EMERGING CHALLENGES

Methane from the Arctic:

Global warming wildcard

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Warming Arctic temperatures could lead to the release of significant methane emissions from thawing permafrost and marine deposits. Sub-regional scale decreases in reflectivity result from loss of snow cover and advancing shrub and tree lines and lead to more warming, permafrost thaw, and methane release. Feedbacks from sub-regional processes produce more methane emissions that then feed into global scale warming trends. These new findings bring an added sense of urgency to advance climate and energy policy decisions.

ARCTIC CLIMATE FEEDBACKS

The Arctic, a key component of the global climate system, is warming at nearly twice the rate as the rest of the world. This warming trend, which is already affecting arctic ecosystems and the people who depend upon them, has been closely monitored over recent decades and is projected to continue throughout the 21st century (ACIA 2004, ACIA 2005). Accelerated warming in the Arctic results from the accumulated effects of 'positive feedback' mechanisms that operate there.

A positive feedback is a reaction to an initial stimulus that amplifies the effects of that stimulus. A negative feedback dampens the effects of the initial stimulus. In the Arctic, both positive and negative feedbacks to warming are at work, but the positive feedbacks dominate present conditions. Some feedbacks are widely known and well understood, while others have been recognized only recently. The rapid reduction in sea ice is one of several significant arctic climate feedbacks that have received a good deal of attention. Another relates to changes in ocean circulation stemming from an increase of freshwater entering the ocean from melting of both land-based ice and sea ice, as well as more precipitation and river runoff.

This chapter will briefly review the major feedbacks, with a focus on one potential feedback which could have very serious global consequences: the release of methane from thawing permafrost soils and from deposits of methane hydrates.

Although methane has a relatively short life-span in the atmosphere of about 10 years, it is a very powerful greenhouse gas with 25 times the warming potential of carbon dioxide (IPCC 2007). Recent findings about potential methane releases from thawing permafrost and hydrate deposits suggest serious cause for concern. Global methane emissions from all sources, both natural and human-induced, are calculated to be about 500-600 million metric tons per year. Recent estimates put current methane emissions from the world's soils at between 150 and 250 million metric

Warming trends are already affecting communities like Cape Dorset, Nunavit, Canada. Ice formation occurs about a month later and ice break up occurs about a month earlier than in the 1960s. This shortened sea ice travel season limits the community's accessibilty to neighbors and to desirable hunting destinantions.

Source: Goujon / Still Pictures

tons of methane per year. A quarter to a third of the total is emitted from the wet soils of the Arctic, making them one of the largest sources of methane emissions on Earth (IPCC 2007).

The consequences of significant increases in methane releases, especially the additional warming, would be felt around the world. Any additional warming will lead to additional ice melt—of glaciers, ice caps, and ice sheets—that will raise sea level around the globe.

METHANE FROM THAWING PERMAFROST

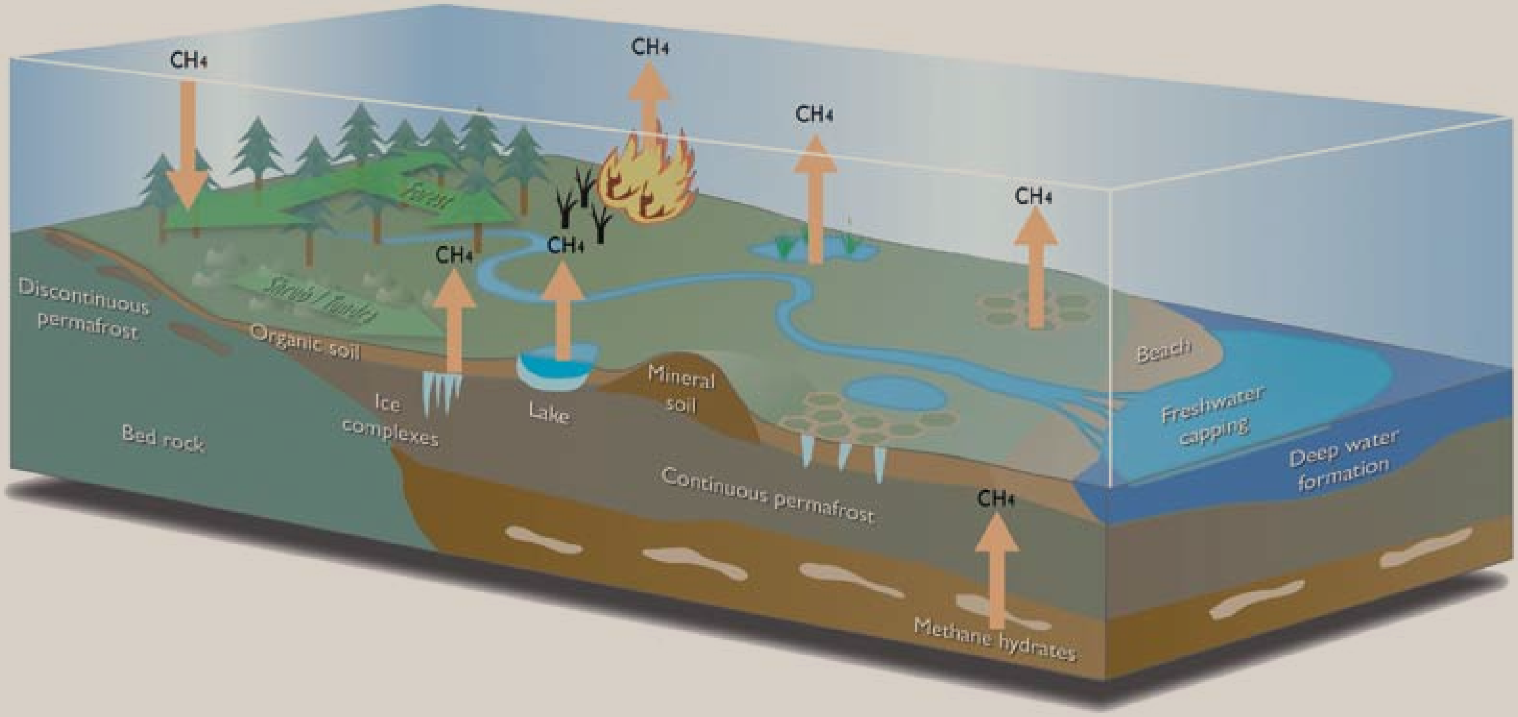
Soil microbes produce and consume methane. The thawing of permafrost in the Arctic creates low-oxygen (anaerobic) and water-logged soil conditions in which microorganisms that produce methane dominate (**Figure 1**). Most of the microbe activity that consumes methane takes place in oxygen-rich (aerobic) and well-drained soils outside of the northern high latitudes (IPCC 2007).

