

AMAP Update on Selected Climate Issues of Concern: Observations, Short-lived Climate Forcers, Arctic Carbon Cycle, and Predictive Capability

EXECUTIVE SUMMARY

C1. The *Arctic Climate Impact Assessment* and the Intergovernmental Panel on Climate Change have established the importance of climate change in the Arctic both regionally and globally. Following those reports, emphasis has been placed on continued observations, a new assessment of the Arctic carbon cycle, the role of short lived climate forcers in the Arctic, and the need for improved predictive capacity at the regional level in the Arctic.

C2. The Arctic continues to warm. Since publication of the Arctic Climate Impact Assessment in 2005, several indicators show further and extensive climate change at rates faster than previously anticipated. Air temperatures are increasing in the Arctic. Sea ice extent has decreased sharply, with a record low in 2007 and ice-free conditions in both the Northeast and Northwest sea passages for first time in recorded history in 2008. As ice that persists for several years (multi-year ice) is replaced by newly formed (first-year) ice, the Arctic sea-ice is becoming increasingly vulnerable to melting. Surface waters in the Arctic Ocean are warming. Permafrost is warming and, at its margins, thawing. Snow cover in the Northern Hemisphere is decreasing by 1-2% per year. Glaciers are shrinking and the melt area of the Greenland Ice Cap is increasing. The treeline is moving northwards in some areas up to 3-10 meters per year, and there is increased shrub growth north of the treeline.

C3. Black carbon, tropospheric ozone, and methane may contribute to Arctic warming to a degree comparable to the impacts of carbon dioxide, though there is still considerable uncertainty regarding the magnitude of their effects. Black carbon and ozone, in particular, have a strong seasonal pattern that makes their impacts particularly important in the Arctic, especially during the spring melt. These climate forcers are also relatively short-lived and have the potential for relatively rapid reductions in emissions and thus in atmospheric levels. There are various options

for emissions reductions that can be taken in northern regions and globally. Improving quantitative estimates of the potential benefits of reducing emissions of short-lived climate forcers requires improved climate modelling capability.

C4. The Arctic carbon cycle is an important factor in the global climate system. Considerable quantities of carbon, much of it in the form of methane are stored in the Arctic. Should these be released to the atmosphere, they will increase greenhouse gas concentrations and thus drive further climate change (an example of positive feedback). At present, the Arctic appears to be a sink for carbon dioxide and a source for methane. Climate change is likely to result in more carbon dioxide being released to the air but also more being absorbed in the ocean and by growing plants on land and in the ocean. The change in net releases of carbon dioxide and methane is difficult to predict. It appears unlikely, however, that changes in the Arctic carbon cycle will have more than a modest influence on global climate over the next 50-100 years, but large uncertainties exist.

C5. Global climate models are limited in their ability to provide reliable, regional-scale projections of various climate parameters. Current and planned projects and programs aim to improve understanding of regional processes, the role of short lived climate forcers, and local impacts of climate change. Improved regional-scale models and projections will help bridge the gap between global studies and models and local impacts and changes in the Arctic, and improve evaluation of adaptive and mitigative actions, particularly concerning local impacts and the likely benefits of reducing emissions of short-lived climate forcers.

Recommendation on monitoring:

- *Sustain and enhance the current level of monitoring of climate change, updating information on key aspects of the Arctic climate system (C2)*
- *Enhance and expand networks of monitoring and observation points for short-lived climate forcers, building on existing networks, such as the WMO Global Atmosphere Watch Programme (C3)*
- *Initiate and maintain circumpolar measurements of carbon fluxes within the Arctic and imports to and exports from the Arctic (C4)*
- *Integrate and expand monitoring efforts to enhance understanding of cause-effect relationships and temporal and spatial variability driving regional scale climate (C5)*

- ***Recommendations for studies to address gaps in knowledge:***
- *Conduct studies on non-carbon dioxide climate forcers to improve understanding of their role in Arctic climate and develop recommendations for national and international follow up action (C3)*
- *Conduct studies on the Arctic carbon cycle to identify key sensitivities and major feedbacks to regional and global climate (C4)*
- *Develop reliable regional-scale climate models to support assessment of impacts and evaluation of the effectiveness of adaptive and mitigative actions (C5)*

Introduction

This report provides an update on selected topics concerning Arctic climate change, which remains a major issue of concern. In 2004, the Arctic Monitoring and Assessment Programme (AMAP), together with the program for the Conservation of Arctic Flora and Fauna (CAFF), and the International Arctic Science Committee (IASC) produced the *Arctic Climate Impact Assessment*¹ (ACIA). The comprehensive ACIA built on a chapter in the earlier *AMAP Assessment Report: Arctic Pollution Issues*, published in 1998², and its accompanying plain-language summary, *Arctic Pollution Issues: A State of the Arctic Environment Report*³, released the year before. AMAP is currently conducting a more thorough update on certain aspects of Arctic climate change (Changes in the Cryosphere: Snow, Water, Ice, and Permafrost in the Arctic) for delivery in 2011. This new study will incorporate results of the International Polar Year. A preliminary report on the Greenland Ice Sheet component of this study will be presented in the fall of 2009 as an Arctic Council contribution to the UNFCCC COP15.

