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Arctic Sea Ice

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EXECUTIVE SUMMARY

In the last few decades, the Arctic atmosphere has warmed by about twice the global average, and as much as anywhere else on the planet. This had led to very significant physical and biological changes of the Arctic environment. The consequences include rapid increases in the melting of glaciers, and an increase in freshwater runoff. But the most remarkable change is the reduction of the extent of summer sea ice in the Arctic seas and a more modest reduction in winter. All of these changes feedback strongly into the climate system, resulting in stronger seasonal variations of salinity, heat transfer from the ocean to the atmosphere, and potential consequences on ocean circulation.

Nearly all the marine wildlife in the Arctic is dependent on sea ice for some part of its life cycle, and these recent changes are already having an impact on all trophic levels from phytoplankton through to higher predators (birds and seals). Humans too have been affected, particularly the lives of indigenous people.

Although the Arctic changes are perceived as remote from Europe, the impacts are not. The warming is causing a rise in global sea level, and regime shifts in the marine ecosystems which support high-latitude fishing industries. There are opportunities too. Access to the significant reserves of oil and gas in the Arctic should also become easier. The Arctic shipping route between Europe and the Far East will become increasingly available, saving up to 50% in time and fuel. Tourism to the Arctic seas is likely to increase. All of these activities will lead to increased risk of accident, and hence pollution.

Understanding of the highly-coupled physical and biological systems of the Arctic is far from complete. Monitoring of the key variables in the Arctic is also patchy. The major unknowns that limit the accuracy of future projections include the emission levels of carbon dioxide arising from the burning of fossil fuels, the increase in methane levels caused by the release of clathrates from the warming ocean, and changing capability of the oceans to absorb increased carbon dioxide. There are likely to be significant impacts on the ecosystem as the Arctic seas become ice free in summer. Every trophic level will be affected: for example, top predators that use sea ice for breeding and hunting, the lower trophic levels will be altered by increased acidification of the ocean, and further changes to the Arctic fisheries are expected.

1. INTRODUCTION

The Arctic Ocean is large and roughly circular and covers over 14 million km^2. It is nearly land-locked, surrounded by Russia, the United States (Alaska), Canada, Greenland, Iceland, Norway, and Finland. Much of the Arctic Ocean is claimed by the surrounding nations; only a small region around the North Pole is outside existing economic exclusion zones. There have been suggestions to make this region an international space with international governance (Berkman, 2008).

About half the Arctic Ocean comprises shelf, representing about 25% of the world's ocean shelves. The deep ocean comprises two basins separated by the Lomonosov Ridge. The most important Arctic seas are shown in Figure 1, together with the extent of sea ice in recent decades including the record minimum year of 2007. This minimum is far ahead of most models predictions, and indeed there have been a suggestion that the sea ice has passed a tipping point i.e. an irreversible change (Lindsay and Zhang, 2005).

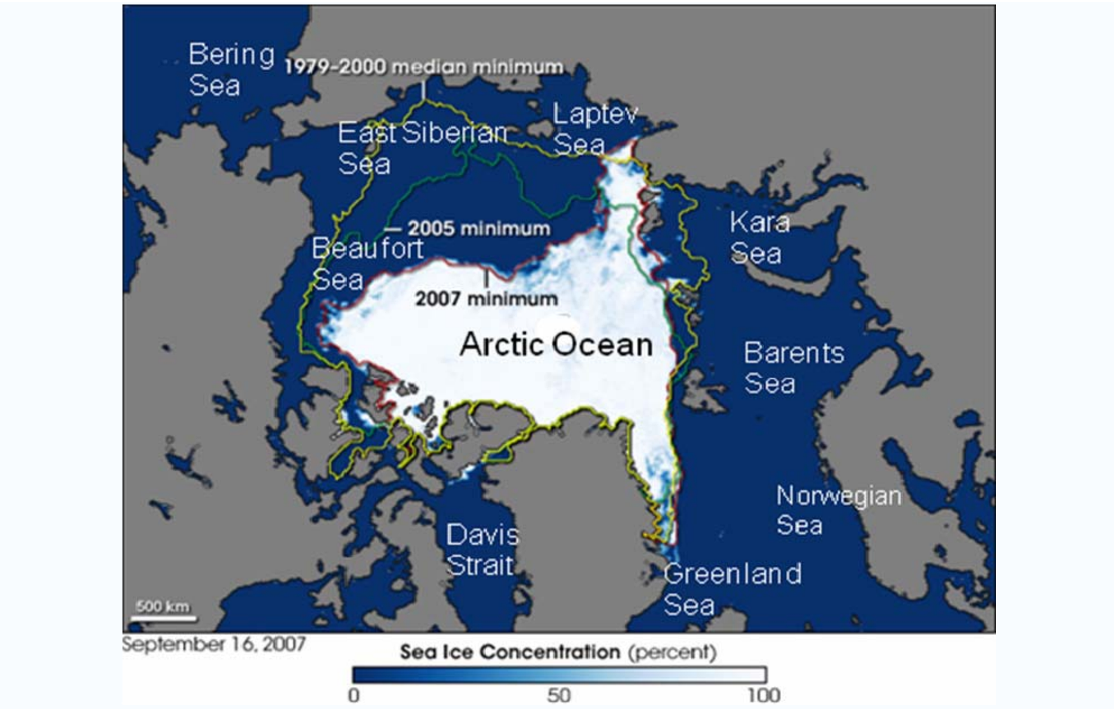

Figure 1: Major seas comprising the Arctic Ocean. Also shown is the extent of the sea ice at the minimum extent of the sea ice in September for three occasions - the median for the period 1979-2000 (yellow), 2005 (green) and 2007 (white area outlined in red). (Based upon data from National Snow and Ice Data Centre)

Much of the Arctic has seen a dramatic rise in air temperature over the last three decades, as indicated in Figure 2. Accompanying the air temperature rise are alterations to sea ice distribution, atmospheric and ocean circulation, ocean temperature, cloud cover, and salinity. Ozone levels have also reduced during the Arctic spring. In response to these many changes, there has been an upsurge in studies of the Arctic. Both the Arctic Climate Impact Assessment (2005) and the Intergovernmental Panel on Climate Change (2007) have provided in-depth analyses of the state of the Arctic. These documents contain many detailed references; key facts are summarised here and updated, where appropriate. The major sections of this report cover changes of the physical environment, the impacts on the biota of the

Arctic, a summary of the wider impacts, especially concentrating on the effects on Europe and an assessment of future changes.