Current methane emissions from arctic soils and lakes

Modelled and measured estimates of methane emissions from northern high latitude land ecosystems in the late 20th century range from 31 to 106 million metric tons per year. This range of uncertainty has increased in recent years as new feedbacks have been recognized. Estimates of methane absorption are much lower, ranging from 0 to 15 million metric tons (Zhuang and others 2004). A recent process-modelling study has estimated that the annual net methane emission rate at the end of the 20th century for the region was 51 million metric tons. Net methane emissions from permafrost regions north of 45°N include 64 per cent from Russia, 11 per cent from Canada, and 7 per cent from Alaska (Zhuang and others 2004).

Recent research points to the potential importance of arctic lakes as methane sources (Walter and others 2006). Permafrost is ground that has remained frozen for two or more consecutive years. It underlies most arctic landscapes, varying from a few to several hundred metres thick. Permafrost promotes the formation and persistence of lakes, and in some Arctic regions as much as 20 to 30 per cent of the land area is covered by lakes. (Smith and others 2007, Riordan and others 2006). When permafrost thaws it creates thermokarst: a landscape of collapsed and subsiding ground with new or enlarged lakes, wetlands, and craters on the surface. Large expanses of modern boreal and subarctic regions are remnants of past thermokarst. A broad survey reported significant methane emissions from boreal, subarctic, and arctic lakes (Bastviken and others 2004). Few studies have attempted to estimate lake methane fluxes for the whole of the northern high latitudes, but a recent study, using data from Siberia and Alaska, estimated that arctic

Figure 1: Major Arctic methane sources



Methane (CH_4) comes from a variety of sources in the Arctic. These include emissions generated by microbes in thawing permafrost soils, from lakes and ponds, from fires, and from methane hydrates.
Sources: ACIA 2004 and ACIA 2005.

Hotspots, seen at the surface here as slushy circular areas, are created by methane bubbling up from a lake bottom in Northern Siberia.
Source: Katey Walter

lakes emit 15 to 35 million metric tons of methane per year (Walter and others 2007a).

Changes in future methane emissions from arctic soils and lakes

Business-as-usual climate scenarios for the 21st century estimate that the Arctic region's methane emissions, resulting from more permafrost thawing and rising soil temperatures, will range from 54 to 105 million metric tons of methane per year—the upper figure doubles the current level (Zhuang and others 2006). A coupled model of wetland and climate dynamics also projects that emissions from this region will double (Gedney and others 2004).

These scenarios do not consider the complex interactions among thermokarst dynamics, fires, and changing hydrology in wetlands and peatlands (Jorgenson and others 2007, Zimov and others 2006). Such interactions in thermokarst could lead to higher methane emissions than simulated. These estimates also do not include the potentially huge contribution from the thawing of decayed organic matter in thermokarst lakes (**Box 1**).

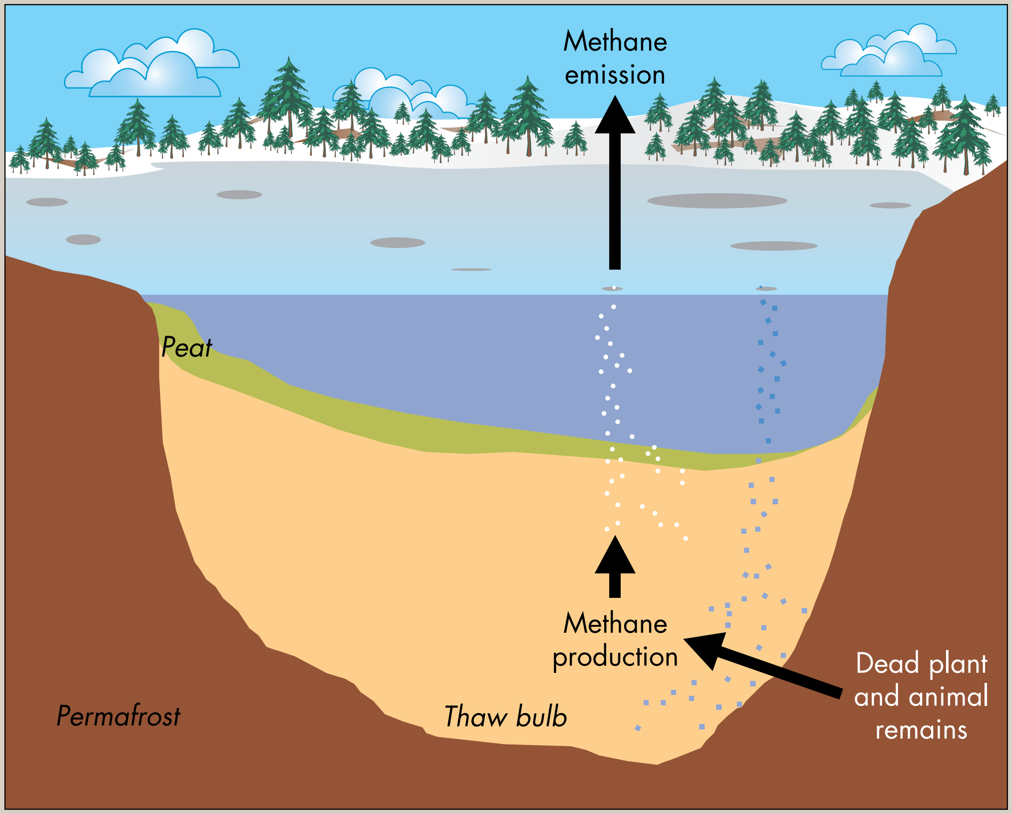
Dramatic increases in these emissions are likely to take place if permafrost thaws at an increasing pace and critical surface portions of soil and lake environments become warmer and wetter. There are at least three different mechanisms behind increased methane emissions:

Box 1: Methane emissions from arctic lakes associated with degradation of permafrost

A potentially very large arctic source of methane to the atmosphere is the decay of organic matter in the form of dead plant, animal, and microbial remains that have been frozen in shallow permafrost (1-25 metres below the surface) for tens of thousands of years. This important source of atmospheric methane is not currently considered in modelled projections of future warming.

