CLIMATE CHANGE AND THE POLAR REGIONS

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Stretching back to Scott's doomed *Terra Nova* expedition, the enigmatic polar regions have long been a source of fascination for explorers and scientists alike. Today the polar regions remain a fertile ground for scientific exploration, serving as natural, interdisciplinary laboratories for the pursuit of new knowledge that can refine our understanding of the Earth system. However, the reality of climate change has meant they have taken on a new poignancy, for these frozen worlds are undergoing rapid changes with global impacts.

The polar regions provide an unrivalled time-machine, giving us insight into past climates through ice cores. As layer after layer of snow falls, a climate history accumulates. As the snow compacts to ice it traps tiny bubbles of air with it. By drilling down through the ice we are able to delve back in time. From the air bubbles we can determine the carbon dioxide levels in the atmosphere in the past and by analysing the water in the ice we are able to estimate the temperature (the latter is possible because the oxygen in the water comes in different chemical forms known as isotopes and the ratio of those isotopes varies according to the temperature of the atmosphere when the snow was formed).

As part of an international effort drilling deep into the ice in Antarctica, my colleagues at the British Antarctic Survey (BAS) have acquired a climate record going back an incredible eight hundred thousand years – a full six hundred thousand years before *Homo Sapiens* is thought to have evolved in Africa. As the orbit of the Earth has moved slowly, over tens of thousands of years, closer to or further away from the Sun, the temperature has varied between short warm periods and long, much colder ice ages. The carbon dioxide levels have varied up and down too, in step with the temperature. The evidence suggests that carbon dioxide is released by the ocean in warmer periods and taken up in cooler times. The greenhouse effect then kicks in and, according to the carbon dioxide levels in the atmosphere, the temperature rises or falls further. This all describes the slow natural cycle of climate change.

However, since the start of the industrial revolution, the burning of fossil fuel has meant carbon dioxide in the atmosphere has rapidly increased by about 40%, to a value that far exceeds that found in the ice core record. This has short-circuited the natural cycle – changes to the Earth's orbit are not significant over this brief time period, but the greenhouse effect has meant that temperatures have risen substantially. Now the average surface temperature is about 0.8°C warmer than at the beginning of last century.

Not everywhere has warmed by the same amount: the Arctic has seen the greatest

. . . a climate history accumulates . . .

Fig 1: A section through an ice core showing the trapped bubbles of air (© British Antarctic Survey)

. . . changing the ocean circulation . . .

temperature increase over the past few decades and the Antarctic Peninsula has also seen considerable change. I visited Iqaluit in the Canadian Arctic in 2010 and the local people told me how the changes they have seen over recent decades have impacted their daily lives, as their ice-world rapidly melts into a watery mud-scape. The loss of sea ice in the Arctic has been particularly dramatic. The sea ice reaches its minimum extent each year at the end of the summer melt season in September. In 2012 it covered just 3.4 million square kilometres, almost 50% less than the average coverage over 1979-2000. This is a huge reduction in area that is roughly equivalent to three quarters of Europe!

The changes to the polar regions can impact the rest of the planet. Some recent studies have linked unusual weather in the UK and North America to the decline in Arctic sea ice, and a comprehensive review[1] has detailed the impact of the melting of the polar ice sheets on global sea level, concluding that they have collectively contributed about 0.6 mm per year since 1992. Relatively warm water from the Southern Ocean can be brought up under Antarctica's ice shelves and melt them from below. Evidence suggests that this is resulting in the loss of ice from the West Antarctic Ice Sheet[2] and associated sea level rise. About 10% of the world's population, a similar or greater proportion of the infrastructure and many of the great trading hubs and world cities are in low-lying coastal regions and are thus at risk from sea level rise[3].

Despite their similarities there

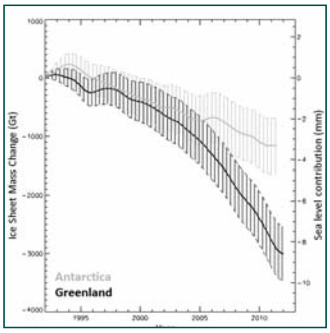

Fig 2: Changes in ice sheet mass and the contribution to sea level. Adapted from Shepherd et al, 2012.

are also key differences between the Arctic and the Antarctic. The most fundamental is perhaps that Antarctica is land surrounded by ocean whereas the Arctic is an ocean surrounded by land. A consequence of this is that strong winds are able to circulate around Antarctica in a way that does not happen to the same extent in the Arctic. As the climate changes, these Antarctic winds are anticipated to increase in strength and this may alter the amount of carbon dioxide that is taken up by the Southern Ocean, which at present equates to about 10% of man-made emissions, by changing the ocean circulation. A reduction in the ocean uptake would mean the atmospheric levels of carbon dioxide would rise faster and that would increase the rate of climate change.