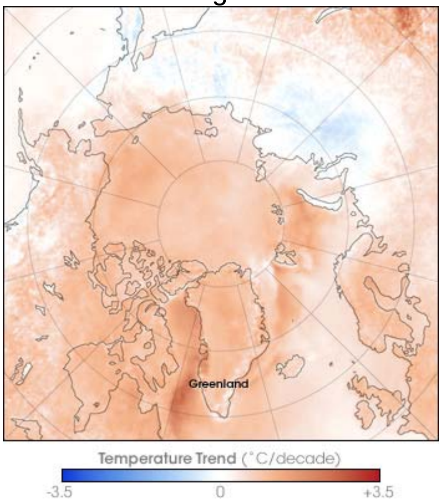

Figure 2: Rise in mean annual Arctic air temperatures per decade since 1981 (NASA map by Robert Simmons; data supplied by J. Comiso, Goddard Space Flight Center.)

2. THE CHANGING PHYSICAL ENVIRONMENT

2.1. Sea ice

Sea ice plays a crucial role in the Earth system. Apart from its direct influence on the radiative balance via its albedo (reflectivity), it also regulates ocean-atmosphere exchange processes (gases, heat and moisture), ocean stratification, salinity and atmospheric circulation. The extent of the leads (gaps between ice flows) and polynias affect local cloud cover and precipitation. Sea ice is fundamental in the formation of deep water masses, and thus is a major driver of global ocean circulation.

There has been a downward trend in Arctic late-summer sea ice extent since satellite observations began in 1980. A decade ago, the typical sea ice extent at maximum melt (minimum cover) at the end of summer was ~6.5 million km^2. But there have been marked reductions since then (Figure3). During September 2007, there was a record minimum sea ice extent, leaving only 4.3 million km^2 covered by sea ice (Comiso *et al.,* 2008). September 2008 was the second greatest minimum, with the corresponding area being 4.5 million km^2.

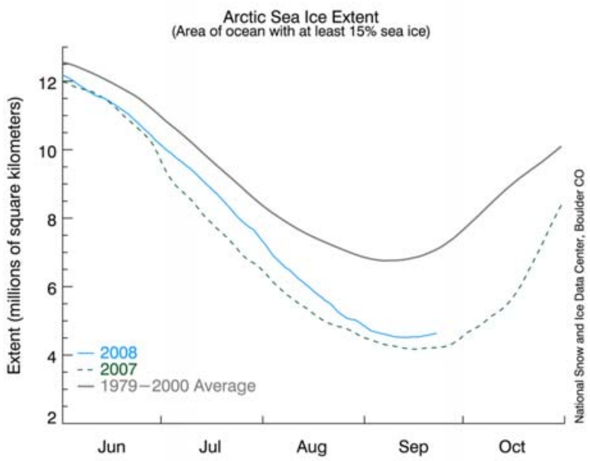

Figure 3: Extent of Arctic Sea Ice through the summer of 2007 and 2008 compared with the average between 1979-2000 (from www.nsidc.org/).

The maximum sea ice extent occurs in March, and this too has been reducing, though not as markedly as late-summer changes, from about 15.7 million km^2 in 2001, to 14.7 million km^2 in 2007 i.e. about 1% per annum in the 21^{st} century.

Sea ice thickness, and the snow upon it are very important variables in ice-ocean-atmosphere interactions. Sea ice insulates the warm ocean from polar air and controls the heat exchange. Snow cover on sea ice modifies its thermal and mechanical properties. Because of its very low thermal conductivity and high albedo even a thin snow cover exerts a strong influence on the heat exchange between the atmosphere and the ocean. Furthermore, thick snow acts as a mechanical load and can depress the sea ice surface below its freeboard. This can result in flooding of the snow-ice interface and the conversion of snow to ice. Thus, an accurate knowledge of snow thickness is essential for determining the overall heat and mass budget in the Polar Regions. Sea ice thickness is particularly difficult to determine, but progress is being made using data from space (e.g. Laxon *et al.,* 2003; Kwok *et al.,* 2004), however, most evidence comes from submarine data. The annual mean ice thickness reduced from 3.7 m in 1980 to a minimum of 2.5 m in 2000. The spatial contour map of the temporal mean draft varies from a minimum draft of 2.2 m near Alaska to a maximum just over 4 m north of Ellesmere Island (Rothrock *et al.,* 2008). Subsequent data suggest ice thickness has continued to thin dramatically. Figure 4 shows the age of sea ice in June 2008, compared with the average from 1983-2000 (Drobot *et al.,* 2008). It shows that there is now very little multiyear (2+) ice, and when combined with the greatly reduced summer sea ice extent, suggests sea ice volume is at an all time low. This result is consistent with observations by Giles *et al.* (2008) who found that the average winter sea ice thickness, after the melt season of 2007, was 0.26 m below the 2002/2003 to 2007/2008 average, and in the western Arctic was 0.49 m below the six-year mean.

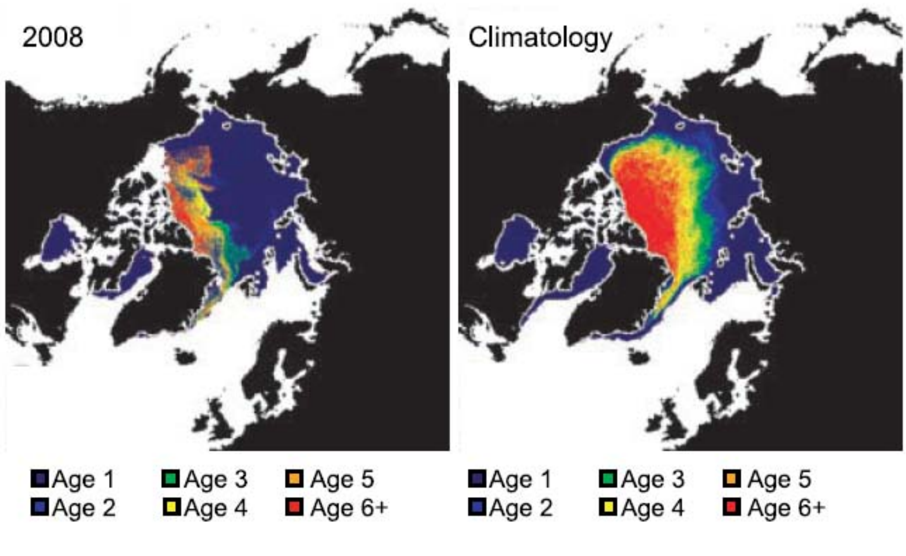

Figure 4: Changes in sea ice between June 2008, and the average climatology 1983-2008 (from Drobot et al., 2008)