The amount of carbon stored in the organic matter of arctic permafrost is staggering. It is estimated to be around 750 to 950 billion metric tons—equal to or larger than the nearly 800 billion metric tons of carbon currently in the atmosphere in the form of carbon dioxide (Zimov and others 2006, ACIA 2005, Smith and others 2004). This figure does not include carbon contained in deeper permafrost, in hydrates within or under the permafrost, or other non-permafrost soil carbon pools.

About 500 billion metric tons of carbon are now preserved in the high ice-content permafrost in northeast Siberia (Zimov and others 2006). If this territory warms as rapidly as projected under business-as-usual greenhouse gas emission scenarios, carbon compounds bubbling up from newly thawed bulbs in thermokarst lakes could become a powerful amplifying feedback to warming. One estimate is that an additional 50 billion metric tons of methane could be released to the atmosphere from Siberian thermokarst lakes alone, an amount that is ten times the current atmospheric methane burden (Walter and others 2007a). The expansion and formation of thaw lakes in northeast Siberia observed over the past few decades suggest that this feedback may already be happening (Walter and others 2006).



The figure shows a cross section of a thermokarst lake and methane bubbling dynamics.
Significant methane production and emission is associated with the initial thaw of permafrost, as organic matter from permafrost becomes available in lake bottom sediments to fuel methane-producing microbes. Methane produced in youger sediments at the top of a thaw bulb escapes broadly across lake surfaces at low bubbling rates. Methane produced at greater depths in older lake sediments, or in previously frozen soils that thawed beneath lakes, is emitted from thaw bulbs at lake bottoms through columns that bubble up to the surface. These point-sources and hotspots of bubbling have exceptionally high rates of emission. Thermokarst lakes form on time scales of decades to centuries and persist as long as several hundred to 10 000 years.
Source: Walter and others 2007a, Walter and others 2007c.

1. The thawed or active layer reaches deeper and the soils stay wet, producing anaerobic conditions that favor methane-producing microbes to break down organic matter and stored peat.
2. The expansion and warming of thermokarst lakes leads to increased breakdown of old organic matter as it thaws and becomes more available to methane-producing microbes.
3. When the thawing reaches layers where methane is trapped with frozen water, forming hydrate deposits, destabilization of pressure and temperature regimes could release huge amounts of methane from terrestrial and submarine permafrost areas.

Recent findings suggest that these changes are already occurring. Studies in Alaska, Canada, and northern Scandinavia have found wetter ground surface conditions in areas where the permafrost margin is receding (Walter and others 2006, Walter and others 2007a). This increases methane emissions over the landscape as a whole (Christensen and others 2004, Johansson and others 2006). There is also clear evidence that the number and area of thermokarst lakes in northern Siberia are increasing—as are their associated methane emission hotspots. These landscape changes have profound implications for the global atmospheric methane budget (Walter and others 2006, Walter and others 2007a).

METHANE FROM HYDRATES

An enormous amount of methane on Earth—storing more carbon than all the proven reserves of coal, oil, and gas—is frozen into an icy material known as methane clathrates or hydrates. Clathrate is a general term for a chemical compound in which molecules of one substance are physically enclosed within a cage-like structure formed by molecules of another kind. Hydrate is the specific term when the cage is made of frozen water molecules. Most of the hydrates that exist on Earth are filled with methane and they are dispersed at low concentrations and under pressure deep within sediments around the globe.

Methane hydrates become unstable as temperature increases or pressure decreases, and the methane escapes to the atmosphere where it functions as a powerful greenhouse gas. Gradually, methane reacts with atmospheric oxygen and converts into carbon dioxide and water. Carbon from methane hydrates will eventually accumulate in the atmosphere as carbon dioxide just as carbon from fossil fuels does. Stability calculations show that methane hydrates will become destabilized in response to warming of only a few degrees Celsius. Given the tremendous reservoir of carbon in methane hydrate deposits, any large-scale destabilization of methane hydrates could have enormous global consequences.

Ocean hydrates

Most methane hydrates are in sediments of the world's oceans, including those of the Arctic Ocean. These hydrate-bearing sediments are deeply buried in layered deposits up to several hundred metres below the sea-floor. The deposits are formed when organic carbon, produced by phytoplankton in the sunlit surface layer of the ocean, sinks to the sea-floor and may become buried along with plankton shells and terrestrial clays. Sediments continue to accumulate for centuries and millennia. Eventually, hundreds of metres below the sea-floor, microbes produce methane from the remains of plankton. If enough methane is produced, some of it gets trapped at high pressure into methane hydrates. In locations of very active methane generation, methane hydrate can migrate up toward the sea-floor and produce massive solid lenses of frozen gas hydrate.

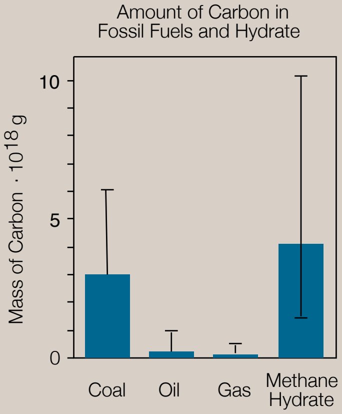
The ice worm *Hesiocaeca methanicola* was first discovered on this methane hydrate lens emerging from the sea-floor of the Gulf of Mexico (Fisher and others 2000).

