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Climate Change and the Arctic: An Overview

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Introduction

The Arctic is home to some of the world's most distinctive mammals, millions of migratory and resident birds, a rich ice-edge community, and some of the world's major fisheries. It is a biologically and culturally unique environment, and one of the last places on Earth where natural conditions still prevail over much of the region.

Unlike the ice-bound Antarctic, the Arctic has been home to humans for more than 10,000 years. Today, the region is culturally, politically, demographically and economically diverse, with settlements ranging from small indigenous communities to modern industrial cities. Indigenous cultures include: Aleuts, who live primarily in coastal southwest Alaska; Inuit, who live on the coast and inland from northwestern Alaska east to Greenland; Athabascans, who live mainly inland in eastern Alaska, the central Yukon, and the Northwest Territories of Canada; the Saami of northern Fennoscandonavia; and Native groups in northern Russia.

The Arctic is also a region particularly vulnerable to human-induced climate change. What happens to the Arctic in response to human-induced climate change concerns us all. The area and its people serve as indicators for what may occur in other regions, and to the planet as a whole.

This background paper gives an overview of the Arctic environment and its importance to the globe as a whole. It discusses the dramatic changes in climate and related systems that have occurred at high northern latitudes over recent decades, and further examines the implications of future climate change.

Global Influences of Human Activity

Human modification of the natural environment is an ancient phenomenon. It has been estimated that around 75 percent of the habitable land on the planet has been disturbed to some degree. [1] This disturbance has been accompanied by increasing human population levels, sustained, in turn, by increasing industrial activity and more intensive agriculture. Some of the impacts associated with these activities have been appreciated for centuries. For example, pollution due to the extraction of metals has been recorded since the time of the ancient Greeks. [2] Today, human activity is the most important determining factor in the global release of potentially polluting metals. In short, humans have significantly altered the planetary biological and geological cycles, or biogeochemical cycles, of these chemicals.

The Industrial Revolution, the start of major industrial activity, marked the point of the rapid and serious alteration to a number of biogeochemical cycles. These include the chlorine, sulphur, nitrogen and carbon cycles. Some of these biogeochemical cycles are being influenced by deforestation and agricultural practices. The wide-scale burning of fossil fuels to provide energy has also directly influenced the natural carbon and sulphur cycles. In turn, some of the energy produced has been used to convert nitrogen and chlorine to other chemical forms, thus influencing the global cycle of these elements. [3,4]

Greenhouse Gases

Carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) concentrations have risen steadily in the atmosphere since the beginning of the Industrial Revolution. Ice core records show that from the end of the last ice age 10,000 years ago, the concentration of carbon dioxide in the atmosphere was relatively constant until the beginning of the 18th century. Pre-industrial concentrations have risen by around 30 percent [from around 280ppm (parts per million volume) to 358ppm by 1994] . [3] Methane, another component of the carbon cycle, also rose in atmospheric concentration by some 145 percent [from around 700ppb (parts per billion volume) to 1720ppb] over the same period while nitrous oxide has increased by around 15 percent (from around 275ppb to 312ppb). In addition, from the 1940s onward, industrially produced chemicals such as chlorofluorocarbons (CFCs), have been progressively released into the atmosphere.

What these gases all have in common is that they act as "greenhouse" gases. The atmosphere is relatively transparent to most of the incoming solar radiation which heats the surface of the earth. By contrast, energy emitted from the Earth is absorbed by water vapour and other "greenhouse" gas molecules and retained within the atmosphere. Water vapour is the largest contributor to the effect, but the contributions of the other gases, particularly that of carbon dioxide, are also important. Although gases such as methane and nirtous oxide are present in the atmosphere at lower concentrations than carbon dioxide, molecule for molecule these gases are more effective at trapping heat emitted from the Earth.‡

Atmospheric carbon dioxide levels will increase unless emissions from the burning of fossil fuels are brought under control. Studies suggest that in pre-industrial times the atmosphere contained 590 billion