The changes in sea ice thickness and extent are largely attributable to the increased air and sea temperatures and to changes in atmospheric circulation. In the last 30 years, the average Arctic air temperature has risen by about 2°C (Figure 2), but with some spatial variability. For example the Barents Sea has risen by ~3-4°C in winter. The albedo of sea ice can be as high as 85%, and the reflectance of water about 15%. Therefore when sea ice melts much more energy is absorbed in open water, leading to additional sea ice melt, i.e. a positive feedback effect. The distribution of sea ice is also affected by atmospheric circulation patterns and specifically the Arctic Oscillation (AO) (see later).

Between 1979 and 2005 in the Bering Sea, the ice edge was influenced significantly by variations in easterly winds. The Barents Sea ice edge over the same period was driven primarily by two factors: anomalies in sea-surface temperatures, particularly close in time to the maximum extent, and by southerly winds. There is also considerable variability in the Arctic on time scales from inter-annual to multi-decadal (e.g. 1930s warm period). Whilst the modern general circulation models tend to reproduce reducing sea ice distribution, most are too conservative regarding the impacts of greenhouse gas forcing (Stroeve *et al.,* 2007). The 2007 minimum sea ice extent has been attributed to a significant change of the atmospheric circulation pattern, combined with the more gradual effects arising from increased greenhouse gas concentrations (Zhang *et al.,* 2008).

A reduced presence of land-fast ice on the northern coast of Alaska has been reported due to later formation and earlier breakup compared with the 1970s. The timing of breakup correlates well with onset of thawing air temperatures, and the observed change in breakup dates may be part of a longer-term trend (Eiken *et al.,* 2007). Reduced land-fast ice results in the coastal regions becoming more exposed to storms, causing increased coastal erosion but also a greater supply of nutrient to the seas. The Canadian Archipelago is the region where there is most coastline, and, as such, where these effects will be most important.

Salt is mainly expelled from sea ice during formation. The resulting saline water is more dense, hence sinks, and thus contributes significantly to driving ocean circulation as discussed in the next section. In the spring, when sea ice melts, freshening of the ocean occurs, and nutrients within the sea ice are released, leading to phytoplankton blooms upon which most of the Arctic marine ecosystem depends, also described later.

2.2. Atmosphere and Ocean Circulation

The circulation of sea ice cover and the ocean surface layers are closely coupled and largely driven by winds. In the 21st century, the pattern of surface ocean circulation has been dominated by a clockwise rotation of the surface waters in the Beaufort Sea (the Beaufort Gyre). In addition there is an anticlockwise flow in the Barents Sea region. These regimes both contribute to a strong trans-Arctic basin flow from Siberian Russia, across the Arctic Ocean and then through the Fram Strait. As a result there is a large export of sea ice from the Arctic Ocean. The relative importance of these two circulation patterns is strongly controlled by the Arctic Oscillation (AO) index.

The "high index" of the AO is defined as periods when the average sea-level pressure at 20°N exceeds the Arctic sea-level pressure. Under these conditions, there are enhanced surface westerlies in the north Atlantic, and warmer and wetter conditions than normal in northern Europe. This is often called the ‘warm phase’ of the AO and it has been more dominant since about 1999 (Figure 5). The patterns of wind and ocean current draw additional relatively warm water further into the Arctic, and cause a thinner mixed layer in the ocean. When AO index is low, high pressure is sited over the Arctic, and during this ‘cool phase’ there is much less warm air and less warm water is advected into the Arctic, i.e. it is much more isolated. The mid-late 1990s was a period when this regime dominated.

Figure 5 shows considerable year-to-year variability, much higher variability than many other regions of the world. There are consequent impacts on the climate system and hence the year-to-year changes in many phenomena such sea ice cover, frequency and severity of winter storms, and stocks of various fish. The modes of climate variability in the Arctic are a very active research topic, and understanding their causes and effects is far from complete.

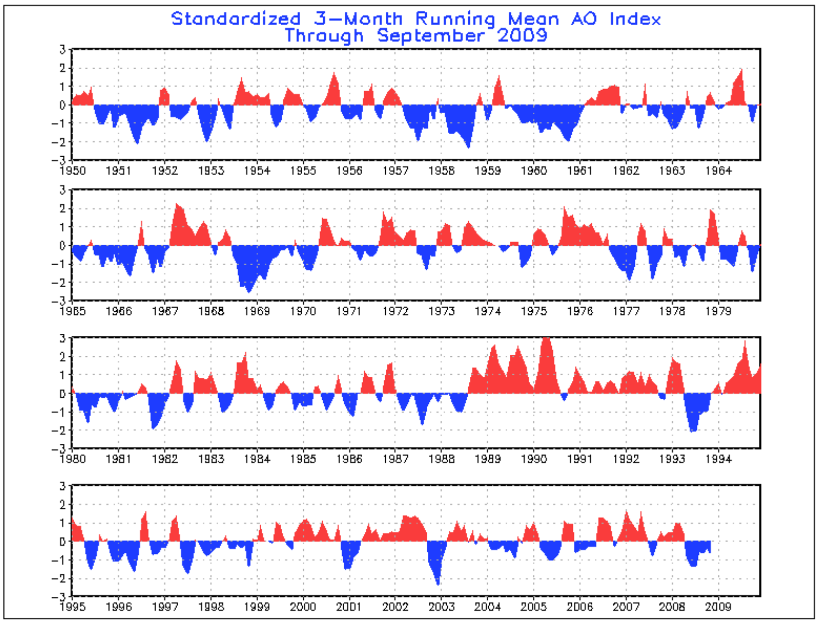

Figure 5: The AO index over the last 58 years.
http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/month.ao.gif