Source: Ian R. MacDonald, Texas A&M University

Oceanic gas hydrate deposits hold an estimated 2 000 to 5 000 billion metric tons of carbon as methane, with some estimates ranging up to 10 000 billion metric tons (Buffett and Archer 2004, Milkov 2004). For comparison, coal, the most abundant fossil fuel, is estimated to hold about 5 000 billion metric tons of carbon (Rogner 1997) (**Figure 2**). Methane originating from sub-marine hydrate deposits can leave the sediment in three possible forms: dissolved, bubbles, and hydrate pieces. Dissolved methane is chemically unstable in the oxygen-containing water column of the ocean where it converts to carbon dioxide. Bubbles of methane are typically only able to rise a few hundred metres in an ocean column before they dissolve. Hydrate pieces float in water just like regular ice does, carrying methane to the atmosphere much more efficiently than in solution or as bubbles (Brewer and others 2002).

Currently, methane emissions from hydrates (including both ocean and permafrost sources) are estimated to be about 5 million metric tons per

Figure 2: Comparing amounts of carbon in methane hydrates and fossil fuels



Proven reserves of fossil fuels (solid bars) and potential unconventional resources, (thin lines), such as tar sands and oil shales. Estimates of methane in hydrate deposits are shown as a range (thin lines) and best estimate (bar).

Sources: Archer 2007, Rogner 1997.

year, with a possible range of 0.4 to 12.2 million metric tons (Wuebbles and Hayhoe 2002).

Gas hydrates associated with permafrost soils

Hydrates can be found in deposits associated with permafrost in the Arctic. However, because hydrate stability depends on conditions of relatively high pressure, they are not likely to persist in shallow permafrost. Sediment and soil permeability is another factor that can influence hydrate persistence. Sometimes freezing groundwater creates a sealed ice layer in the soil, which can raise the pressure in pore spaces in the rock or soil below (Dallimore and Collett 1995).

The total amount of methane hydrates in permafrost soils is not clear—estimates range from 7.5 to 400 billion metric tons of carbon (Gornitz and Fung 1994). The likelihood of sudden destabilization of these methane hydrates in response to climate change is also not clear.

Methane hydrates locked in sediments and soils may become exposed to the waters of the ocean along melting arctic coastlines. As the ice melts and soils thaw, the land surface collapses and more ice, soils, and sediments are exposed to ocean erosion. The northern coast of Siberia is particularly vulnerable to erosion and entire islands have disappeared in historical time (Romankevich 1984). Concentrations of dissolved methane in seas along that shelf were measured at 25 times the atmospheric concentration, suggesting the escape of methane hydrates as well as emissions of methane from thawing permafrost in the shallow marine environment and biological activity (Shakhova and others 2005).

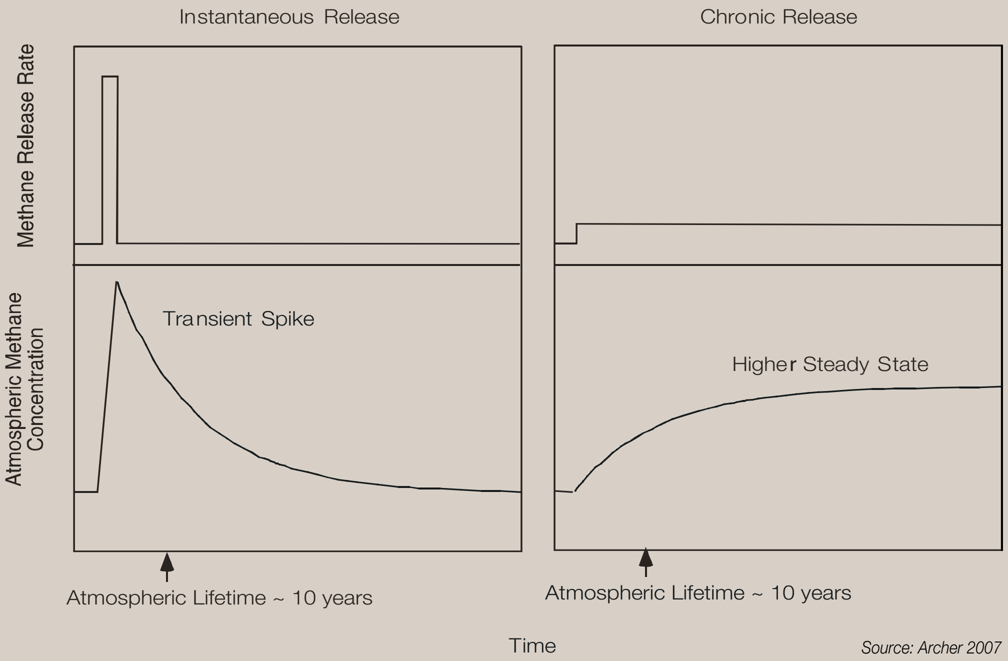
The future of methane hydrates

Methane hydrate research is opening up new avenues to scientists, including the possibility of extracting methane hydrates for energy purposes (**Box 2**).

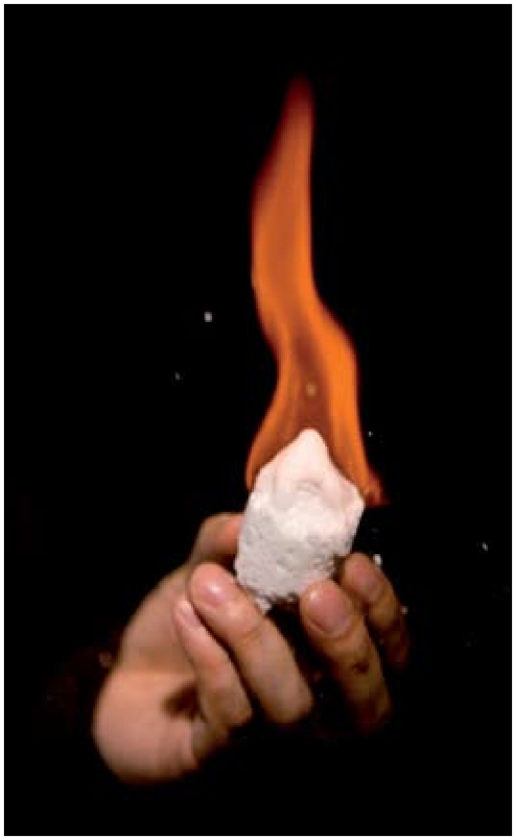
When considering the potential effect of methane hydrates on climate change, the difficult questions that scientists have not yet resolved include:

- how much methane hydrate exists
- how it might destabilize in response to ongoing warming, and
- how and at what rate the methane released by hydrate melting could reach the ocean or atmosphere.