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‡ The relative radiative effect of different greenhouse gases has been estimated by the IPCC and called their Global Warming Potential (GWP). As the reference molecule, carbon dioxide has a GWP of one. For a time horizon of 100 years, methane has a GWP of 21 and nitrous oxide of 310. The typical range of uncertainty for GWPs is +/- 35 percent. [3]

tonnes of carbon as carbon dioxide. Between 1765 and 1991 this rose to 755 billion tonnes. [5] Scientists from the Intergovernmental Panel on Climate Change (IPCC) estimate that current emissions are around 7.1 billion tonnes of carbon annually. Around half of this is absorbed into the terrestrial and oceanic sinks of carbon dioxide and the balance remains in the atmosphere. This buildup results in the currently estimated rates of carbon dioxide concentration increase of around 0.4 percent per year. [3]

The potential for industrialisation and the burning of fossil fuels to increase atmospheric concentrations has been appreciated since at least the turn of the century following the work of Svante Arrhenius in 1895. [6] With an outlook typical of the cultural optimism at this time, Arrhenius suggested generally beneficial effects. This view has been considerably modified in modern times by concerns about possible large scale negative consequences. [7]

Temperature Rise and Climatic Change

Scientists predict that as levels of greenhouse gases increase in the atmosphere, a greater proportion of the heat radiated from the earth will be retained in the lower atmosphere, resulting in an average warming of the Earth's surface. Computer models can be used to predict the scale of the temperature rise and other changes in climate. Drawing from climate models developed by the world's major climate centres, the IPCC has estimated that relative to 1990 the Earth's surface will warm by 1 to 3.5 degree C by 2100. [8] It is estimated that air temperatures have increased by between 0.3 and 0.6 degree C since the late 19th century and by 0.2 to 0.3 degree C over the last forty years. [9] In historical terms the increases in surface air temperature projected by the IPCC are extremely large. They will be greater in all probability than any following the emergence of the Earth from the last ice age 10,000 years ago.

Any increase in temperature of the scale estimated will be associated with major climatic changes around the world. Although there are still many uncertainties in estimates of global climate change, it is likely that the magnitude of global temperature change will fall within the range estimated by the IPCC. Prediction of precise and regionally specific changes in climate remains unclear at this stage. Limitations exist in the models due to our poor understanding of total global and regional processes and consequent failure to consider all the possible influencing factors. The potential controlling feedback mechanisms are also only poorly understood. The natural variability of the climate system also masks many trends and this can only be compensated for by considering data obtained over a very long time period. [10] Nonetheless, the IPCC considers that "climate has changed over the past century" and that "the balance of evidence suggests a discernible human influence on global climate." [11] More recent refinement of the mathematical models and other scientific techniques used to detect and attribute climate change has provided further strong evidence that the observed trend in global temperature over the last century is unlikely to be solely of natural origin. [12, 13]

A consistent feature of climate models is that they project intensified warming in the northern polar regions. Hence the Arctic could well act as an area where the first effects of global change will be unequivocally identified . [14-17] In addition, the Arctic environment has a significant role in establishing global circulation patterns which in turn influence both weather and climate.

The Arctic

A Harsh Terrestrial Environment

The Arctic Region is broadly defined as the region to the north of the limit of tree growth in the circumpolar boreal forests (or taiga). The limit may also be defined in terms of temperature, as the region north of the 10 degree C July isotherm† , which tends to move the boundary to the north by as much as 200 kilometres. The area is divided into the low Arctic region which corresponds to the tundra and the high Arctic region which corresponds to the polar desert. This classification is based upon the plant communities which predominate. These major regions are in turn subdivided; some differences exist between North America and Eurasia, particularly in the transition between the high and low zones. In practice the divisions show a gradual gradation rather than a defined border.

In general, low shrub tundra occurs just north of the tree line while tussock tundra and sedge-moss tundras (mires) have become established according to how well the land is drained. Poor decomposition of plant materials in waterlogged areas leads to the formation of peat. The low Arctic gives way to polar semi-desert and polar desert environments where lichens and mosses predominate.[14-16,18] Extensive snow and ice cover exists in winter. There are also large areas of permanent ice and snow cover. Large areas of land remain frozen for two or more consecutive summers and this is known as permafrost. Only a relatively thin surface layer of this thaws in summer. The permafrost restricts drainage so that extensive areas become waterlogged. Some 1.5 million square kilometres above 60°N can be classed as wetlands. Bogs and fens are the most common form of wetland.