Unlike in the Arctic where sea ice has been decreasing everywhere, in the Antarctic there has been a complicated pattern of sea ice change in recent years with some regions showing an increase and others a decrease. It has been suggested that this may be due to the changing wind patterns[4]. Along the Antarctic Peninsula the sea ice has been decreasing, which some scientists suspect has led to ecosystem changes. Shrimp-like krill appear to have dropped in number significantly over recent decades, perhaps by as much as 80%. A key part of their lifecycle is spent under the sea ice and so a change in sea ice can have direct consequences. Krill are a central component of the food web and therefore their demise has the potential to affect many other species. Decreases in populations of Adélie and chinstrap penguins have been observed along the Antarctic Peninsula[5], and there are no longer any emperor penguins inhabiting Emperor Island where once there were some 150 breeding pairs[6]. It is not known whether these losses are directly attributable to the sea ice changes, but a link is plausible.

been observed by BAS scientists[7].

A final compelling reason to focus on the polar regions is that they harbour some of the key risks of rapid or irreversible change such as melting permafrost releasing methane, influx of fresh melt water disrupting the Gulf Stream and collapsing ice sheets raising sea level. The ice core record from Greenland highlights the fact that dramatic changes have occurred in the past, especially around the North Atlantic, with periods of temperature change in Greenland of 10°C in less than a human lifetime. Similarly in Antarctica dramatic changes have been observed, such as the sudden collapse in a matter of weeks of Larsen B ice shelf (more than twice the size of

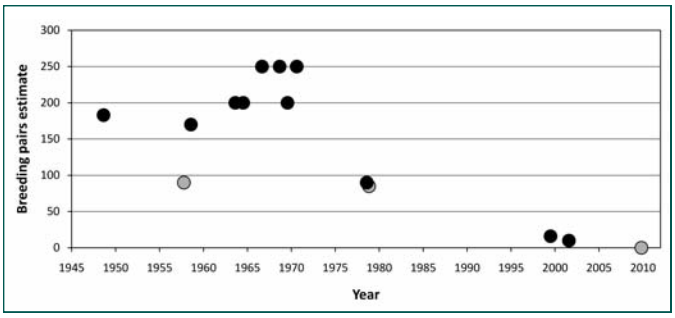

Fig 3: Estimated number of emperor penguin breeding pairs on Emperor Island. Black circles indicate counts made during winter and grey circles counts made later in the breeding season during spring, potentially after some egg/chick loss. From Trathan et al, PLOS One, 2012.

The other critical aspect of ecosystem damage related to man-made carbon dioxide emissions is ocean acidification. The oceans are thought to be acidifying at a faster rate than at any time in the past 300 million years. This acidification has a particular impact on calcareous skeletons or shells of marine life and some of the first signs of damage to marine snails in the Southern Ocean have recently

Greater London), which occurred in 2002. The geological record indicates that Antarctica's ice sheets have varied in extent considerably in the past and there are concerns that large parts of the West Antarctic Ice Sheet could collapse in the future, leading over several centuries to more than 3 metres of sea level rise.

Thus the polar regions, though remote, are rightly

. . . no longer emperor penguins inhabiting Emperor Island . . .

emblematic of threat posed by man-made climate change, both in terms of their own survival and their global impacts.

How then can science help policy-makers and society in general make well-informed decisions concerning the future? The modern industrial economy is deeply rooted in a fossil-fuel based system, with carbon emissions steadily increasing year-on-year. An examination of the latest climate projections [8] indicates that without action to reduce our emissions we are likely to move beyond a threshold of 2°C increase in global average surface temperature compared with pre-industrial times by the middle of this century. By the end of the century on our current emissions trajectory we could exceed 4°C, taking us into a very different world where the risk of rapid or irreversible change is greatly enhanced.

To prevent this, global emissions need to peak soon – within years rather than decades [9]. That necessitates transformational change on a scale that is simply not currently happening. Rising to that grand challenge will require leadership and political will, together with technological and social innovation, and the engagement of society as a whole. Success would mean preserving the polar regions as a source of fascination for future generations of scientists and explorers, and perhaps more importantly protecting society from the worst of the damaging impacts of climate change.