Figure 3: How the methane release rate affects atmospheric methane concentrations



Source: Archer 2007



The icy material of methane hydrates looks like ice, but burns if ignited.
Source: National Research Council Canada

While methane is a powerful GHG, once it oxidizes its carbon element still affects the climate as carbon dioxide. The consequences of increased amounts of methane entering the atmosphere depend on whether it is released instantaneously or at a slow, chronic pace (**Figure 3**).

One scenario poses a sudden release over a short period of enough methane to significantly change proportions of atmospheric components. This would generate a spike in methane concentration, which would then decline. Currently, there are 5 billion metric tons of methane in the atmosphere. It would take another 50 billion metric tons of methane to double the warming effect we are already experiencing from the carbon dioxide build-up in the atmosphere. Some scientists believe that methane spikes have entered the atmosphere in the past but finding a credible mechanism that could release so much methane so fast remains a challenge (Archer 2007, Schiermeier 2003).

Box 2: Methane hydrates as a possible energy source?

Estimates of the total inventory of methane in hydrate deposits globally are comparable to or larger than the rest of the traditional fossil fuel deposits combined, raising the notion of extracting the hydrate methane as a source of fossil energy. Burning methane emits carbon dioxide, but compared to other fossil fuels substantially less of it is emitted for the energy produced.

Most of the methane hydrate deposits are probably not concentrated enough for economic extraction (Milkov and Sassen 2002). The most likely near-term targets for methane hydrate extraction are deposits associated with permafrost soils on land and in the shallow ocean. At least 50 wells were drilled in the Messoyakha field in Siberia (Krason 2000). An international consortium has drilled a series of wells in the Mallik field on Canada's Mackenzie delta (Chatti and others 2005, Kerr 2004). Porous and permeable hydrate-bearing marine sediments that are relatively accessible lie offshore of Japan and the Pacific Northwest of North America, and in the Gulf of Mexico. In other places such as the Blake Ridge off the coast of South Carolina in the United States, access to methane hydrates is limited by impermeable sediments and/or low concentrations, making economic extraction unlikely in the near term (Kvenvolden 1999).

Mining of methane hydrates has risks. There is a possibility that methane extraction could destabilize parts of the continental slope (Chatti and others 2005, Grauls 2001, Kvenvolden 1999). Some have considered replacing methane hydrates with carbon dioxide hydrates, thereby sequestering carbon dioxide and maintaining the stability of the continental slope in the process (Warzinski and Holder 1998).

The prognosis for methane hydrate mining is that it could perhaps supply about 10 per cent of our methane extraction around 10 years from now, similar to growth in coal-bed methane over the last 30 years (Grauls 2001, Kerr 2004). Methane hydrates could thus be a significant source of energy—but not as large as might be inferred from the estimates of total methane in the global hydrate reservoir.

Box 3: Major climate feedbacks operating in the Arctic

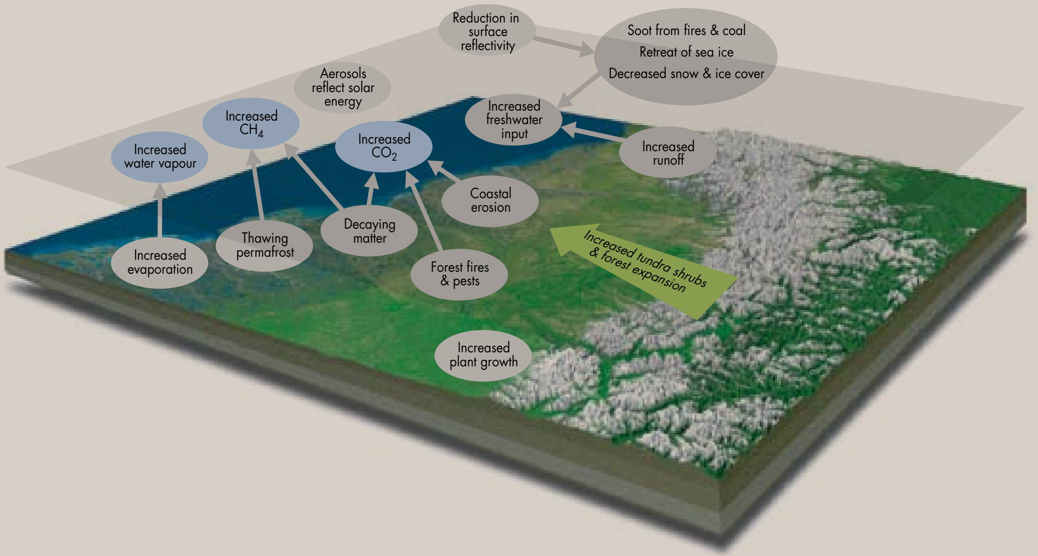
Major Arctic feedbacks that increase warming

- Warming leads to more evaporation and thus more water vapor—a key greenhouse gas—in the atmosphere.
- Warming melts snow and ice, reducing surface reflectivity, thus increasing absorption of solar heat. Increased tundra shrubs and soot from increasing wildfires and fossil fuel burning that darken snow and ice also reduce reflectivity.
- Warming leads to thawing permafrost, more rapid decomposition of soil organic matter, more frequent fire and insect disturbances, and increased coastal erosion followed by decomposition of the eroded material. All of these lead to more releases of the greenhouse gases methane (CH_4) and carbon dioxide (CO_2).