Tundra ponds are generally small and highly acidic but support life in the bottom sediments. In lakes, the ecology is also driven by ice-cover and the timing of the spring melt. Those which are not too nutrient poor support a sparse flora of algae which serves as food for a limited population of small animals. Where nutrients are less limiting, a sufficiently high production in the waters and sediments can support fish. The most widely occurring fish species in inland Arctic waters is the Arctic char. [15, 16]

The Arctic environment is characterised by its coldness and by extremely short growing seasons (1 to 2.5 months) as compared to temperate regions. There is extreme variation in light and temperature. Summer periods are short. The sun never rises very high in the sky and this limits the amount of incoming solar energy despite the long summer days when solar radiation is higher than anywhere else on earth. Up to 90 percent of this incoming energy is directed back away from the Earth by the reflective snow and ice surfaces. In addition the Arctic loses heat into space as infrared radiation. This heat loss is compensated for by heat exchange in the atmosphere and in ocean currents. These currents carry relatively warm air and water northwards while cold air and water are moved southwards.

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† A line on a map of the Earth's surface connecting points having the same temperature at a given time or the same average temperature for a given period.

As a result, the prevailing climate and weather patterns in coastal areas influenced by waters from the Pacific and Atlantic are generally more temperate than continental areas. Indeed, the various combined effects of geology, ice and climate leads to considerable diversity of terrestrial habitat. [16]

In the Arctic, low temperatures slow biological processes, snow and ice limit the light available to plants and liquid water only becomes available after the snow and ice have melted. Both plants and animals show extensive adaptations to these extreme conditions. [16] Many bird species found in the Arctic are migratory, taking advantage of abundant summer food supplies and leaving in winter. Other organisms are adapted to survive the year round by laying down reserves of energy in the form of fat. Terrestrial food chains are generally short.

A Fertile Marine Environment

Marine systems in the Arctic are characterised by very complex food webs but with only a very few key species directly connecting the various levels. [15,16] The central basins of the Arctic Ocean itself are considered to be one of the least productive major water bodies on the planet but recent work has suggested that they support a significant food web. [19] Even the pack ice has high productivity with small plants living within and on the ice. By contrast, intense production takes place elsewhere in Arctic waters. The biologically richest areas occur at the edge of the ice and in the continental shelf seas. Some of these shelf areas are among the most productive ecosystems in the world.

Perennial pack ice covers about 8 to 9 million square kilometres of the Arctic Sea, growing to a maximum of 15 to 16 million square kilometres in the period from November to February. Areas of open water (polynyas) in the ice field may be temporary or persistent and recurring. [20] Persistent openings in the ice also act as a focus for intense marine production by allowing earlier penetration of light and facilitating mixing of nutrient poor with nutrient rich water. [21] The polynya can also be highly important to bird populations [22] and to wintering mammal populations. [15, 23] Even in the central Arctic these ice areas can comprise 1 to 2 percent of the total area. Expanding in summer, they play a significant role in heat exchange between atmosphere and water which influence local and to a lesser extent regional weather patterns. [21]

The seasonal accumulation and melting of sea-ice results in high productivity at the edge of the ice and in the shelf seas and also contributes to the formation of a salt driven layering of the water. This keeps plants close to the sunlit surface. The ice-edge bloom of microscopic plants and bacteria supports a complex food web [24] which follows the retreating ice edge. In some areas, freshwater inflow from north flowing rivers creates highly productive estuarine zones. In the Barents Sea, cooling and ice formation result in a complete turnover of the water column, and in other northern sea areas surface water is enriched annually with nutrients from deeper waters.

The marine boundary of the Arctic is formed when the water of the Arctic Ocean, cooled and diluted by melting ice, meets the warmer saltier water of the southern oceans. The position of this Polar Front is relatively stable from year to year. [15, 16] To the south of this front nutrients can be brought to the surface by summer storms, while at the front itself, considerable vertical mixing can take place throughout the year. Despite the short growing season, the supply of nutrients forms the basis of a rich fauna supporting highly profitable fisheries.