The climate information presented in this report is, therefore not the result of a comprehensive assessment of Arctic climate change issues, but rather is an update on some of the work that has been undertaken by AMAP as follow-up of the *Arctic Climate Impact Assessment*. The report draws upon peer-reviewed publications as well as workshops conducted under AMAP's

¹ REFERENCE#1
² REFERENCE#2
³ REFERENCE#3

auspices. From these materials, this plain-language summary has been written to capture the main messages and make them accessible to general readers. The summary has been reviewed by the authors of the scientific reports, by the members of the AMAP Working Group, and through national review processes in each Arctic country. These reviews have ensured that the summary is an accurate representation of the scientific reports.

The *Arctic Climate Impact Assessment* provided a comprehensive view of the topic through the early 2000s. The 2007 report of the Intergovernmental Panel on Climate Change⁴ affirmed the findings of the ACIA and acknowledged the importance of the Arctic within the global climate system. The reduction of summer sea ice means more sunlight is absorbed, leading to additional warming. The cycling of water and carbon with, to, and from the Arctic also has the potential for substantial regional and global impacts. Observations since the ACIA was published show that climate-driven changes are occurring even faster than were anticipated in that Assessment. This report summarizes recent observations of changing climate parameters, a review of the significance of short-lived climate forcers and prospects for their mitigation, a new evaluation of the Arctic carbon cycle, and new initiatives to improve understanding of the cryosphere and the ability to model climate changes and impacts at the regional scale.

Arctic Report Cards

To track changes in Arctic environment, the U.S. National Oceanic and Atmospheric Administration (NOAA) produced a report titled “State of the Arctic: October 2006.”⁵ Since then, AMAP and CAFF have contributed to subsequent annual “report cards” on the Arctic. This section provides a summary of what has changed, based on the three reports issued to date.

Air continues to warm, and atmospheric circulation is highly variable

Surface temperatures around the Arctic have continued to be higher than the 20th century average. The year 2007 was the warmest on record, continuing a trend that began in the 1960s. In contrast to a previous warming phase in the 1930s, the current warming covers the entire Arctic

⁴ REFERENCE#4

⁵ REFERENCE#5

and extends south to the mid-latitudes. A recent exception is the Bering Sea region, which experienced below-average temperatures in the winters of 2006 and 2007. As a result, winter ice extent returned to its long-term average, although summer ice retreated far to the north in 2007 and 2008.

Figure A4 from “Arctic Report Card 2008” [or A1]

Atmospheric circulation in the Arctic typically oscillates between two general patterns. This phenomenon is known as the Arctic Oscillation (AO), and is similar to (and connected with) the El Niño/La Niña switch in the southern Pacific. The Arctic Oscillation is measured against an index, with positive values indicating one dominant pattern and negative values indicating the other. A negative AO index means weaker winds, lower winter temperatures, and more sea ice. A positive AO means the opposite. The oscillation between positive and negative AO values is the main source of climate variability in the Arctic.

From the mid-1980s to the mid-1990s, the AO was strongly positive, consistent with rising temperatures and reduced sea ice. From the mid-1990s to about 2006, the AO moved between weakly positive and weakly negative values. In 2007 and 2008, the AO was again strongly positive, though not quite as high as it had been in the 1980s and 1990s. Recent patterns in temperatures and barometric pressure, however, differ from the characteristic patterns seen during the 20th century under positive and negative AO values. These changes may reflect alterations in atmospheric circulation patterns in the Arctic.

Figure A2 from “Arctic Report Card 2008”; perhaps Figure 7 from “State of the Arctic 2006”

Summer sea ice has decreased dramatically

The most striking change in the Arctic in recent years was the great reduction in summer sea ice extent in 2007. In March of that year, the sea ice had covered nearly all of its long-term average extent. By September, however, sea ice covered only 4.3 million square kilometers, 23% less than the previous record low of 5.6 million square kilometers in 2005 and 39% lower than the 1979-2000 average. Most of the loss occurred in the Beaufort, Chukchi, and East Siberian Seas. In 2008, despite cooler weather in spring and summer, the minimum sea ice extent was 4.7

million square kilometers, the second lowest ever recorded. For the first time in existing records, both the Northwest and Northeast Passages were ice free.