Major Arctic feedbacks that reduce warming

- Tiny particles (aerosols) put into the atmosphere from increasing fires can reflect solar energy away.
- Warming leads to increased plant growth, which takes up more carbon dioxide. Boreal forest ecosystems that migrate northward sequester even more carbon in vegetation and soils.
- As ice melts and precipitation and runoff increase, there is increased freshwater input to the oceans. This slows the thermohaline circulation and reduces ocean heat transport to the region.

Source: McGuire and others 2006.



Sources: ACIA 2004, ACIA 2005.

A more likely possibility for our future is a gradual increase in the continual rate of methane emission to the atmosphere from hydrate and thermokarst sources over a longer period. Human-induced methane sources, such as rice paddies, the fossil fuel industry, and livestock, have already doubled the methane concentration in the atmosphere since the 1800s. A source of about 50 billion metric tons of carbon released over 100 years would double atmospheric methane yet again. A methane flux this large from hydrates in the coming century is difficult to predict, but is well within what is possible.

CHANGES IN NATURE

Methane feedbacks operate within the context of a wider set of Arctic climate feedbacks (**Box 3**). Some of these climate feedbacks are already changing the natural environment and are associated with surface reflectivity changes and the release and uptake of other greenhouse gases besides methane.

Changes in reflectivity

Under climatic conditions that have prevailed for millennia, the surface of the Arctic is very bright because of the cover of snow, ice, and sparse vegetation that reflects much of the Sun's radiation back into space. Earlier snowmelt in spring and later snow cover onset in autumn substantially reduce reflectivity—from about 80 per cent of incoming short-wave radiation reflected away to only 20 per cent. This heats up the region in addition to the global average temperature increases that help melt the snow and ice in the first place (**Figures 4 and 5**).

In the Alaskan tundra, for example, from 1970 to 2000 the increase in atmospheric heating due to earlier snowmelt and the resulting decrease in reflectivity is estimated to be 10.5 watts per square metre (Chapin and others 2005). To put this estimate in context, the global average amount of solar energy that reaches the Earth's surface per second is about 168 watts per square metre. Across all Arctic lands, changes in the seasonality and duration of snow cover are estimated to have increased atmospheric heating by around 3 watts per square metre between 1970 and 2000 (Euskirchen and others 2007).

The Arctic snow cover is expected to continue to decrease in this century. One warming scenario that assumes business-as-usual increases in GHG emissions in the 21st century estimates that the annual number of snow cover days across the Arctic will decrease by about 40 days. Currently the arctic snow cover lasts for about 200 days every year. A change of this magnitude will likely bring an increase in Arctic atmospheric heating of more than 10 watts per square metre during the 21st century. This is about 2.5 times the warming expected from a doubling of atmospheric carbon dioxide concentrations (4.4 watts per square metre) (Houghton and others 2001).

Soot or black carbon settles as a surface deposit in the Arctic from increasingly frequent wildfires in the boreal forest and from coal and diesel fuel burned locally and in other regions. It falls on snow and ice and further reduces reflectivity (Stohl and others 2006, Flanner and others 2007). Fire frequency is increasing in boreal North America (Kasischke and Turetsky 2006) and elsewhere in the Arctic and the additional deposition of soot could further increase warming.

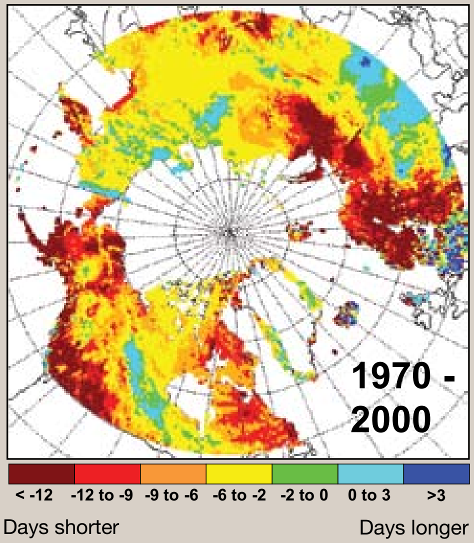
Shrub cover is also increasing. Experimental studies demonstrate that arctic summer warming of 1°C significantly increases the growth of existing shrubs within a decade (Arft and others 1999). In general, there appears to be increased shrub growth throughout much of the Arctic (Callaghan and others 2005) (**Figure 6**). This is best documented in arctic Alaska, where shrub cover has increased about 16 per cent since 1950 (Tape and others 2006). Although vegetation changes to date appear to have had minimal effects on atmospheric heating in arctic Alaska, complete conversion to shrub tundra has the potential to increase summer heating in the region by about 8.9 watts per square metre (Chapin and others 2005).

Trees are also advancing northward and upslope in the Arctic. Over the last 50 years, tree line advances have been documented in Russia, Canada, and Alaska (McGuire and others 2007). In mountainous areas of Scandinavia, the tree line has moved upslope over the last 50 years as temperatures have warmed (Callaghan and others 2004). If the tundra in northern Alaska converted completely to tree cover, local summertime heating would increase by around 26 watts per square metre (Chapin and others 2005).

Masking of the snow by increased shrub and tree cover in early spring and increased heat energy capture by increased shrub and tree cover in summer act as strong positive feedbacks to climate warming (Chapin and others 2005). Modelling of vegetation change in the Barents Region of the Arctic projects that by 2080 the changes could decrease reflectivity nearly 18 per cent in both summer and winter (Wolf and others in press).