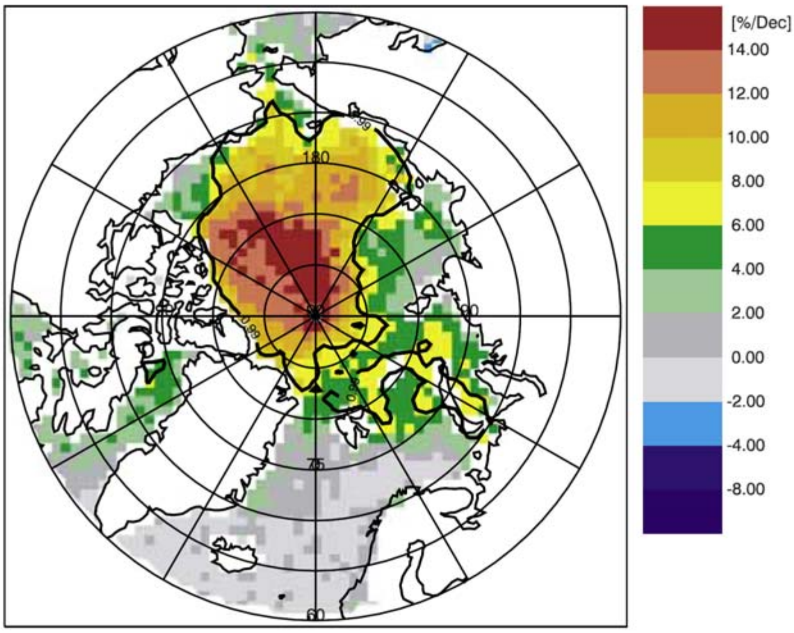

Figure 6: Linear changes in cloud cover over the period 1980-1998 in percentage change per decade in the spring (Schweiger, 2004).

There has been a near-linear increase in cloud cover over the central Arctic in the previous two decades (Schweiger, 2004). The seasonal variation of polar clouds changes is important and presently is poorly represented in climate models leading to considerable uncertainty in predictions of sea ice thickness and extent (Eisenman *et* *al.,* 2007). Clouds trap long wavelength radiation in winter, and thus keep the Arctic warmer than it would otherwise be. Thus an increase in winter cloud cover reduces the growth of sea ice. Diminishing sea ice cover also leads to greater transfer of heat and moisture from the ocean to the atmosphere, especially in winter. An increase in cloud in summer reduces the melt of sea ice.

The major ocean circulation pattern brings warm (~8 °C) saline Atlantic water into the Arctic Ocean and the Nordic Seas. This water cools and sinks and returning back at depth to the Atlantic over the Greenland-Scotland Ridge. This is called the Atlantic meridional over-turning circulation and forms a significant part of the thermohaline circulation. There is a similar flow pattern from the Pacific but the volume of water is estimated to be only about 10% of that of the Atlantic system. Also Atlantic waters are more saline than those of the Pacific because of warm water brought from the tropical Atlantic where considerable evaporation occurs, hence increased salinity.

There is a strong seasonal variation in salinity; high in autumn as sea ice forms excluding salt and low in spring when ice melts, freshening the sea. The seasonal variation of sea ice extent is clearly greater than in the previous decades, so the initial interpretation is that the ocean driven circulation would increase, however, this is complicated by the fact that the thickness of sea ice is reducing thus the seasonal variation of the volume of sea ice formation is not fully quantified yet.

There are further variations in salinity caused by the discharge from ice caps on Greenland and elsewhere in the Arctic in summer, combined with that from Canadian and Russian rivers that flow into the Arctic seas. The latter constitute about 10% of the entire world's freshwater discharge into seas. This lowers salinity, making the water more buoyant, thus forming a layer 100-200 m thick that covers the Arctic Ocean. In recent years, there have been marked changes in amplitude and seasonality of river discharge. Also the upper layers of the Arctic Ocean that are ice free, experience seasonal variation in temperature related to the changes of atmospheric temperature.

Discharges from Arctic rivers are also a very important source of dissolved organic carbon and other minerals. Battin *et al.* (2008) described how increases in Arctic stream and river discharges are leading to more dissolved carbon and nutrients are reaching the Arctic seas. In the future, increased rainfall and warming over the North Atlantic are both expected as a result of increased greenhouse gas concentrations. This will freshen the ocean further both directly and through increased run off.

Models simulate only a gradual weakening of the thermohaline circulation in response to global warming through the 21st century (Gregory *et al.,* 2005; IPCC, 2007). In 2004, the Rapid Climate Change Programme was established to measure changes in ocean circulation in the Atlantic. The array is deployed ~27°N, and is thus affected by the complex interplay of the Gulf Stream and wind-driven effects in the Atlantic Ocean (Bryden *et al.,* 2005; Cunningham *et al.,* 2007). Attribution of any changes in the Arctic Ocean to those elsewhere is not straightforward. In terms of UK interests and response, the contribution of the Arctic to the global ocean circulation can and should be routinely monitored at the overflow sites, such as the Greenland-Scotland ridge.

As CO_2 concentrations rise, more is absorbed by the ocean increasing its acidity. This topic is discussed in detail by Turley *et al.,* (2009). Cold waters can dissolve more CO_2 than warm waters thus any effects of increased acidification are most likely to be observed at high latitudes. Warming waters reduces the ability of water to retain dissolved CO_2, thus the polar oceans will become a less effective sink for carbon.

However, in the Arctic, these effects may be offset by the increased area of the ocean directly accessible to the atmosphere, and possibly increased biological productivity drawing more carbon into the ocean through the so-called biological pump. In the Southern Hemisphere, where the circumpolar winds have increased by ~20% in recent decades, effectiveness of the Southern Ocean as a carbon sink has been reduced (Le Quéré *et al.,* 2007). Whether this process is important for the Arctic has yet to be determined.

Data sets are not sufficiently long or complete to allow definitive statements to be made about many of the long-term trends in the salinity, ocean temperature and currents of the Arctic Ocean. The data that do exist show considerable variability on all timescales from seasonal, through inter-annual to decadal. Whilst many of the general principles of the processes governing the interactions of sea-ice, ocean and atmosphere are well understood, accurate quantification is still elusive.

2.3. Ozone and UV radiation

Modelling work indicates that the ozone hole over the Arctic will eventually diminish and return to pre-ozone-hole levels by about 2060. There are main two factors affecting the precise timescale of recovery. The first is the reduction of the chloro-fluoro-carbons in the atmosphere; these are gradually decaying with time as the loss rate is now greater than the rate of emission. However increasing levels of CO_2 in the stratosphere results in colder temperatures there, which increases the probability of reaching the critical temperature for ozone destruction (~-78°C).