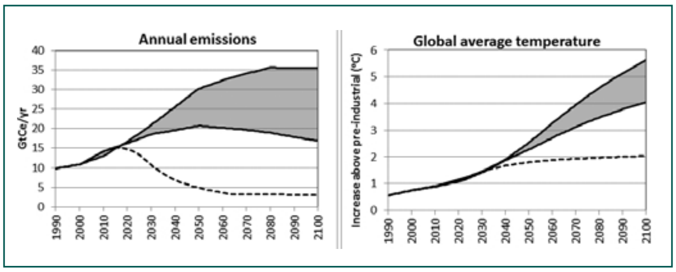

Fig 4: Annual emissions of greenhouse gases and associated global average temperature for three future emissions scenarios. The solid lines show two 'business-as-usual' scenarios: a fossil fuel intensive (A1FI) one and a more diverse energy mix (A1B). The dashed line shows a strong climate change mitigation policy where global emissions peak in 2016 and decrease by 5% per year thereafter). Adapted from Arnell et al, 2013.

References

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CLIMATE CHANGE AND THE POLAR REGIONS

CLIMATE CHANGE AND THE POLAR REGIONS: impacts of a disappearing Arctic sea ice cover

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Since the Industrial Revolution, the Arctic has been warming more rapidly than any other region, with an amplification factor of 2-4 over the planet as a whole. Since 1850 this rapid warming has produced a temperature increase (averaged over the year) of 3°C for stations north of 60°N, while the planet as a whole has experienced 0.8°C. Since 1950 the sea ice extent in every season has been seen to be reducing. In particular the summer (mid-September) sea ice extent shrank from 8 million km^2 in the 1970s, to only 4.2 million km^2 in 2007, and to an all-time low in 2012 of 3.4 million km^2. Viewed from space, the top of the world now looks blue instead of white in summer, a profound change. This shrinkage is expected to continue. Some climate models predict an 'ice-free' Arctic summer by 2040 while others predict an ice-free September within a very small number of years, before 2020 and possibly as early as 2015. An empirical analysis based on ice volumes rather than just areas also predicts a fundamentally ice-free Arctic by summer 2015 using satellite-tracked ice areas and submarine-surveyed ice thicknesses. On this basis there seems little doubt that by summer 2015 the Arctic Ocean will be fundamentally ice-free, with probably a narrow fringe of older (multi-year) ice remaining around the north coasts of Ellesmere Island and Greenland, these being the only areas where multi-year ice, once

. . . change in planetary albedo . . .

dominant in the Arctic, retains a strong presence.

The summer retreat of sea ice has been accompanied by a significant decrease in sea ice extent in other seasons, notably an earlier start to the spring retreat, also by a decline of more than 40% in sea ice mean thickness and a reduction of 73% in the frequency of pressure ridges, which have always been a significant barrier to navigation.

This reduction in sea ice area is having major impacts on both a regional (Arctic) and a global scale. Of special concern are positive feedback loops, where a change in sea ice extent initiates another undesirable or unexpected change. The first of these is a change in planetary albedo, leading to an acceleration of the global warming rate. Albedo, the fraction of incoming solar radiation reflected by a surface, is high for fresh snow (0.8-0.9) and even dirty melting snow and ice (0.5-0.6) but low for open water or bare land surface (less than 0.1). This means that the loss of sea ice area in summer is associated with a large increase in absorbed solar radiation. This is made worse by the fact that the northern hemisphere snowline is also retreating; in June 2012 the snow area showed a record 6 million km^2 negative anomaly relative to the average for the past 30 years, clearly driven by warmer air masses moving over Arctic land areas due to sea ice loss in the ocean itself. It has been estimated that the loss of summer sea ice and snow area on land are together giving, through albedo change, the same additional global warming as the last 25 years of added CO_2.

A second easily detected change is an acceleration in the summer melt of the surface of the Greenland ice sheet, leading to Greenland making a greater contribution to global sea level rise. Prior to 1985 no summer melt was detectable on Greenland, but the area subject to melt has steadily increased (in early July 2012 97% of the ice sheet surface showed melt) and Greenland is now contributing 300 km^3 of water annually to the world ocean (an average of 142 km^3 per year since 1992, but rising steadily), making it the largest single contributor to global sea level rise. As a result, estimates of global rise this century are now being revised upwards: in IPCC AR4 they were 30-70 cm, but higher values, with a wider range of uncertainty, are expected from AR5. This leads to an increased risk of disastrous storm surges in vulnerable areas like the Bay of Bengal.

In addition, another potential risk from the Arctic relates to methane release. Methane is being released as permafrost on land slowly melts, and already global atmospheric methane levels, stable in the early 2000s, are being observed to increase, with the source being identified by modelling as the Arctic. More serious and immediate may be an offshore release. Scientists estimate that approximately 50 Gt of methane is ready for abrupt release at any time in the East Siberian Arctic Shelf area (ESAS) alone, due to the shallow continental shelf seabed warming as summer sea ice retreats, which causes offshore permafrost to melt. Recent observations by Semiletov et al indicate that underwater methane release, in the form of large bubble plumes, is already occurring in this region. Economic modelling attributes $60 trillion in costs to this one effect, with the economic burden felt disproportionately (80%) by poorer regions.