The species richness and high productivity of marine ecosystems is in stark contrast to the tundra and mountain heath environments. It is explained by the relatively benign, although still harsh, conditions in the sea. The Arctic has long held an attraction for ecologists [14] seeking to understand the highly visible adaptations to these extreme environments. Moreover, after Antarctica, the Arctic areas have been disturbed much less than most other areas of the planet, with large areas still regarded as pristine.[1] However, human impacts from external sources are increasing. Recent important areas of study include: the apparent northwards migration of pesticides and industrial pollutants; contamination of the environment with toxic metals as a result of mining and smelting; and air pollution giving rise to an "Arctic Haze, " a form of smog and acid precipitation. [15, 16]

The Arctic and Global Ocean Circulation

The highly simplified representation of the Arctic environment above hardly does justice to the sheer complexity and diversity of Arctic systems. The significance of the physical and chemical processes taking place in the Arctic extend far outside the region. This polar area has been described as a "refrigerator in the equator to pole transport of energy. " [16] Mid-latitude low and high pressure weather systems are the results of the heat exchanges between the warm and cold water and air masses. This results in semi-permanent low pressure systems centred around the Aleutian Islands and Iceland which bring moist air northwards in the winter. In the Atlantic, the Iceland low pressure system is coupled with a high pressure system centred near the Azores. [25]

As well as being an area where nutrients are recycled and released into the water, the Polar Front region in the North Atlantic plays a fundamental role in the driving of ocean currents. At the Polar Front near Greenland, Iceland and the Labrador Sea, warm, salty water from the North Atlantic is cooled by Arctic waters and by intense heat loss to the atmosphere. These waters become more dense and then sink to the deeper layers of the ocean. Salt rejected as sea-ice forms also increases the density and contributes to the process. Although a slow process, this sinking takes place over a wide area and each winter several million cubic kilometres of water sink and begin moving slowly south along the bottom of the Atlantic Ocean towards Antarctica. This process is known as thermohaline circulation because it is driven in part by temperature and partly by salinity differences.

The dense, cooled water becomes part of what is termed the Ocean Conveyor and the water eventually returns to the surface in the Indian and Pacific Oceans. As warm water returns to the Atlantic, the current moves polewards as the Gulf Stream and North Atlantic Drift. [15,16,26] In reality, the processes taking place in the Arctic are extremely complex. [27, 28] Global circulation of the water in the ocean currents takes place over time scales of centuries. In addition, the formation of deep-water also takes carbon dioxide dissolved from the atmosphere into the deep ocean. The Arctic region, therefore, plays a fundamental role in ocean circulation patterns, which in turn determine climate patterns over the rest of the globe.

The Arctic and Climate Change

The significance of climate change with respect to the Arctic region is twofold. On the one hand, climatic change can be expected to change Arctic systems. On the other, these changes themselves may well induce other changes of global significance. Modelling studies have suggested that the Arctic will warm by more than the global average. [8, 15, 16] Thus far, scientists have been unable to differentiate human impacts from natural variation. In addition, temperature increases are unlikely to be uniform over the whole area. Models have given results which in some cases are not easily interpreted partly because the likely impact of some factors, such as cloud cover, are poorly simulated.

Observations show that surface air temperatures have increased by about 1.5 degree C per decade over central Siberia and continental North America, and have fallen by a similar amount in the Baffin Bay area. Over the last century, indications of warming have been seen around the northern continental rims of central and western North America and Central Asia. There is a cooling trend for eastern North America to the North Atlantic. [9] Most of the warming in the western Arctic appears to have occurred in winter and spring, with less warming observed in the summer and autumn.

Satellite monitoring has shown that the lower atmosphere of the Arctic has become around 0.05°C warmer per decade. This is a more pronounced change than the global average. The associated cooling in the upper atmosphere has been determined at -1.01 degree C per decade, with the most rapid decreases over Russia. This change is the most pronounced over the whole planet. Borehole studies of permafrost in Alaska have also shown a temperature rise of between 2 to 4 degree C over the last hundred years.[16]

In Alaska, a warming trend of 0.75 degree C per decade has been identified for the last three decades over land bordering the Bering Sea. Over the eastern Bering Sea, temperatures have risen by 0.25 degree C per decade. [29] Modelling results suggest a further rise of 1 to 2 degree C over 20 years and 4 to 5 degree C over 100 years can be expected. West of latitude 141, precipitation has increased by 30 percent between 1968 and 1990. [30] Elsewhere precipitation in high latitudes has increased by 15 percent over the last forty years. [16] On the North American tundra there is a tendency toward earlier snowmelt. The area of land with continuous snowcover over the winter to the south of the sub-Arctic has retreated by about ten percent during the past 20 years. [16] In the Mackenzie River Basin Study, an area which includes parts of the Yukon and Northwest Territories as well as northern British Columbia, Alberta and Saskatchewan, temperatures have increased by 1.5 degree C this century. [31]