People, plants and animals can be affected adversely by increased ultra-violet radiation arising from reduced ozone levels above the Arctic Ocean. There have been several experiments demonstrating that DNA can be damaged in algae and the early life stages of fish by increased UV radiation. However, cloud cover, ice cover and the opaqueness of the water all attenuate the flux of UV radiation reaching the ocean biota. Also the Arctic ozone hole is at a maximum at the same time as the sea ice cover is a maximum i.e. March. Therefore the sea ice acts to protect the wildlife in the Arctic Ocean. Summer migrants have not yet reached the Arctic in the early spring, so they too avoid the worst impacts of the lowest ozone values.

2.4. Future trends in the Arctic climate system

Changes in the physical environment were investigated for the Arctic Climate Impact Assessment (2005) and by the Intergovernmental Panel on Climate Change (2007). Whilst both organisations produced projections for the future state of the Arctic environment, these must be taken with considerable caution. Most important is that future changes are highly dependent on the levels of CO_2 in the atmosphere. This depends not only on the level of emissions but also the effectiveness of the natural sinks. Currently calculations show that 29% of CO_2 emissions are absorbed by land processes, 26% is absorbed by the ocean and 46% of CO_2 emitted remains in the atmosphere, hence the steadily rising levels of CO_2 (Canadell *et al.,* 2007; Global Carbon Project, 2008). The level of CO_2 now is already above the most pessimistic scenario used by IPCC (2001), and the effectiveness of the oceans to absorbed CO_2 is diminishing (Le Quéré *et al.,* 2007). Also some of the parameterisations of Arctic processes, and feedback effects are not that well quantified, as indicated in the text above, hence there is uncertainty in many projections.

The table below, modified from Loeng *et al.* (2005), summarises projections of the changes to the physical conditions in the future. Unless otherwise specified these projected values are very likely to happen according to the authors' best estimates, but given the comments above, the likelihood is that these levels are conservative.

	2020	2050	2080
Air temperature			
annual mean	1-1.5°C rise	2-3°C rise	4-5°C rise
winter	2.5°C rise	4°C rise	6°C rise in central Arctic
summer	0.5°C rise	0.5-1.0°C rise	1°C rise
seasonality	Reduced; warmer winters compared with summer		
Winds	No consensus on winds speed or direction changes Possible local changes, but overall slight reduction in intensity owing to reduced equator to pole temperature gradient		
storm tracks	Northward shift in storm tracks possible		
regional issues	In areas of sea ice retreat, there will be an increase in currents and waves because of longer fetch and higher air-sea exchange processes		
Precipitation/run off			
mean	2% increase	6% increase	10% increase
seasonality	Decrease in run off owing to earlier snow melt; seasonality in precipitation unclear		
Snow on ice	1-2% increase	3-5% increase	6-8% increase
Sea level [1]	5 cm rise	15 cm rise	25 cm rise
Cloud cover			
spring/autumn	4-5% increase	5-7% increase	8-12% increase
winter/summer	1-2% increase	3-5% increase	4-8% increase
Sea ice			
summer	Significant reduction	None	None
winter	Reduction	Further reduction	Continuing reduction
seasonality	Increasing	Reducing	Reducing
Spring ozone levels	Noticeable recovery of ozone hole started	Near pre-ozone hole levels	Ozone hole gone

[1] Current sea level is rising at ~3.2 mm per annum which has increased by a factor of four since ~1880. IPCC 2007 notes that the uncertainty in sea-level rise over the coming next 100 years is very high, as present estimates do not take into account all the fast-ice dynamics processes that affect the ice caps and ice sheets.

2.5. Wider impacts of the physical changes in the Arctic

The impacts of reducing sea ice extent, thickness and duration and increasing air temperatures in the Arctic have non-local impacts also. An important parameter in the entire climate system is the temperature gradient between the poles and the tropical regions which is reducing in the northern hemisphere, owing to the greater rise in Arctic temperatures compared with equatorial latitudes. The UK climate is changing too, (Jenkins *et al.,* 2007), although direct attribution of these changes to those in the Arctic is not yet possible.

Loss of sea ice adds to regional warming but has wider implications. This can come through added warming of the oceans from sea ice loss being released back to air and contributing to the melting of the polar ice sheets and ice caps, adding to global sea-level rise (Shepherd and Wingham, 2007). Rising ocean temperatures increases the possibility of releasing methane hydrates from beneath the Arctic ocean floor. Additional warming has been shown to penetrate up to 1500 km inland with the potential to lead to the melt of permafrost, and release of methane (Lawrence *et al.,* 2008). Methane in the atmosphere is about 25 more potent as a greenhouse gas than CO_2, and there is more carbon in the terrestrial and marine environments in the form of methane, than there is carbon remaining on the planet stored in oil and gas.

The most significant potential changes can be summarised as follows:

- Rising sea level caused by continued warming – thermal expansion of the ocean, and increased glacier and ice sheet melt.
- Northward movement of the storm tracks which normally pass over the UK in winter.
- A slow down of the thermohaline circulation.
- The threat of methane release adding significantly to the greenhouse gas loading of the atmosphere.

3. BIOLOGY OF THE ARCTIC OCEAN

3.1. The foodweb

The foodweb in the Arctic Ocean in principle is quite simple consisting of several trophic levels (Figure 7): phytoplankton consumed by plant-eating animals that are themselves eaten by fish which in turn are taken by sea birds and mammals including man. Compared with middle and equatorial latitudes, there is low diversity in the Arctic Ocean. However, the marine ecosystem is highly specialised with many of the species relying completely at some stage in their life cycle on sea ice. The Arctic marine ecosystem can be resilient in some domains too. For example, many marine communities can withstand high levels of variation in food availability, salinity, and low ocean temperatures.

There are many ways direct and indirect changes in the physical environment affect marine biota. For example, water temperature increases both the metabolism and distribution of organisms, ocean currents transport plankton, and river run-off affects nutrient availability and ultimately food availability. The presence of sea ice provides higher predators with a platform for giving birth, and for foraging. The timing of sea ice formation, melt-back and water temperature, has a major influence on the timing, location, and intensity of biological production. For example, the melting of sea ice in spring results in the stratification of the upper water column that promotes primary production.