Figure S1 from “Arctic Report Card 2008”

Less obvious but still significant is the continued thinning of Arctic sea ice. Recent satellite data support previous observations that sea ice at the end of the melt season is thinner than it used to be, and that the trend is continuing. One cause of this trend is the loss of perennial ice, floes that last through at least one summer. Perennial sea ice extent has been decreasing since at least 1957, and has been dropping even more sharply in recent years. Thinner, younger ice is more susceptible to rapid melting from warmer waters and air, increasing the potential for more dramatic declines in ice extent.

Figure S4 from “Arctic Report Card 2008”

Arctic Ocean surface waters are warming

Consistent with the rapid retreat of sea ice in the summer of 2007, the surface waters of the Arctic Ocean have been warming in recent years. In 2007, some ice-free areas were as much as 5° C warmer than the long-term average. Overall, Arctic waters appear to have warmed as a result of the influx of warmer water from the Pacific and the Atlantic. In addition, the loss of sea ice means that more solar radiation is absorbed, heating surface layers further.

Figure O2 from “Arctic Report Card 2008”

The circulation of surface waters in the Arctic Basin is driven by wind. Wind patterns reflect the state of the Arctic Oscillation. In recent years, circulation has been generally anticyclonic, as expected with a weak AO index. One result is that freshwater tends to accumulate in the Arctic Ocean, especially in the Beaufort Gyre. Along the Eurasian coast, freshwater from rivers is a major influence, especially because river discharge has increased over the past century at least. Recently the patterns of ocean circulation have kept river water close to the coast rather than spreading towards the central basin. In 2007, the extensive melt of sea ice put vast quantities of relatively fresh water into the surface layers of the Arctic Ocean.

Sea level in the Arctic Ocean followed the Arctic Oscillation until about 1996, influenced

primarily by barometric pressure. After that, sea level continued to stay above the long-term average despite the switch of the AO from strongly positive to weak and fluctuating. This suggests that other factors have come into play, such as ocean expansion from heating, increased freshwater content, or the effects of wind.

Figure O4 from “Arctic Report Card 2008”

The terrestrial Arctic also shows signs of change

On land, several indicators show continued warming around the region. Permafrost, defined as ground that has remained below the freezing point for at least two consecutive summers, is warming. At its margins, permafrost is thawing. In northern Alaska, temperatures at depths below seasonal influence show a warming trend since at least the 1970s. The trend has not been uniform, and indeed has had a few periods of cooling, but overall the temperatures have risen by 0.5°C to 2°C. In 2007, the trend turned upwards again.

Figure L2 from “Arctic Report Card 2008”

Plants respond more quickly to changes in temperature. They grow more vigorously and densely when the air is warmer. This response can be detected from satellites by measuring the greenness of the landcover. Most of the Arctic, especially tundra areas, showed increased plant growth over the period from 1981 to 2005. Some areas, especially in the boreal forest, have showed a slight decline. Over longer periods, warming has led to increased shrub growth north of the treeline as well as a slow movement of the treeline itself. In Russia, treeline has displaced tundra patches as quickly as 3-10 meters per year. In Scandinavia and Canada, tree growth near treeline has become denser, with some indication of slow movement into previously exposed areas.

Figure L1 from “Arctic Report Card 2008”

Figure 2 from “Recent Changes in Vegetation”, under the Land tab in “Arctic Report Card 2008”

Snow cover in the Northern Hemisphere appears to be declining at about 1-2% per year, depending on the method used to measure it. Because snow reflects sunlight back into space, less snow is a positive feedback to warming trends. In 2007, the average snow cover was 24.0 million square kilometers, which is 1.5 million square kilometers below the 38-year average, and the

third-lowest figure on record.

Any way to get a comparative version of Figure L3 from “Arctic Report Card 2007”? The map is more interesting than the graphs (Figure L4 in the 2007 report and Figure L3 in the 2008 report), which on first inspection do not suggest much change ...

Glaciers can be difficult to use as indicators of change, in part because melt area is not as direct a measure of change as the change in mass of a glacier, but mass is more difficult to measure. Changes in mass correspond to accumulation or loss of ice. Nearly all glaciers studied are decreasing in mass, resulting in rising sea level as the water drains to the ocean. Excluding Antarctica and Greenland, the rate of sea level rise from glacial melt is estimated at 0.58 millimeters per year from 1961 to 2005, with a higher rate of 0.98 millimeters per year between 1993 and 2005. The largest contributors to this rise are glaciers in Alaska, the Arctic, and the high mountains of Asia. By 2100, glacial melt may increase sea level by a further 0.1 to 0.25 meters.