. . . more prolific spring plankton bloom . . .

Set against these unfavourable, and deeply worrying, regional physical changes are positive regional economic opportunities. Oil exploration and production will be easier; the favoured option of a dynamically positioned drillship supported by a group of icebreakers breaking up ice around it to relieve potential pressure is applicable to first-year ice areas which now compose most of the Arctic ice cover, though the environmental threat of an under-ice blowout remains a potent factor.

Shipping will be easier: both the Northern Sea Route (across the north of Russia) and the Northwest Passage are now ice-free for 2-3 months per year, and in 2012 40 commercial ships sailed through the Northern Sea Route including a loaded liquified natural gas (LNG) carrier. In future, with an ice-free summer Arctic, a true trans-Arctic shipping route from Bering Strait to Europe via the North Pole will be possible, and even in winter the first-year ice and lack of pressure ridges will allow ice-strengthened ships to cross the Arctic. Already the retreat of sea ice, and its penetrability to radiation even before its disappearance (via light penetration through melt pools) are resulting in an earlier and more prolific spring plankton bloom in ice-free regions, suggesting that a future Arctic will have a high fisheries potential. Tourism will undoubtedly flourish. At the same time, global risks to various economic sectors will increase: it has been hypothesized that the retreat of sea ice is connected with, and may be a causal factor for, the change in shape and nature of the jet stream which has been a factor in 2012 drought, crop losses and weather extremes at mid-latitudes including Hurricane Sandy. If this is found to be the case, then insurance losses alone make sea ice retreat one of the most expensive natural fluctuations currently afflicting the earth.

. . . melt of the surface of the Greenland ice sheet . . .

WHY SHOULD THE UK CARE ABOUT THE ARCTIC?
An oceans and climate perspective

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We all know that the Arctic is the cold bit at the northern end of the planet, but a functional definition is actually quite tricky. An easy choice might be "north of the Arctic circle", where the Arctic circle is the parallel of latitude 66˚34′ N. For any latitude at or north of it, the sun can remain continuously above (or continuously below) the horizon for twenty-four hours. However, this definition would cut off the southern third of Greenland, and since Greenland supports an ice cap about three kilometres thick, it should sensibly be included as "Arctic". A practical definition would most likely entail use of the word "cryosphere", which means the part of the planet influenced by the freezing of water, but more care is needed: it is snowing in Hampshire as I write this, but that does not make Hampshire part of the Arctic. Similarly, altitude is relevant: permanent glaciers exist at the tops of high mountains, like the Alps and Kilimanjaro, but they are not Arctic either.

It is illuminating to take an imaginary tour around the latitude circle of 60°N, starting in the UK: the Shetland Islands span a degree of latitude, from Sumburgh Head at 59°51′N to Muckle Flugga at 60°51′N. The climate of the Shetlands is cool, damp and breezy. Now travel eastwards, across the northern North Sea to southern Scandinavia, passing close by Oslo and Stockholm, then crossing the Baltic – which freezes in winter – to the environs of Helsinki and St. Petersburg. Stretching ahead are the trackless wastes of the Siberian permafrost and tundra, one-third of the circumference of the Earth at this latitude – 6000 kilometres. Perhaps the major geographical features here are the great rivers – the Lena, the Yenisei and the Ob – which, with the many lesser rivers, drain 10% of the Earth's total flow of river water into the Arctic Ocean; and in winter, these rivers freeze. In clipping the northern end of the Sea of Okhotsk, our tour leaves Siberia, passing across the Kamchatka Peninsula to enter the Bering Sea, the northernmost extremity of the Pacific Ocean, covered with sea ice in winter at this latitude.

> . . . cut off the southern third of Greenland . . .

> . . . trackless wastes of the Siberian permafrost . . .

Continuing east, we touch land on Alaska, running close to the coast of south central Alaska; Anchorage is a little to the north, and Juneau to the south. Next, the Canadian interior bears comparison to Siberia, albeit less extensive. We soon run into some interesting bodies of water. Hudson Bay (which freezes in winter), and Hudson Strait (which also freezes in winter), its connection to the Labrador Sea, a marginal basin of the North Atlantic. The Labrador Sea is a very interesting place because it is one of very few locations in the world ocean where deep convection occurs. Strong, cold, winter winds pull so much heat out of the ocean that the water can become dense enough to overturn to depths of up to two kilometres. At the eastern edge of the Labrador Sea lies Cape Farewell, the southern tip of Greenland; then the East Greenland Current, with its winter burden of sea ice, much of which flows out of the Arctic through Fram Strait, far to the north. Finally we meet the temperate waters of the eastern North Atlantic, and return to the Shetlands.