The Barents and Bering Seas are among the most productive on Earth. As a result, they are critically important for Arctic communities, commercial fisheries, and, in summer, they are essential feeding grounds for animals and birds that winter at lower latitudes. Thus the likely changes to the Arctic climate and sea ice, and their projected changes on the ecosystem will have major economic and cultural repercussions.

Phytoplankton is responsible for about 60% of the productivity in the Arctic Ocean. These single cell plants, of which there are about 300 species in northern high latitudes, live both within the water column and in the sea ice. Although phytoplankton generally grow more slowly in the Arctic than in warmer areas, near-freezing temperatures do not delay the onset of the initial period of very high production. Sea ice plays the most critical role controlling light and affecting nutrients. The timing of the bloom depends upon the retreat of the ice edge. There is considerable year-to-year variability in this retreat at any particular location, hence the timing of the bloom also varies markedly. Over the winter, there is deposition of minerals on the sea ice. When it melts, nutrients are released contributing to the initial phytoplankton bloom. A later bloom can also occur when ocean temperatures are usually warmer and zooplankton growth is enhanced. Changing sea ice patterns will have a dramatic effect on the timing of blooms and thus on the ecosystem; the Bering Sea is an example where this has occurred in the last decade (section 3.5). Two other factors reduce the amount of light entering the ocean, increases in cloud cover (see Figure 6) and precipitation provided that it falls as snow on sea ice (Walsh, 2008); these are less important than the changing sea ice distribution.

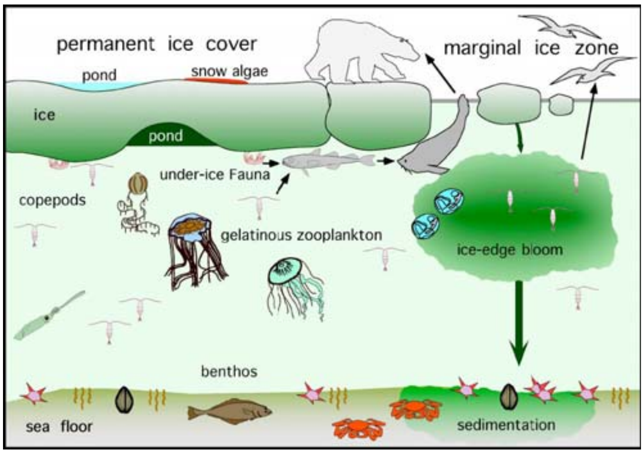

Figure 7: Schematic representation of the Arctic coastal marine ecosystem illustrating the reliance on sea ice and the various trophic levels from phytoplankton, through zooplankton to higher predators. From ICARP II (2005).

Bacteria constitute most of the remainder of the ocean productivity. Rates of bacterial production are determined mainly by the amount of decaying organic matter available (Rich *et al.,* 1997). There are upwards of 10^{12} bacteria cells per cubic metre in the water column (Steward *et al.,* 1996). Phages, a group of highly species-specific viruses, are even more abundant than bacteria, and they have a critical role in regulating bacteria and phytoplankton abundance (Bratbak *et al.,* 1995). Carbon cycling in the Arctic pelagic system may not be as simple as first thought. Thingstad *et al.* (2008) showed that bacteria, with increased access to organic carbon might dominate the uptake of nutrients, thereby reducing, not increasing, phytoplankton growth in the Arctic Ocean and hence the potential food supply for zooplankton. As indicated above, increased dissolved organic compounds are likely in the Arctic seas as a result of increased run-off from the rivers in Canada and Russia.

In terms of biomass, zooplankton (krill and copepods) and zoo benthos comprise over 50% of the total Arctic biomass. They have adapted to cold conditions by having life cycles that are two to ten times longer than corresponding species in temperate conditions. There are estimated to be ~260 marine meso-zooplankton but they are not uniformly distributed through the Arctic Ocean. For example, krill (euphausiids), swarming shrimp-like crustaceans, are common on the Atlantic side of the Arctic Ocean and in the Bering Sea, but are rare in the central Arctic Ocean.

The benthic fauna differ substantially between the continental shelves and the abyssal areas of the Arctic where waters are both warmer and more saline. In the Bering Sea and the Canadian Archipelago, the benthos is primarily of Pacific origin whereas in the Barents Sea and the central Arctic, Atlantic fauna dominate carried by the Atlantic inflow and strong boundary currents. Although over 2000 bethic species have been identified in the Arctic, there is little quantitative information from the Russian Arctic region. By contrast the North American sector is quite well sampled and studied. Hotspots of biological diversity occur in areas of mixing between cold polar waters and temperate waters, below predictable leads in the sea ice, and in the marginal ice zone.

In 1999, large numbers of the Pacific diatom, *Neodenticula seminae,* were found in the Labrador Sea, the first record in the North Atlantic for more than 800,000 years. The event coincided with modifications in Arctic hydrography and circulation, increasing flows of Pacific water into the North-west Atlantic and extensive ice-free water north of Canada in the previous year. Trans-Arctic migrations from the Pacific into the Atlantic are likely to occur more frequently in the future as Arctic ice continues to melt and becomes more mobile (Reid *et al.,* 2007). It is interesting to note that the rate at which a ship frozen into sea ice took to cross the Arctic Ocean during the International Polar Year was a factor of two higher than a hundred years earlier (www.taraexpeditions.org).

3.2. Top predators in the Arctic

Birds, seals whales and bears represent about 1% of the biomass. Many seabirds and some marine mammal species either migrate to the Arctic during the summer or can cope with the long periods when food supplies are limited. In general, the permanent residents store large quantities of reserve energy in the form of oils during periods when the food supply is abundant.

The polar bear has a circumpolar distribution with an estimated population of 22,000. As their main prey is seals and they are largely pack ice animals, the fate of the polar bear is intimately linked to the movement, duration, and structure of sea ice and with recent changes, populations are forecast to fall (Stirling and Parkinson, 2006). DeWeaver (2007) projected a 42% loss of optimal polar bear habitat during summer in the Arctic by mid century and then concluded that this would lead to a reduction in the polar bear population by two thirds. However, there are great uncertainties over both projections.

Walrus, like polar bears, are circumpolar with an estimated population of ~250,000, of which 200,000 belong to the Pacific sub-species, the remainder being the Atlantic sub-species. Walrus haul out on pack ice in most months of the year but sometimes use land when there is insufficient sea ice.