Greenland’s ice sheet continues to melt

The Greenland ice sheet is the largest in the northern hemisphere and has been studied extensively. The ice sheet has experienced summer temperatures consistently above the long-term average since at least the mid-1990s. Temperatures along the coast have followed the same pattern, reversing an earlier cooling trend in West Greenland from the 1960s to the 1990s. In 2007, temperatures at various locations were generally above average, though not for every season of the year.

Melting on the ice sheet in 2007 was the most extensive since record-keeping began in 1973. The area experiencing melt was 60% larger than in 1998, the year with the next largest area in the record. Melting lasted on average 20 days longer than usual, up to 53 days longer than usual at elevations between 2000 and 3000 meters between the north and south domes of the ice sheet. The Jakobshavn Isbrae, Greenland’s largest glacier, continued the rapid retreat begun in 2001. The Tissarissoq bay on the south side of the fjord became ice free in 2007, probably for the first time in centuries and perhaps longer. Other outlet glaciers in southern Greenland, such as the Kangerlussuaq Glacier and the Helheim Glacier, show the same pattern.

Figure G1 from “Arctic Report Card 2008”

Figure G3 from “Arctic Report Card 2008”

Short-lived Climate Forcers

Carbon dioxide is the main driver of global climate change, but black carbon (or soot), ozone, and methane may have a combined effect comparable to those of carbon dioxide, both in the Arctic and globally. While there is still considerable uncertainty regarding the magnitude of effects from these substances, these forcers of climate change do not stay in the atmosphere nearly as long as carbon dioxide, and thus will respond more quickly in the short-term to reductions in emissions. Part of the powerful Arctic impact of these short-lived forcers comes from their seasonal nature, with the strongest impacts coming from late winter to mid-summer. Each forcer has unique characteristics important to designing appropriate mitigation measures. Reductions would additionally benefit the health of Arctic residents and, indeed, people around the world, providing another reason for prompt action.

Black carbon, methane, and ozone may be substantial contributors to Arctic warming

Black carbon consists of small, dark particles emitted into the atmosphere from inefficient burning, such as wood stoves and diesel engines. It warms the Arctic in two ways. First, a haze layer of dark particles in the atmosphere absorbs sunlight, which contributes to overall global warming including that occurring in the Arctic. Most of the black carbon that reaches the Arctic atmosphere is emitted from sources in the northern mid-latitudes. Second, some of the airborne black carbon that reaches the region is deposited onto ice and snow, resulting in a darkening of the surface. Since dark surfaces absorb more solar radiation, this enhances melting. Recent extensive modeling indicates that in Greenland, up to 80% of deposited black carbon is from such sources in the northern latitudes, divided equally between North America and Europe. On Arctic sea ice, the figure is 70%, with a greater proportion coming from Europe and perhaps northern Asia.

“Warming in the Arctic since Pre-Industrial Times” figure, with uncertainty in the caption; could use Figure 11 from Technical Report 1, which also shows the global estimate ...

Could also use photos of sources of short-lived forcings ...

Further sampling of snow and ice in the Arctic will help validate these modeling results. Because deposition in late winter and spring has the greatest impact on the spring melt, seasonal reductions in emissions, such as reductions in springtime burning in agricultural areas, will be particularly important.

Ozone, which is important in the stratosphere for protecting the Earth from ultraviolet light, also forms in the lower atmosphere or troposphere. It is the product of chemical reactions starting with various pollutants, such as carbon monoxide, nitrogen oxides, and organic compounds such as methane. Ozone is a greenhouse gas, acting worldwide, but has a strong seasonal effect in the Arctic in winter and early spring when a blanket of smog forms over the Arctic. The aerosol components of “Arctic haze” have been examined in previous AMAP reports⁶. Ozone in winter lasts for up to two months, since it is not broken down by sunlight as quickly as in summer, when it lasts at most for a week or two. Although the mechanism is different than that of black carbon, ozone-driven warming can also have a strong seasonal effect, particularly in spring and during the spring melt. Most tropospheric ozone in the Arctic comes from North America.