Regional differences in temperature trends are predicted by climate models. For example, models applied to the Nordic Arctic area have predicted a rate of temperature rise of 0.3 degree C per decade for Iceland and the Faeroe Islands, and 0.45 degree C per decade for eastern Finland and the northern extremes of Sweden. Summer warming is predicted to range between 0.25 to 0.3 degree C whereas in some areas winter warming is likely to range between 0.35C to 0.6 degree C per decade. Precipitation is likely to increase by between 3 to 6 percent per degree of warming. [32]

Observed trends, therefore, are broadly consistent with the results of modelling exercises. The full impacts of climate change on the Arctic, however, are extremely difficult to assess because of the intricate interactions between physical and biological factors. Overall, the hydrological cycle of the Arctic links atmospheric moisture transport, precipitation, river runoff, sea-ice and ocean circulation in a single system [33] and this in turn helps drive global ocean circulation. Hence, in considering potential impacts of climate change in the Arctic it is important to also consider how these changes may themselves cause wider impacts and indeed how they may actually reinforce the warming trend. It is predicted that practically all snow and ice features of the Arctic will be affected by continued warming of the Earth's atmosphere. [33, 34] The freeze-thaw line is likely to be shifted significantly northwards, and this will be accompanied by dramatic impacts.

Temperature Change and Impacts on Arctic Terrestrial Ecosystems

Vegetation is the terrestrial environment's life-sustaining feature. Rapid temperature increases in the Arctic are expected to push climate and vegetation zones northward at rates faster than many plant and animal species will be able to adapt. [15]

Such dramatic shifts in vegetation could jeopardize many animal populations, since abundant vegetation, at the right time, is critically important to all terrestrial wildlife. Grazing animals such as reindeer, caribou and muskoxen closely track seasonal vegetation growth, and depend upon the vegetation for healthy herds and well-nourished calves. This "plant-herbivore" interaction is an important part of tundra life. Without adequate vegetation, the animals become less productive, delay having offspring, and, in many cases, starve.

In the Arctic National Wildlife Refuge, for example, spring has arrived earlier and earlier along the coast. Consequently, caribou have had difficulty migrating from wintering areas in time to take advantage of periods of maximum springtime plant growth. The spring of 1990 was the earliest in nearly 40 years, and by the time the animals reached the plain, their principal food plant had gone to seed. Caribou herd populations could decline significantly should future climate and vegetation patterns prevent proper nourishment of calves. [35] High Arctic Peary Caribou and muskoxen may even be faced with extinction.[36]

Climate change could also affect regular freeze-thaw cycles, which have important implications for reindeer populations in relation to their ability to find food. For example, in the 1996-97 winter an estimated 10,000 reindeer died of starvation on Russia's far northeast Chukotsk Peninsula, after inclement weather patterns formed a thick ice crust over pastures, making it impossible for reindeer to graze. While reindeer populations often suffer from these freeze-thaw cycles, future variations in weather and climate could intensify their effects. [15] Increased late winter rain could cause polar bear dens to collapse before females and cubs have departed. Scientist surveying polar bear habitat near Manitoba, Canada have observed large snow banks used for denning that had collapsed under the weight of wet snow. [37]

Sea-ice and Snow Cover

There is some evidence that between 1978 and 1987 sea-ice extent in the Arctic decreased by around 2.1 percent together with a decrease of open water of 3.5 percent. [38] Data collected by submarine found that the thickness of ice covering 300,000 square kilometres of sea had fallen, decreasing in volume by some 15 percent. [39] It is unclear whether this actually represented an overall trend or normal variation, [40] highlighting the need for additional data. Further work since has indicated that between 1978 to 1994 the extent of Arctic sea-ice diminished by around 4.6 percent while the sea-ice area contracted by almost 6 percent. [41] In the Bering Sea, sea-ice extent has been reduced by about five percent over the last forty years with the steepest decline taking place during the 1970s.[29] Using sophisticated statistical analytical techniques, it has been shown that the mean sea-ice extent in summer over most sectors of the Arctic has fallen substantially, when the period 1961 to 1975 is compared 1976 to 1990. [42] The study detected no trend in winter.