All of these reflectivity-reducing feedbacks amplify warming and outweigh the negative feedbacks at work. One example of a negative feedback is the production of aerosols by wildfires—when soot remains airborne individual particles may reflect sunlight and result in some cooling. The small particles may also accelerate cloud formation at altitudes that could reflect

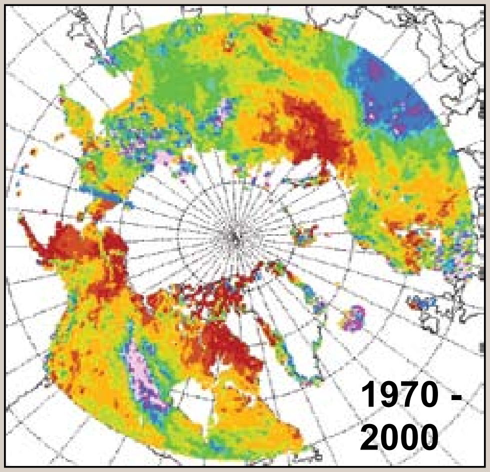
Figure 4: Change in the duration of snow covered ground, 1970-2000



Change in duration of snow-covered ground north of 50° N. The number of days in a year in which the ground is snow covered has decreased by an estimated average of 7.5 days from 1970 to 2000.

Source: Euskirchen and others 2007.

Figure 5: Change in atmospheric heating, 1970-2000



The estimated changes in atmospheric heating associated with changes in the duration of snow cover from 1970 to 2000. Across the Arctic as a whole, the overall reduction in the duration of snow-covered ground of around 7.5 days between 1970 and 2000 is estimated to have caused an increase in atmospheric heating of around 3.0 watts per square metre.

Source: Euskirchen and others 2007.

sunlight. But the potential cooling effects of aerosol soot are outweighed by the warming effect of soot deposited on the surface of the Earth.

The presence of calcareous soils and the varied landscape relief in the Northern boreal forest belt in Kuusamo, Finland provides for vegetation that is relatively rich in species.

Source: K. Salminen/ Still Pictures

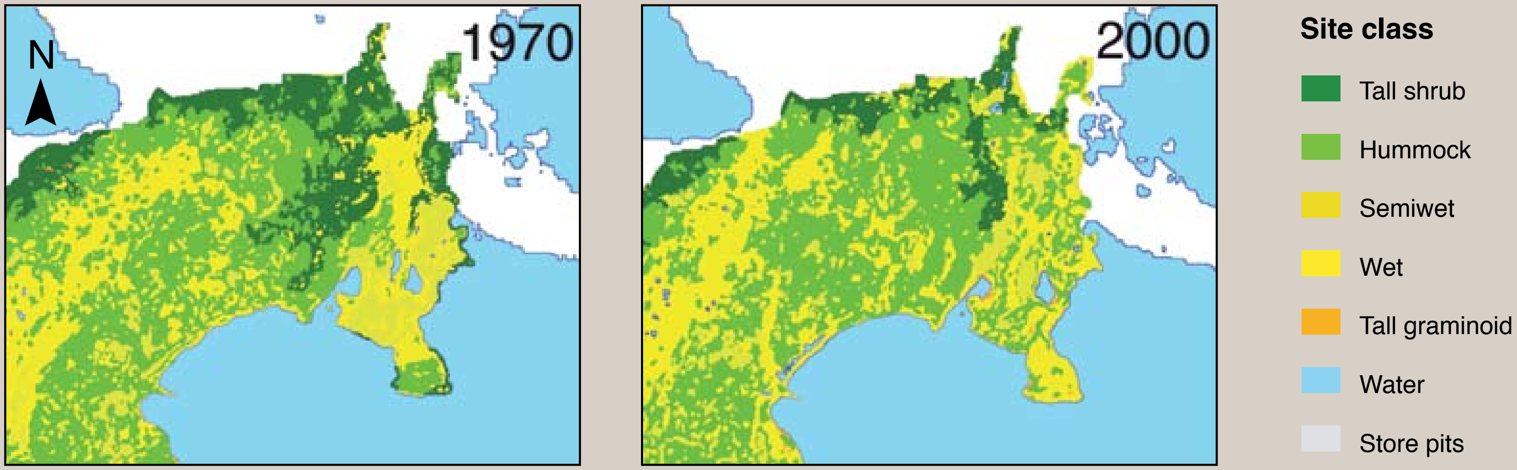
Carbon release and uptake

On the amplifying, positive feedback side, warming leads to increased carbon dioxide release by the decomposition of organic matter in soils, by more frequent fires, by insect disturbances that cause trees to die and decay in forests, and by increased coastal erosion and decay of the eroded material. On the damping-down, negative feedback side, warming also increases consumption of carbon dioxide by plant life on the land and in the sea, which helps to moderate carbon dioxide concentrations in the atmosphere. Because this carbon consumption has dominated for millennia in the Arctic, large amounts of carbon have accumulated in tundra and, to a greater degree, in boreal forest soils. As boreal forest ecosystems move northward, replacing tundra ecosystems, the forest soils could increase carbon storage in the Arctic substantially (Betts 2000, Callaghan and others 2005).

Analyses so far indicate that the warming effect will dominate. The warming caused by reductions in snow and increases in shrub and tree cover will have a stronger effect on the climate system than the cooling effect caused by increased carbon storage (Betts 2000, Chapin and others 2005, Euskirchen and others 2006, Euskirchen and others 2007).

Projected changes in snow and vegetation are also likely to have substantial effects on biodiversity and on northern indigenous peoples. Warming-induced increases in both shrub growth and wildfire reduce the abundance and diversity of lichens, an important winter food for the reindeer on which local people depend (Cornelissen and others 2001, Rupp and others 2006). Other species such as moose may thrive, signifying a broader change in the quantity and types of subsistence resources available to indigenous peoples, who are already faced with shrinking river and sea ice seasons that reduce hunters' access to resources. In Sami, Inuit, Nenets, and other northern cultures with strong traditional ties to the land and sea, these

Figure 6: Vegetation change in Stordalen mire, Sweden 1970-2000



The images show northward colonization by tall shrub species and substantial vegetation change between 1970 and 2000 following permafrost thaw and associated increase in methane flux. This detail is part of an extensive and continuously monitored research programme studying Stordalen mire, which is located about 150 kilometres north of the Arctic Circle in Sweden. The distribution of vegetation site classes have been distinguished through interpretation of colour Infrared aerial images.