Methane is a greenhouse gas recognized under the Kyoto Protocol. It has relatively short lifetime in the atmosphere of about nine years. Methane contributes to global warming both on its own and, under certain conditions, by producing ozone. Whereas reductions in black carbon and ozone would most benefit the Arctic if they occurred in northern latitudes, reductions in methane anywhere in the world at any time of year will benefit the Arctic by reducing overall global warming. Reductions in methane emissions should reduce atmospheric concentrations of greenhouse gases more quickly than would be the case for longer-lived greenhouse gases and thus would have a more rapid effect.

Mitigation efforts could provide benefits in the short-term

A global analysis of the potential benefits of reducing emissions of short-lived forcings globally suggests that reductions in black carbon and methane emissions have the most promise. The seasonal impacts of black carbon and ozone may provide an additional opportunity for rapid

⁶ REFERENCE #6

benefits from seasonal emissions reductions. Improving the quantitative estimates of both the effects of short-lived climate forcers and the potential benefits of reducing their emissions requires improved climate modelling capability.

Figure derived from the table “Absolute and Weighted Anthropogenic Emissions ...”? Would require simplification or some explanation ...

There are a number of options for reducing emissions of these short-lived climate forcers. Those that appear to have the most potential for early and effective action include emissions controls on diesel engines and oil and gas flaring, improvements in agricultural practices such as reduced burning, and capturing or eliminating methane emissions from major industrial and waste treatment sources. Additional measures could be pursued over a number of years, such as identifying major point sources of black carbon and applying existing pollution-control technology, and using pollution-control measures on vehicle engines to reduce emissions of chemicals that in turn produce ozone.

The Arctic Carbon Cycle

The Arctic has been warming rapidly in the past few decades. A key question is how that warming will affect the cycling of carbon in the Arctic system. At present, the Arctic is a global sink for carbon. If that changes, and the Arctic becomes a source of carbon, the feedback to global climate has the potential to enhance warming. This section discusses what is known about the sensitivity of carbon cycling in the Arctic and what still needs to be understood.

Figure 1

Vast amounts of carbon are stored in the Arctic

For the purposes of this carbon cycle analysis, the Arctic has been defined as the Arctic Ocean plus the lands that drain into the Arctic Ocean and its marginal seas or that have permafrost, excluding high-elevation areas farther south such as the Tibetan Plateau.

Combination of Figures 2a, b, c to show a simple line around the area being considered here

This area includes about one quarter of the world’s land where plants grow. In the low

temperatures of the Arctic, much plant matter does not decompose. Instead, it accumulates in thick, carbon-rich soil layers. Thus, the land area considered here contains about one third of the carbon held in the world's terrestrial ecosystems. Furthermore, it holds 40% of the carbon in near-surface soils worldwide. The exchange of carbon dioxide and methane between land and air varies greatly with place and time, as discussed in more detail later.

Figure 4

Oceans contain carbon in various forms. Dissolved organic carbon comes from decaying biological material. Dissolved inorganic carbon includes carbon dioxide and other simple molecules and ions containing carbon. Both organic and inorganic carbon are also present in particulates. Of these forms, dissolved inorganic carbon is the most common, and also has the least seasonal variation. The other forms cycle throughout the year in response to biological activity. Sediments also contain carbon, deposited over time as various materials settle to the sea floor.

Table: Major Stocks of Carbon in the Arctic

Rivers are responsible for most of the direct transport of carbon from land to ocean. In the Arctic, this is especially important because rivers contribute a much larger amount of water relative to the size of the ocean than is true elsewhere. The Arctic Ocean holds only one percent of the world's ocean water, but receives about a tenth of the world's river runoff and about a tenth of the dissolved organic carbon carried from land to sea worldwide. Peatlands in the Arctic provide particularly large amounts of carbon into river systems and thus the ocean. Coastal erosion, too, is a major source of carbon to the ocean.

In addition to the usual sources of carbon, primarily from plant matter, the Arctic appears to have huge quantities of methane hydrates. These are ice-like crystals in which water molecules form cages that each holds one methane molecule. Methane hydrates are stable in cold conditions and under high pressure, and thus are found in permafrost on land and continental shelves and also beneath the sediments of the Arctic Basin. As hydrates warm or as pressure is reduced, the methane is released. The amount of methane hydrate present is not well known, but some global estimates suggest it may rival the amounts of all known sources of gas and oil.

Diagram of a methane hydrate crystal lattice with water and methane molecules?

At present, the Arctic is a sink for carbon dioxide ...

Measuring the flow of carbon throughout the entire Arctic is not a simple task. One approach is to measure atmospheric levels of carbon dioxide. Variations over time and space indicate the movement of carbon to or from the atmosphere. This method provides little insight into the reasons for changing carbon concentrations in the atmosphere. Another approach is to measure actual flows of carbon dioxide and methane at local sites. These data can be scaled up for an entire region, based on the particular characteristics of local climate, vegetation, and so on. Although these extrapolations make a number of assumptions, they do provide information on the specific processes that govern carbon flow.