Only three species of whale live in the Arctic year round, the bowhead whale, white whale (beluga) and the narwhal. They live in ice-covered seas using leads and polynias to surface for breathing. Their populations are estimated to be 11,700, 100,000 and 50,000 respectively. Bowhead whales can still be taken by indigenous people. The current quota that can be landed in the period 2008 to 2012 for Bering-Chukchi-Beaufort Seas is up to 280. The population of bowhead whales has been increasing since 1978 by about 3.2% per year. Many other species of whales, dolphins and porpoises spend the summer in the Arctic, usually in ice free waters. Estimates of these whale populations can be found at www.iwcoffice.org.

The table below summarises the types, habitat and population of seals found in the Arctic. Sea ice plays an important role in the life cycle of at least six of the eight species. Therefore significant changes in sea ice distribution, thickness or extent will have a major impact on the seal population. Estimating populations of seals in the sea ice zone is particularly difficult but unmanned airborne vehicles could be very useful in the future. The diet of most seals includes crustaceans, fish, and cephalopods.

Species	Habitat	Population
Ringed seal	Pack ice seal maintaining breathing holes in thick sea ice; throughout the Arctic	Millions
Harbour seal	Coastal seal with broad distribution from California to Arctic	No reliable population estimates for the Arctic Ocean; more common in the sub-Arctic
Bearded seal	Patchy circumpolar Arctic distribution, breeds on sea ice	Hundreds of thousands
Harp seal	Migratory; breed on sea ice, more north to moult and then disperse the Arctic for the rest of the year	More than 7 million
Hooded seal	Migratory; movements similar to the Harp Seal	More than half a million
Grey seal	Originally abundant in Icelandic waters, and the coasts of Norway and Russia but hunted and culled in 20th century	Estimated numbers in the Arctic Ocean 4500 though numerous elsewhere
Spotted seal	Coastal seal during the breeding season and edge of the ice pack for the rest of the year	No reliable population estimates
Ribbon seal	Pack ice breeders	No reliable population estimates

The life cycle of the vast majority of the Arctic top mammal predators involves sea ice and hence they will have to change behaviour to survive in an Arctic that is ice-free in summer. Further details on the impact of climate change on mammals are provided in a special issue of Ecological Applications (Huntington and Moore, 2008).

3.3. Seabirds

Over 60 seabird species frequent the Arctic, over 40 species breed, and some of the largest seabird populations in the world occur there. Whilst the majority of species are summer visitors, a few species over-winter, including the spectacled eider, black guillemot, ivory gull, and northern fulmar using the sea ice edge and the polynias for feeding. Most Arctic seabirds feed on small fish and large copepods, primarily in the upper waters. The impact of sea ice changes on birds is likely to be indirect through alternation to the lower trophic levels in the foodweb, e.g. timing and assemblages of phytoplankton bloom and the effects of ocean acidification. Many birds that summer in the Arctic over-winter in the UK; these could all be affected by changes to the ecosystem including swans, geese, ducks, divers, waders, auks, terns, gulls, fulmars and skuas.

3.4. Fish and fisheries

Arctic waters are inhabited by more than 150 species of fish. Few species are endemic to the Arctic and most have a circumpolar distribution. At present, there are four fisheries in the Arctic, off Newfoundland, the Barents Sea, the North-East Atlantic including the Norwegian Sea, and the North Pacific (Bering Sea). The most abundant and commercially significant are halibut, cod, capelin, pollock and herring but some exploitation of crustaceans occurs in the Arctic regions including the northern shrimp and snow crab.

A moderate warming of the Arctic seas will probably enhance levels of primary production, i.e. where living organisms form energy-rich organic material from energy-poor inorganic materials through photosynthesis. Secondary production, i.e. the transformation, through consumption, of primary production into other forms is also likely to increase as a result of reduced sea-ice cover. Changing sea ice is likely to increases the habitat range for some key commercial species, such as cod and herring. Such increases in productivity were reflected in the cod fishery increases in the period between ~1920 and 1940 when the climate warmed in comparison with the early 20th century. In the longer term, future stocks are less certain, due to ocean temperature rise, habitat changes and increased ocean acidification affecting benthic and planktonic communities.

There is increasing pressure on fisheries world wide to provide protein either for direct human consumption or to support aquaculture. Thus a key to the future of Arctic fisheries is sustainable management practices. The Arctic countries presently adopt precautionary approaches, with increasing emphasis on the inclusion of risk and uncertainty in all decision-making.

The central Arctic Ocean is not yet exploited owing to the presence of ice. There is no consensus over how the ecosystem will evolve there when it becomes ice-free in summer. Suggestions range from extension of the sub-Arctic ecosystems into the central basin, to domination by jelly fish at least in the first instance.

3.5. Regime shift in the Bering Sea

The Bering Sea is of great importance providing 47% of the US fisheries. It also provides an excellent case study for the impacts of warming waters, and the disappearance of sea ice – these changes have lead to major changes in the ecosystem (Overland and Stabeno, 2004; Grebmeier *et al.*, 2006).

The mean summer temperature of an oceanographic station in the Bering Sea rose by 2°C between about 1996 and 2002. Winter ice concentration has fallen markedly since the 1970s and the equatorward limit of winter ice has moved north. The timing of the phytoplankton bloom is ~2 months later in years when sea ice is absent.

Greenland turbot prefer cold seas and hence the spawning mass has decreased markedly since the Bering Sea has started to warm. Present estimates of stocks indicate the current level is ~18% of that in the 1970s. Other benthic flat fish spawning has also decreased. These changes could simply be a consequence of movement north rather than a decline. In contrast walleye pollock which accounts for 56% of the ground-fish biomass has increased by 400%. Other changes reported include a northward shift of the feeding grounds of walrus, grey whales, horned puffins and salmon, and the distribution of snow crab.

There is an underlying assumption that the ecosystem was in equilibrium before the recent temperature rises. However exploitation by humans of whales, seals, and some fish species over hundreds of years will have made fundamental changes to the upper trophic levels of the ecosystem, so simple attribution of all the changes to the climate is not possible. For example some changes may be an opportunistic response to the removal of some competitive species.

The regime shifts that have occurred both in the Atlantic (Reid *et al.,* 2007), and in the Bering Sea show that the ecosystems can have tipping points - abrupt, significant and probably irreversible changes. Further research is essential to identify where other ecosystems tipping points are likely to occur.