. . . Labrador Sea is a very interesting place . . .

So all round 60°N, it is not just the land but also the seas that freeze hard during winter, with the exception of the north-east Atlantic (and the Shetlands); and it is straightforward to extend this analysis to show that it is the whole north-west European seaboard, encompassing the British Isles and western Norway, that experience a relatively privileged climate, notable for its anomalous warmth. It is said that the UK has a "maritime" climate, but it is clear from the tour of 60°N that simple proximity of a sea or ocean is not sufficient in itself to make a maritime climate a (relatively) warm one. The UK sits on the east side of a warm ocean over which westerly winds blow, and those winds draw their warmth from ocean waters which began their journey to our latitudes far to the south. So why do we have warm ocean waters travelling northwards near the UK?

The answer lies in the complicated mathematics that describe fluid flow on a rotating planet, heated (by the sun) from above; and there are two fluids to consider – the atmosphere, which is not strongly constrained by orography, and the ocean, which is absolutely constrained by land. To pursue the narrative explanation rather than the mathematical, consider the whole of the Atlantic Ocean, from its furthest southern part at its junction with the Southern (Antarctic) Ocean, north through the Equator as far as Iceland. The Atlantic supports a Meridional Overturning Circulation (or MOC), where "Meridional" simply means "in the north-south sense" ("zonal" is the adjective describing "east-west"). It is only in relatively recent decades that the importance of the MOC to climate has been appreciated. The MOC has been called the "Conveyor Belt" because (at its most simple) it represents warm Atlantic waters travelling northwards in the upper ocean (the top kilometre), balanced by a southward transport of cold Arctic waters at depth (between about one and four kilometres depth). The "Overturning" part of the MOC describes how the upper and lower limbs of the "conveyor" are connected – deep waters are drawn up to the surface around Antarctica by divergence caused by sustained and powerful winds, while in the Arctic, the supply of deep waters is maintained by the extreme cold making surface waters dense enough (mainly through cooling) to sink to great depths. Labrador Sea convection (mentioned above) is part of this sinking process. This has been called the "pump and valve" mechanism, where southern winds (and some other processes) are the pump that powers the system, and the northern manufacture of dense waters comprise the "valve", by opening a connection between surface and deep waters.

. . . delivering the heat that makes the UK climate mild . . .

Essentially, the MOC is responsible for delivering the heat that makes the UK climate mild. In 2004, Hollywood released a somewhat absurd blockbuster called "The Day After Tomorrow"; in one memorable scene, climate is changing so fast that it chases a character down a corridor! While scientists such as the present writer had a good laugh at the film's expense, it was much later that I realised that there was one truth contained within this film: that there is no future guarantee of a perpetually benign and stable climate. Studies of past climate and modelled scenarios of possible future climate have revealed a vulnerability of the MOC. The addition of large quantities of fresh water to the northern high-latitude oceans can act like a lid, reducing or stopping the deep convection that opens the "valve" of the MOC, and thereby slowing (or in extreme cases, stopping) the MOC, with the effect that the delivery of ocean heat to the UK's latitudes is reduced: in a warming world, it is possible that localised cooling may occur. A close study of the potential sources of increased fresh water input to the ocean shows that a sufficient quantity could be delivered in three ways: from increased rainfall over Siberia, which would intensify the delivery of river water to the Arctic; by "draining" a layer of diluted seawater occupying the upper two hundred metres of the Arctic Ocean (this would require a change in ocean circulation); and by increasing the rate at which summertime melting of the Greenland ice cap occurs. As a matter of interest, for the terms of this argument, Arctic sea ice does not figure strongly because it is a relatively small quantity of fresh water. We know that over the last several decades, Siberian river flow and the Greenland melt rate have been increasing.

So it is indeed possible that the MOC could be "distressed", to the detriment of UK (and European) climate; but it is important to note that I have described a scenario: a set of circumstances which could occur, but we do not know how likely (or unlikely) it is; no degree of probability is (yet) ascribed. Some aspects of climate are very well understood, such as the impact of increasing atmospheric greenhouse gas concentrations on temperature; but there are many aspects of the (extremely) complex climate system which remain less well-understood, and in need of further study – such as the interaction of oceans and cryosphere and their impact on climate.

. . . the UK has a "maritime" climate . . .