Atmospheric measurements indicate that the Arctic is a modest sink for carbon, with about 400 million tonnes taken from the atmosphere in an average year. This amount can vary greatly from year to year. While different studies generally agree on the size of the sink, they provide different estimates of uncertainty and interannual variation. Changes in weather patterns and variation in forest fire activities are major contributors to the differences among years.

Studies of carbon dioxide flows at specific sites also indicate great variation from year to year. The details of the growing season have great influence on the amount of carbon taken up by plants and also the amount released by decomposition. On the whole, dry tundra systems appear to be sources of carbon, but wet tundra and boreal forest are sinks. Combining various studies and estimates for the terrestrial Arctic, it appears that land areas are a sink for approximately 300-600 million tonnes per year. This amount is 30-60% of the global estimate for the net sink of carbon on land. Growth of trees in the boreal forest appears responsible for most of the sink activity in the Arctic.

Lakes and rivers are a source of carbon to the atmosphere. They also carry carbon to the ocean, as noted earlier. Few measurements of carbon flow have been made in Arctic lakes. In the absence of specific data from the region, global estimates can be scaled down. The Arctic holds 36% of the world's lake surface area and accounts for 10% of global river discharge to the ocean. Taking the same proportions of estimates of global freshwater carbon releases gives an estimate

for the Arctic of 25-54 million tonnes of carbon from lakes each year and 15-30 million tonnes from rivers.

Although the Arctic Ocean is relatively small, its marginal seas in particular are highly productive and thus take up considerable amounts of carbon during the spring bloom. The Arctic is also where much of the world's deep ocean water is formed, as surface waters descend to the depths, carrying carbon with them. Ice cover forms a barrier to ocean-atmosphere exchange, and changes in sea ice will affect the net carbon flow to or from the ocean. There are few direct measurements from the Arctic Ocean, and thus estimates of flow have high uncertainty.

Nonetheless, seawater in the Arctic appears to be a sink for 24-100 million tonnes of carbon per year. This accounts for 1-5% of the global estimate for ocean sink activity for carbon.

Carbon is also carried from land to rivers, from rivers to ocean, and from ocean to ocean. Much of this carbon is in the form of dissolved and particulate carbon. This transport is important for determining where carbon may be emitted to the atmosphere or captured in sediments. There is considerable uncertainty involved in most estimates of carbon transport, but river transport, ocean currents, and coastal erosion appear responsible for the largest amounts.

Figure 7 or variation thereof?

...and a source for methane

Methane is a different story. As with carbon dioxide, the flow of methane involves many factors. Methane also reacts with other molecules in the air. In sum, recent atmospheric studies indicate that the Arctic is a source for 15-50 million tonnes of methane each year, or 3-9% of the global total net emissions from land and sea. Site studies show a higher emission rate, of 31-100 million tonnes per year, from land and freshwater sources combined. The role of small lakes in permafrost areas is greater than previously thought. These lakes are surrounded by carbon rich soils laid down in the last ice age, now being released as the water thaws the frozen soil.

Figure 6

Methane hydrates at present do not appear to contribute much to Arctic emissions. Permafrost effectively seals off the ground below, though as permafrost warms it becomes more permeable.

Most of the emissions from hydrates come from coastal and continental shelf areas where permafrost is warming, thawing, or eroding. Although no estimates have been made for the Arctic specifically, estimating the Arctic share based on the area of continuous permafrost yields a first-order estimate of less than a million tonnes per year. In other words, the contribution from methane hydrates is at present insignificant compared with emissions from land.

Similarly, little information is available to assess the flow of methane to or from the Arctic Ocean, but what data there are suggest a modest contribution as a source. Much remains to be understood, however, about the transport and reactions of methane in seawater in the Arctic.

The response of the Arctic carbon cycle to global climate change is far from clear

In the next decade or two, the boreal forest may continue to grow, absorbing more carbon as trees become larger and treeline expands. On the other hand, forest fires may increase in frequency and extent and insect outbreaks may kill more trees, both of which would release carbon to the atmosphere. Which trend dominates the other depends in part on precipitation. Dry conditions may reduce plant growth and lead to more fires. It is also unclear whether increased carbon dioxide in the atmosphere will stimulate plant growth.