While these changes in themselves are not unequivocal indicators of a trend, they again concur generally with the predictions from modelling exercises. [43] Under doubling of atmospheric carbon dioxide concentrations, a reduction in sea-ice area of between 10 to 50 percent has been predicted by one model, together with a reduction in thickness, particularly in summer. When ice volumes are considered, a 50 percent decrease on average in winter could be followed by a virtual disappearance of sea-ice in the summer.

Normal variability in snow cover coupled with likely regional differences in the rate of temperature increase mean that any such trends are likely to be difficult to identify. Even so, directly measured snow cover over the North American Great Plains suggests that there has been an increase over the last century, whereas in the Canadian prairies, snow cover has declined.[34] In Alaska, there is evidence that springtime disappearance of snow cover occurred some two weeks earlier in the 1980s than in the 1940s and 1950s.[17] Data from lakes in central Canada show a warming of several degrees Celsius and lengthening of the ice free season by several weeks over a twenty year period beginning in the late 1960s. The modelled predictions [34] suggest that winter snowlines in the Arctic could move northwards by 5 to 10° of latitude. Snowfall will tend to begin later and snowmelt will be start earlier. This will extend the snow free season, although in some regions, more frequent open water may actually lead to more snowfall downwind due to increased evaporation from the water surface.

Effects on Ecosystems

Higher temperatures and longer growing seasons could increase the growth and production of some Arctic Ocean photoplankton. Some species are more sensitive to temperature than others and this is likely to lead to changes in the composition of the photoplankton community. Changes in the composition of the ecosystem are also likely to result from the invasion of Arctic waters by temperate species.

Reductions in sea-ice extent and algae could, in turn, lead to profound reductions in overall biological productivity in the Arctic seas. The entire ice-associated community could be threatened, including dependent fish species, such as polar cod. Arctic and migratory whale species, such as the narwhal and beluga whales, and gray and bowhead whales, would be affected, since they feed along the ice edge. Birds and mammals may be affected by climate-induced changes in ice openings, which serve as critical "outposts" for feeding, breeding and migration. [44]

Animals that depend on the ice as a platform, such as ringed seals, walruses and polar bears, would be left vulnerable by the loss of their habitat. [44] Walrus may suffer first, since they are dependent over much of their range on seasonal sea-ice. Polar bears could also become extinct if the Arctic ocean is free of summer ice for long periods, or if seasonal sea-ice changes affect ringed seals, their main prey.

If further warming occurs, ice is likely to break up earlier and freeze later, extending the open-water season in summer and fall. This change would reduce the amount of time polar bears can use sea-ice for hunting. This hunting time is especially important for female bears, who often fast for up to eight months to den and raise their cubs. If ice break-up occurs even two or three weeks earlier, fewer adult female bears would be able to hunt and store enough body fat to produce and successfully wean cubs. Lower reproduction rates among the bears would quickly reflect the females' lost hunting time. [37]

In addition to providing shelter, snow also supports life on land. The health of many plant and animal communities largely depends on the persistence, thickness and timing of snow cover. If Arctic snowfall declines, animals who build winter dens out of snow may suffer. Increased snowfall, on the other hand, is likely to alter vegetation cover and affect animal survival and reproductive success. [45] A significant increase or decrease in snowfall would upset the present delicate balance of the Arctic environment.

Effects on the Transfer of Heat

The reduction of snow cover and sea-ice will affect one of the most important feedback systems in the Arctic environment. By reducing the reflection of solar energy from the surface of the Earth and sea, more energy can be absorbed by the ground surface. In turn this leads to an increased flow of heat from the surface to the atmosphere. The resulting temperature rise may bring about further loss of snow and ice, completing a positive feedback loop and reinforcing the original effect. One possible offset against this is the evaporation of water from the surface leading to increased cloud cover, but at the present the relative importance of the two processes is impossible to assess. [33]

The sea-ice also controls the transfer of heat from the relatively warm ocean to the cold atmosphere. Hence, ice reduction either in area or thickness could lead to increased heat transfer and interaction with winds. [16] This would allow the air to pick up moisture and make the Arctic cloudier. This in turn would change regional weather patterns. The role of clouds, however, continues to be one of the major uncertainties in climate models.