4. HUMAN IMPACTS

As sea ice retreats in summer, the North-West and North-East passages will be regularly ice free providing much shorter trade routes between the Atlantic ports and those in the Pacific. The route can save between 35 to 60 per cent in time and fuel from Europe to the Far East compared with passing through either the Suez or the Panama Canal, as shown on Figure 8 depending upon which ports are used. The Table summarises two examples of possible savings. As a result, the shipping industry may benefit from climate change. However, ice bergs, especially in the vicinity of Greenland, are likely to be a continuing threat to shipping. In addition the length of the ice free season will remain highly variable. There are also unresolved issues, such as passage fees through territorial waters, however, these can be offset by the fees normally charged for passing through the Suez and Panama Canals.

Figure 8: The trip difference between North-east passage (white) and traditional routes (yellow) (Modified from Scandinavian Shipping Report No 16, 2008).

Departure port	Destination port	Distance via Suez (nm)	Travel time (days at 14 knots)	Distance via North-east passage (nm)	Travel time (days at 14 knots)	Savings (days)
Felixstowe	Tokyo	11062	32.9	7178	21.4	10.5
Oslo	Tokyo	11633	34.6	6607	19.7	14.9

A second large increase in Arctic shipping is expected from the exploitation of the oil and gas reserves. About 25% of the known remaining petroleum and gas reserves lie under the Arctic seas. Whilst the exploitation of this resource may be easier in seas with less summer sea ice, more mobile sea ice will be a threat to shipping and infrastructure. . About half a million tonnes of grain per annum are moved from the Canadian prairies through Churchill, then to international markets through the Arctic seas. Tourism by ship in the Arctic is small but likely to increase with time. Mineral exploitation has also occurred in the Arctic in the past but does not currently involve significant shipping. Any upsurge in shipping activity in the Arctic, especially by ships that are not ice strengthened, will increase the risk of damage, leading to pollution of the fragile Arctic ecosystem.

Many indigenous communities of the Arctic rely primarily on the sea and the sea ice for the resources and for safe travel both to the hunting areas and between communities. Changing sea ice conditions are already having an impact on their traditional way of life as access to hunting grounds becomes less predictable and the range and numbers of seals, whales, polar bears, birds and fish alters as a result of climate change. Increased erosion is already having an impact on some Inuit communities with settlements under threat of collapse and inundation from the sea. Projections for further sea ice decline imply these impacts will become more severe with time.

5. SEA ICE AND BIODIVERSITY IN THE ARCTIC – FUTURE PROSPECTS

Climate models consistently show the Arctic to be one of the most sensitive regions to climate change. All predictions indicate that sea ice will diminish in duration, extent and thickness both in the summer and the winter. There is no consensus amongst the models as to how quickly. The recent observational evidence indicates that changes are happening much faster than predicted by most models. Most predict that the Arctic will be ice free in September within 40 - 60 years.

These changes in sea ice will have feedback effects on the climate system. For example heat exchange between the ocean and the atmosphere will increase in the absence of the insulation properties of sea ice. The complete loss of summer Arctic sea ice will result in approximately 0.5° C global warming as a consequence of the albedo-temperature feedback. This factor is already included in climate models (IPCC, 2007). The break up of sea ice will be earlier and freezing will be later.

Arctic ecosystems are highly specialised and most rely to a great extent upon sea ice, either directly or indirectly. Reductions in sea ice will shrink the marine habitat for polar bears and ice inhabiting seals and both resident and migrant sea birds. The rate of change of sea ice conditions appears to be significantly faster than the evolutionary changes of most plants and animals. Some migration of species might be possible, but not all species are sufficiently mobile. Any increase in human presence in the Arctic, either for social or economic purposes, could put further stress on habitats and species through activities such as increased ocean noise, pollution, contamination of food chain and expansion of habitation.

The Arctic environment has far fewer long term and baseline measurements than most other parts of the world. Thus, as this short review has revealed, trends and long-term modes of variability, such as the Arctic Oscillation, are very difficult or impossible to determine. In many areas there has been a welcome increase in monitoring through organisations, such as the Conservation of Arctic Flora and Fauna (CAFF) and Arctic Ocean Diversity - a project of the Census of Marine Life. These efforts need to continue.

The modelling both of the Arctic climate and the ecosystem need considerable development before very reliable projections are likely to be possible. For the climate system, increased spatial resolution is required and this will bring with it the need to include new and improved processes (e.g. clouds) and additional feedback links. For the ecosystem, the linking of all trophic levels is essential. A key limitation to accurate projection is deciding what CO_2 increase to include within the models; currently the level is above the upper estimate of the IPCC 2001. A further important unknown is the rate at which methane will be released from the Arctic permafrost and marine clathrates as both the air and the ocean warm.

6. KEY LINKS TO OTHER ECOSYSTEM LINKAGES REPORT CARD REVIEWS

Ocean acidification results from increased absorption of CO_2 into the ocean and the Arctic seas will become more acidic than temperate and equatorial latitudes as cold waters can retain more CO_2. The impacts include changes on phytoplankton assemblages and the ability of calcifying animals to make and maintain their shells. Turley *et al.* (2009) provide much more details on the impacts of such changes on marine organisms.

Arctic sea ice reductions in the future mean fundamental changes of habitat for some species and impacts on all trophic levels in the ecosystem. Thus species, such as the iconic polar bear, and birds that winter in the UK, and fisheries are all under threat as a result of the changes. New, warmer habitats may allow invasion by more temperate (alien) species into Arctic waters, including different pests and diseases.

Indigenous people are already being markedly affected by changing sea ice conditions both in terms of accessibility of hunting grounds and safe transport between communities. Excellent opportunities do exist to exploit the ice-free waters for passage between the Pacific and Atlantic Oceans via the Arctic routes, saving time and fuel. Access to oil and gas reserves will also be easier, so considerable economic benefits could accrue.

In summary, the Arctic climate is changing very quickly, faster than any previous time in the instrumental or the paleo record. Impacts on the wildlife and human activity are also large and significant. Projections all indicate that the Arctic will continue to warm substantially and sea ice will continue to diminish both in summer and to a much lesser extent in winter. This will lead to some economic benefits and increased threats too. Large local changes to the Arctic climate are likely to occur and these will have wider impacts, for example through the release of methane from the marine and terrestrial environments. Every level of the Arctic ecosystem will be impacted, including the many summer migrants. Fisheries too will be affected - regime shifts already observed at lower latitudes are possible.

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