Over the next half century to a century, the northward movement of deciduous forest types may reduce carbon storage in the boreal forest overall. Broadleaf deciduous forests typically store less carbon than coniferous forests of the type that now dominate the boreal zone. Although shrubs are moving into tundra areas, the movement of the actual treeline is very slow and will likely only have an effect on the carbon cycle of the Arctic over the course of several centuries.

Thawing of near-surface permafrost will mobilize stored carbon. Different studies show different patterns over time, but agree that much carbon will become available by the end of this century. Furthermore, fire in permafrost landscapes may accelerate thawing, a factor that has not been considered in studies to date. Once permafrost is thawed, the release of carbon depends primarily on the wetness of the soil. Wetter soils will release more methane but relatively less carbon dioxide than dry soils. Recent trends in the Arctic indicate that landscapes are typically drying as a result of climate change.

The impact of Arctic carbon cycle changes on global climate appear likely to be modest. One study projected a potential maximum release of 50 billion (i.e. thousand million) tonnes of carbon from the Arctic terrestrial environment through this century, far lower than the 1500 billion tonnes that are expected to be released by even low-end estimates of fossil fuel burning over the same period. This and other studies also found that the Arctic may continue to be a sink for carbon, depending on responses to increased carbon dioxide in the atmosphere and other factors.

Variation of Figure 8

In the marine environment, too, feedbacks from climate to carbon can be both positive and negative. Reduced sea ice will allow more exchange of carbon from sea water to the atmosphere. It will also allow more light to reach the water, stimulating more plankton growth and thus uptake of carbon. Melting of ice will mean more freshwater in upper ocean layers, which can reduce biological activity and result in less carbon being taken up by biota. These effects will act very differently in each season, making projections of the net change even more difficult.

As the ocean warms, it can hold less dissolved carbon dioxide. Furthermore, warmer water may lead to increased production of carbon dioxide and methane through decomposition and other biological activity.

The discharge of water from land to sea increased in the Arctic throughout the 20th century, and is projected to continue to rise and perhaps accelerate during the 21st century. Increased water flow will likely mean increased carbon transport, though the relative proportions of different types of carbon are difficult to predict. One possibility is that carbon carried by rivers ends up stored in coastal sediments. Another possibility is that this carbon decomposes in the water column and is released as carbon dioxide and methane.

Variation of Figure 9

The release of methane from gas hydrates currently locked in permafrost is likely to be a very slow process. Most hydrates are at considerable depth and so would not be affected in the short-term by near-surface thawing. Furthermore, methane moving upwards from hundreds of meters underground would most likely be oxidized before reaching the surface and thus reach the

atmosphere as carbon dioxide and water rather than as methane. Nonetheless, the fate of gas hydrates remains largely uncertain in both the short- and long-term.

Further research should focus on sensitive elements of the carbon cycle

Current understanding of the Arctic carbon cycle is limited by considerable uncertainties. Even the question of whether the Arctic will be a source or a sink for carbon depends on the extent to which increased carbon dioxide in the atmosphere will stimulate plant growth. The interactions between climate and carbon cycling in many other areas of the Arctic environment are similarly unclear.

Integrated studies of regional carbon dynamics are needed to provide better information on key elements of the Arctic carbon cycle. Such studies should link observations of carbon dynamics to the processes that influence those dynamics. The resulting information should be incorporated into modeling efforts that connect carbon dynamics and climate. The studies should focus on sensitive parts of the system, for example areas experiencing major changes or thresholds such as permafrost loss or increased fire disturbance. Similarly, more research is needed on the relative importance of various processes to determine whether carbon uptake or release will predominate.

A major challenge for carbon modeling is connecting fine-scale observational studies with the larger scales at which models describe the environment. Observational networks should be designed to capture regional variations and also reveal the underlying processes that govern carbon dynamics at various scales. That information can be used to model the interactions among various parts of the carbon cycle. Observational studies should also focus on small- and large-scale processes so that both can be incorporated in models.

For example, uptake of carbon through photosynthesis and release through decomposition depend greatly on local temperature and moisture. Growth or loss of wetlands can be measured at larger scales, as can disturbances such as fires. Since all these factors affect the carbon cycle, studies that ignore one or more of these influences will not provide an accurate picture of carbon dynamics. In turn, models will not be able to capture the major influences on the carbon cycle if they do not reflect all of the major factors that are involved.

The improved understanding of carbon dynamics can be incorporated first in simpler models where the basic ideas can be tested. Then, more complex models that couple air, land, and sea can be developed or revised based on new and better understanding of the fundamental factors involved. This in turn will allow a more confident exploration of the relationships between climate change and carbon cycling in the Arctic.

Figures? Detailed sections from Figures 8 and 9 to emphasize sensitive parts of the system? Photos of key elements? Scaled diagram to show importance of capturing micro, meso, and macro scale processes?