Effects Upon Ocean Currents

In one scenario, barometric pressure could be reduced in the Arctic.[16] This could give rise to more cyclonic storm systems particularly in winter. Changes in wind patterns could influence temperature and humidity, and hence the formation of sea-ice and the circulation of water in ocean currents. A specific concern is the likely behaviour of the thermohaline circulation. Increased precipitation and melting of ice could make the upper layers of the Arctic less saline. This could change the formation of deep water at the polar front. [46]

A change in the thermohaline circulation, therefore, could shut down the Ocean Conveyor. Alternatively, based on evidence from sediment cores, the site where deep water forms could shift southwards. This would end the influence of warm waters from the Gulf Stream and North Atlantic Drift along the coast of the Western Atlantic. Paradoxically, this could lead to areas of Europe and Scandinavia cooling by up to 5 degree C. Thereafter, these regions would experience the global temperature rise, but starting from a point where the warming effects of Atlantic waters were absent. This possibility is supported by geological evidence of previous phenomena following large inputs of low salinity water into the Arctic seas. [15, 47]

In addition to the profound effects that a temperature drop would have upon regional climate and weather in Europe and Scandinavia, changes to the transport of atmospheric carbon dioxide from the atmosphere into the oceans could also be expected. If atmospheric levels of carbon dioxide were increased by this a positive reinforcement of additional increases in global temperatures could occur.

Terrestrial Ice

Glaciers and Ice Sheets

Despite showing some regional variation, studies indicate that the majority of Arctic glaciers are in retreat.[34] With continued warming this loss of glacial mass is expected to continue. The Bering Glacier, North America's largest glacier, is an example of a major glacier in retreat. Originating some 25 kilometres east of the US border in Canada, the Bering Glacier flows 191 kilometres to its terminus in south central Alaska. The areal extent of the glacier is over 5,170 square kilometres and in some places the glacier is over 800 metres thick. During the last 10,000 years the size of the glacier has varied in response to climatic changes. [48]

Since the beginning of this century the glacier's frontal region has declined 130 square kilometres in area. In addition to the overall retreat of the glacial front the Bering Glacier has thinned dramatically over the past century. Aerial photography shows that parts of the glacier have thinned by as much as 180 metres in the last 50 years and in some places the glacier has lost between 20 to 25 percent of its thickness. [48]

In general, Alaskan glaciers have suffered ice thickness decreases of 10m over the last 40 years. A retreat of 15 percent appears, on average, to follow from each 1 degree C rise in temperature. [29] It is predicted that the largest Gulf of Alaska glaciers should persist into the 22nd century.

The significance of melting glaciers is global. Over the period 1890 to 1990, it is estimated that the mid-range contribution of global glacial retreat to recent sea level rise was 3.5 centimetres. [49] Total sea level rise over this period was around 18 centimetres (within a 10 to 25 centimetres range). The 3.5 centimetres contribution of glaciers is therefore significant. In the future, global sea level is expected to rise by between 13 to 94 centimetres. With mid-range estimates of 16 centimetres and 28 centimetres respectively, most of this projected rise is attributed to thermal expansion of waters and increased melting of glaciers and ice caps. [49]

However, increased precipitation could cause some glaciers to increase in size, or remain stable, particularly at high latitudes and altitudes, at least in the short term. The response will also partly depend upon weather patterns. It is known that high Arctic glaciers also melt quickly following certain shifts in the semi-permanent weather systems which become established in the Arctic region. [34] Meltwater could also contribute to changes in the Ocean Conveyor system, by decreasing the salinity of Arctic seawater.

