical data sources presents a significant challenge, as the records are all still in paper form and would need to be digitised to be of use. In addition to making full use of existing data sources, relatively limited sums of funding allocated to data rescue projects can bear significant benefits, both in terms of cost-effectiveness and scientific value.

BOX 6: Using submarine data for science

In areas of thick multi-year sea ice cover, the ice acts as a barrier between the atmosphere and the ocean, stopping energy from wind from being transferred to the sea and generate waves. As the ice pack shrinks and begins to break up, this protective barrier is being lost and more sea is exposed to wind, which produces turbulence in the water, mixing it up.

Little has been known previously about the effect of sea ice loss on wind-generated mixing, and how this is likely to affect ocean circulation. Few observations have been available, because of the difficulties of surveying by ship in ice-covered areas.

Researchers involved in the SEATS project were given access to data gathered by instruments aboard a Royal Navy submarine, so that they could compare ocean mixing in ice-covered areas with that in areas free from ice[7]. The understanding they have gained will enable scientists to better represent wind-driven mixing in models and so allow more accurate predictions of future climate.

Fig. 11: Collection of images showcasing UK Arctic involvement (photo credits: British Antarctic Survey, Cammell Laird, S. Andrews - University of York, National Oceanography Centre, European Space Agency)

Facilitating contacts with users of science

Connecting the worlds of academia and politics is an ongoing challenge that also affects the world of Arctic science and policy. Although many forums exist in the UK and abroad to increase collaboration both among Arctic scientists and Arctic policymakers, and between these two groups, many researchers are still unsure about how to engage with decision-makers. Bridging the gap between Arctic science and policy requires a balancing act on both sides. Policymakers are required to balance evidence provided by Arctic scientists against other, potentially conflicting, interests, while scientists have to balance scientific accuracy with the requirement to simplify the science to make it accessible.

Notwithstanding the above, the Arctic offers a unique opportunity to increase knowledge exchange between scientists and policymakers, as science lies at the core of the UK's Arctic strategy. This requires scientists to engage with non-academic audiences and discuss the implications of their findings for Arctic policy. This knowledge exchange should be facilitated through regular and long-term engagement between the policy and the scientific community. Research Councils, the NERC Arctic Office and international Arctic forums have a crucial role to play in facilitating this dialogue. This policy report is an example of a concrete initiative to engage with the Arctic policy community and discuss the Arctic climate research carried out in the NERC ARP. Similar initiatives, under the auspices of the Research Councils and the Government, could continue supporting the dialogue between Arctic science and policy.

The dialogue between Arctic scientists and policymakers also allows for capacity-building on both sides. Through repeated interaction and open discussion, scientists can develop greater understanding of the world of policy, while policymakers acquire the necessary scientific literacy to make sense of complex Arctic science, generating a positive feedback loop of greater understanding and interest for Arctic science. Science advice to Government could be provided at the highest level through a high-level policy guidance group, similarly to the EU high-level guidance panel.

Beyond knowledge exchange, sustained engagement over time may have positive effects on collaboration between scientists and policymakers. The contribution of scientific research to solving the most pressing policy challenges in the Arctic could be significant, if policymakers were to be involved in the definition of the research questions. Similarly, more could be done to engage with a diverse range of stakeholders jointly. Different communities: businesses, charities, NGOs, academia and policymakers discuss many Arctic policy-related issues bilaterally. However, the complexity of the Arctic requires fora to discuss issues across the worlds of NGOs, science, business and politics. The Government could play an essential role in facilitating such a multi-stakeholder forum on the Arctic.

Appendix 1: List of projects reviewed

All projects are listed at http://arp.arctic.ac.uk/

Project	Topic	Area
ACCACIA	Aerosols, clouds, climate change	Svalbard (Norway)
APPOSITE	Arctic climate prediction feasibility	Pan-Arctic
Canadian Archipelago Oceanography	Ocean circulation, climate change	Canada, Greenland
CYCLOPS	Permafrost melting, carbon cycling	Northwest Territories, Yukon Territory (Canada)
Eurasian Arctic	Carbon cycling, climate change	Eurasia
HYDRA	Carbon cycling, greenhouse gas budgets	Northwest Territories, Yukon Territory (Canada)
LAC	Carbon cycling in lakes, climate change & vegetation change	Alaska, Greenland, Norway
Landslide-Tsunami	Submarine landslide risks, climate change	Norwegian Sea
MAMM	Greenhouse gases	European Arctic
Methane budget	Methane release, oceans, terrestrial, climate change	Pan-Arctic
Methane hydrates	Methane release, oceans, climate change	Svalbard (Norway)
SEATS	Ice cover changes, ocean circulation, climate change	Arctic Ocean
TEA-COSI	Freshwater pulses, ocean circulation, climate change	Arctic Ocean

Appendix 2: Further reading

Informative lay reviews and case studies of Arctic climate change causes, effects, and predictions include:

Web resources:

Methane emitted also in cold months: http://www.climatechangenews.com/2016/01/06/Arctic-methane-emissions-greater-than-previous-estimates/

Drying permafrost thaw areas release CO_2 rapidly: https://www.scientificamerican.com/article/melting-tundra-releases-carbon-dioxide-quickly/

Arrival of spring marks CO_2 pulse in polygonal tundra: https://phys.org/news/2016-12-scientists-pulse-CO2-emissions-Arctic.html

Permafrost thaw in polygonal tundra results in drying and soil collapse: http://www.innovations-report.com/html/reports/earth-sciences/a-glance-into-the-future-of-the-Arctic.html

Climate change induces vast erosion of coastlines and organic carbon: http://blogs.agu.org/landslideblog/2017/01/06/collapsing-Arctic-coastlines/

Permafrost thaw collapses land masses and exposes ancient soils: http://www.bbc.com/earth/story/20170223-in-siberia-there-is-a-huge-crater-and-it-is-getting-bigger

Basic descriptions of Arctic: http://www.terrapolaris.com/5/Arctic/the-Arctic-in-general/arktische-landflaechen/

Basic information on greenhouse gases: https://www.epa.gov/ghgemissions

Useful up-to-date illustrations of global greenhouse gas budgets: http://www.globalcarbonatlas.org/en/content/welcome-carbon-atlas

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