Improving predictive capacity for the Arctic region

Assessing the future course of climate change in the Arctic requires understanding processes, feedbacks, and impacts at the regional scale. This scale is essential to bridging the gap between global studies and models and local impacts and changes in the Arctic. This section provides an introduction to several initiatives in this area, which will be addressed in more detail in future reports.

Reliable regional-scale modeling is needed to support Arctic process and impact studies

A recent evaluation of global climate models was conducted in preparation for the Climate Change and the Cryosphere: Snow, Water, Ice, and Permafrost in the Arctic (SWIPA) study. 25 models were evaluated for their ability to simulate 20th century climate parameters such as surface air temperature, sea level atmospheric pressure, and summer sea ice extent. The models varied greatly in their abilities, with some models performing well for some criteria but not for others. Simply put, there is no single best model for all purposes. For the short-term, model selection must be done carefully and documented well to maintain the integrity of the overall projections of changes in the Arctic. In the longer term, Arctic climate studies require reliable regional-scale models that can capture the various parameters of interest for different process and impact studies.

The SWIPA project itself is intended to develop more detailed and thorough knowledge about ongoing processes, supporting more accurate projections about the Arctic cryosphere and allowing better assessment of impacts on local, regional, and global scales. The project builds on

work done through the International Polar Year (IPY), the Intergovernmental Panel on Climate Change, and the Arctic Council, as well as other national and international programs. Specifically, SWIPA will integrate scientific information on the impacts of climate change on ice, snow, and permafrost in the Arctic, considering impacts within the Arctic and beyond. It will update existing scientific information with results of relevant new research and monitoring.

The effects of short-lived climate forcers also require further study. Improving the quantitative estimates of these effects and the potential benefits of reducing emissions of non-carbon dioxide forcers requires improved climate modeling capability.

Finally, assessing social and economic impacts of climate change typically requires detailed information at local scales. Global climate models, though powerful and complex, must operate on a coarse geographical scale to keep their computation requirements within reason. This means, however, that their outputs do not have sufficient resolution for many impact studies. Until sufficiently detailed regional models are developed, downscaling of climate model outputs offers additional tools to support local-scale impact assessments. Projects using this approach are underway in the Arctic and will provide additional insight into the reliability and utility of various downscaling methods.

Summary

The Arctic continues to warm. Since publication of the *Arctic Climate Impact Assessment* in 2005, several indicators show further and extensive climate change. Air temperatures are increasing in the Arctic. Sea ice has decreased sharply, reaching a record low in 2007. Surface waters in the Arctic Ocean are warming. Permafrost is warming and, at its margins, thawing. Plants are growing more rapidly, with trees and shrubs appearing farther north. Snow cover in the Northern Hemisphere is decreasing by 1-2% per year. Glaciers are shrinking and the Greenland Ice Cap is melting. Most of the significant outlet glaciers of the Greenland Ice Cap have accelerated, retreated, and thinned, leading to increased loss of ice from Greenland, especially since 2003.

Even if there is still considerable uncertainty regarding the magnitude of their effects, black

carbon, tropospheric ozone, and methane may contribute to global and Arctic warming to a degree comparable to the impacts of carbon dioxide. Black carbon and ozone, in particular, have a strong seasonal pattern that makes their impacts particularly important in the Arctic, especially during the spring melt. These climate forcings are relatively short-lived and have the potential for relatively rapid reductions in emissions and thus in atmospheric levels. There are various options for emissions reductions that can be taken in northern regions and globally.

The Arctic carbon cycle is an important factor in the global climate system. Considerable quantities of carbon and methane are stored in the Arctic. If released to the atmosphere, they could increase greenhouse gas concentrations and thus drive further climate change. At present, the Arctic appears to be a sink for carbon dioxide and a source for methane. Climate change is likely to result in more carbon dioxide being released to the air but also more being absorbed by growing plants on land and in the ocean. The balance between these two responses is not clear, but it appears unlikely that changes in the Arctic carbon cycle will have more than a modest influence on global climate in the next 50-100 years. There is, however, considerable uncertainty involved, especially over longer time periods.

Global climate models are limited in their ability to provide reliable, regional-scale projections of various climate parameters. Current and planned projects and programs aim to improve understanding of regional processes, the role of short lived climate forcings, and local impacts of climate change. Improved regional-scale models and projections will help improve evaluation of adaptive and mitigative actions, particularly concerning local impacts and reducing emissions of short lived climate forcings, which may be of comparable importance to carbon dioxide in driving temperature increases.