Glaciers show a delayed response to climate change of years to decades. In the case of a very large mass of ice such as the Greenland Ice Sheet, this lag phase will be longer. Already, parts of the margin of the Greenland Ice Sheet appear to have retreated significantly over the past century, despite a short-lived "thickening" of the ice during the 1970s and early 1980s. [34] Estimates made of the likely contribution of the Greenland Ice Sheet to sea level rise range from between 1 to 4 centimetres by the year 2100 but could under some scenarios reach over 1 metre by the year 2200. [50]

Permafrost

Permafrost currently underlies around 25 percent of the land area of the Northern Hemisphere [51] and much is close to melting point and hence sensitive to small changes of temperature. It is predicted by computer modelling that permafrost zones will move northwards by between 500 and 1,200 kilometres. A significant proportion of the permafrost in the Arctic is close to 0 degree C and therefore particularly sensitive to increasing temperatures.[16] A 16 percent shrinkage in total permafrost area is projected by the year 2050.[34] It is possible that total shrinkage could be as high as 25 to 44 percent with the continuous permafrost cover reducing in area from 29 to 67 percent according to other models.[52] The regional rate of thawing is likely to be variable and as the thaw penetrates deeper into the permafrost, lag times will increase. In Northern Alaska, permafrost has warmed by between 2 to 4 degrees C over the last century and some discontinuous permafrost in Southern Alaska is thawing. Permafrost in Russia and China has also warmed over the last two decades. [34]

Permafrost melting will undoubtedly be an important consequence of climate change. Changes in the depth of the layer which thaws in the summer will modify biological and geological processes, but in the tundra the overall effect on the permafrost structure could otherwise be relatively slight. Thawing will be associated with considerable disturbance and change in areas like Alaska, Canada and Siberia where discontinuous ice-rich permafrost underlies much of the land area. Where the permafrost is rich in ice, land will be susceptible to subsidence. Further south, there would be a shift to discontinuous permafrost with degradation of ground ice and much more severe effects.

Such changes will allow increased erosion and damage to surface vegetation. Exposed dark soil surfaces are more efficient at absorbing solar heat than vegetation, so disturbed ground could reinforce the thawing of the permafrost. The thawing of large amounts of underground ice can substantially modify the landscape by causing ground subsidence and the forming of pits, troughs and mounds. This type of terrain is called thermokarst. In lowland areas thermokarst will lead to the formation of many lakes which will continue to be enlarged by erosion over a long period of time. Thermokarst will increase both coastal retreat and inland erosion. The depressions formed by this subsidence may be several metres deep [29] as has been recorded in both Alaska and Russia. Permafrost melting in the Mackenzie River Basin has led to widespread river-bluff landslides and increased erosion. In Alaska, extensive coastal retreat has been observed [29] following the thawing of permafrost.

As permafrost thaws, infrastrusture such as pipelines, housing, air strips, roads, and water and sewage systems will be damaged. The redesign and replacement of many of these systems will be required.

Impacts of thawing permafrost are likely to extend beyond simple physical disturbance. Thermokarsts could act as a focus for colonising immigrant species replacing the specialised Arctic flora. By the year 2020, vegetation zones under a 2 degree C temperature rise could have moved up to 500 kilometres northwards. [16] Other estimates suggest that the advance of vegetation and climate zones northwards could be equivalent to 1 metre an hour, over 8 kilometres per year. [15] Many Arctic plants are unlikely to be able to adapt to such changes or to adjust their ranges to keep pace.

There are possible mechanisms of positive reinforcement of climatic warming could come into play as a result of the thawing of permafrost. The thawing of permafrost will allow drying of some upper soil areas and decomposition of organic matter. This in turn will release carbon dioxide and possibly methane into the atmosphere, increasing the concentrations of greenhouse gases. This effect could be substantial if more than a fraction of the 450 million tonnes of carbon in soils of all tundra systems or of the 50 million tonnes in Arctic soils is released as carbon dioxide or as methane. [34]

Conclusions

The global build up of greenhouse gases and associated climate change has the potential to dramatically alter the Arctic environment and its ecosystems The Arctic is particularly vulnerable to climate change, and indeed in some areas the impacts of changes in climate are already evident. Future climate change is likely to threaten both marine and terrestrial wildlife. From plankton to polar bears, many species could suffer or disappear entirely. While the implications of warming on the Arctic are complex and not yet fully understood, they extend well beyond these immediate areas and may have dramatic global repercussions, including increases in sea level due changes in the mass balance of Arctic glaciers and, possibly the Greenland Ice Sheet. Local warming may, in fact, accelerate global warming and its effects.

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