Source: Malmer and others 2005

changes have profound nutritional and cultural consequences. As treelines and shrub cover move northward, new species and resources will follow. According to ecosystem research, the Arctic will experience both disappearing climates, with associated ecosystem decline, and novel climates with niches to be filled (see Global Overview). Some of the changes evident in the Arctic are also occurring in high mountain systems at every latitude. Melting ice, deposits of soot, and subsequent changes in surface reflectivity as well as thawing permafrost and encroaching vegetation are altering weather patterns far beyond the regions where so much climate change is underway (**Box 4**).

LOOKING AHEAD

Methane release due to thawing permafrost in the Arctic is a global warming wildcard. The balance of evidence suggests that Arctic feedbacks that amplify warming, globally and regionally, will dominate during the next 50 to 100 years (McGuire and others 2006) (**Box 5**).

As warming continues, these feedbacks will likely intensify. We may be approaching thresholds that are difficult to predict precisely, but crossing such thresholds could have serious global consequences (see Global Overview). This highlights the urgent need for policy responses to reduce future warming—to avoid crossing such thresholds (**Box 6**).

Our understanding of the interactions, relative importance, and projected net balance among the various feedbacks at work in the Arctic is far from complete. In light of these uncertainties and vulnerabilities, it is important that we improve our understanding of how changes in the Arctic will influence global climate. An important step will be to map the locations and to determine the quantities of methane hydrates, their possible responses to further climate change, and the routes and rates by which they could enter the ocean or atmosphere.

It is already clear that the global climate is vulnerable to Arctic feedbacks and that the consequences of those feedbacks could be disastrous. The only way to reduce the magnitude of these consequences is to dramatically reduce and stabilze concentrations of GHGs in the atmosphere. In addition to long-term reductions in emissions of carbon dioxide and the other long-lived greenhouse gases, a near-term focus on reducing emissions of methane and soot, which have shorter atmospheric lifetimes, could be of particular value. The potential consequences of large amounts of methane entering the atmosphere, from thawing permafrost or destabilized ocean hydrates, would lead to abrupt changes in the climate that would likely be irreversible. We must not cross that threshold. Reversing current human-induced warming will help us avoid such outcomes entirely (Hansen and others 2007).

Box 4: Melting glaciers and thawing permafrost beyond the Arctic: the Qinghai-Tibet Plateau

Source: Xinhua News Agency

Source: Jicheng He/Chinese Academy of Sciences

Thawing permafrost is affecting high altitude environments as well as those at high latitudes. The Qinghai-Tibet Plateau contains about 5.94 million hectares of glaciers with 5 590 km^3 of ice. It is also underlain by 150 million hectares of permafrost. The permafrost ice volume is more than double that of the glaciers. This Plateau is the source of the Changjiang (Yangtze) and Huanghe (Yellow) Rivers, which are at the heart of agriculture, forestry, fisheries, and other aspects of downstream economic activities and environments. These rivers also carry large amounts of soil to their lower basins.

The persistent increase of ice melting on the Qinghai-Tibet Plateau due to continued warming will inevitably affect the economy and environment in China and surrounding regions. During the last half century, global warming has accelerated melting on the Plateau. Its glaciers decreased by seven per cent, leading to a 5.5 per cent increase in runoff in northwest China. However, the high temperatures that caused the glaciers to melt also caused increased evaporation across northwest China and triggered more droughts, expanded desertification through soil erosion, and increased sand and dust storms. Northern China has suffered from severe dust storms which have been attributed to desertification in the northwest. For example, on April 17, 2006, a single dust storm dumped about 336 000 metric tons of dust on Beijing, causing hazardous air quality in the capital (Yao and others 2007).

Changes in snow and vegetation are likely to have substantial effects on biodiversity. Here, reindeer dig for lichens after a recent heavy snowfall.

Source: Inger Marie Gaup Eira/www.ealat.org

Box 5: Summary of key messages

- Arctic methane emissions are projected to at least double in this century. This doubling is due to an increase in the area of wetlands created by thawing and continued warming of these wet organic soils. These factors will lead to increased global warming.
- Thawing permafrost in northern Siberia alone is projected to release an amount of methane ten times the current atmospheric methane burden by bubbling out of thermokarst lakes.
- Methane hydrates represent a future source of long-term ongoing methane emissions.
- Reductions in arctic snow cover have reduced surface reflectivity, causing nearly as much local heating as the carbon dioxide forcing over the past 30 years. The effects of this feedback loop are expected to increase with future warming.
- If shrubs expand to cover all the arctic tundra, this could increase local summer heating by twice as much as the current carbon dioxide forcing.
- Arctic climate feedbacks have global implications, because they produce significant contributions to global atmospheric carbon concentrations. The increase in GHGs causes climate change that brings rising sea levels, intensified storms, and threatened ecosystems on a global scale.

Box 6: Policy considerations

Investments in climate and energy research

There is a critical need to substantially increase research investments for understanding the processes of climate change, assessing the likely impacts on people and places, and expanding the adaptive capabilities of human and natural systems. This discussion of Arctic and global feedbacks emphasizes the urgency of meeting the huge technological challenge we face: how to manage the transition to low-carbon energy systems. This transition includes increasing energy efficiency, reducing carbon intensity, and promoting biological and geological sequestration of the carbon dioxide produced by fossil fuels. Investments directed towards methane-related research and development should provide a better understanding of methane hydrates and their potential as a cleaner fuel source, as well as integrate methane cycles into global process models, including those that model climate changes.

Knowledge Partnerships

It is essential that decision makers have a thorough knowledge base upon which to craft policies and fully understand the consequences of different pathways, including the risks of unintended consequences that cross dangerous thresholds. As new energy options are considered, a complete analysis of the risks and benefits should be undertaken, considering both local and global effects. Knowledge about climate change and its impact on nature and people, as well as technological and policy solutions, should be shared broadly through a range of facilitating partnerships to communicate the urgency of the challenge and the wealth of opportunities. Specifically, better understanding of methane cycles and how they affect, and are affected by, climate change feedbacks will depend on the ability of knowledge partnerships to bridge the gap between science and policy.

Global political responses

Addressing the emerging challenges presented by the warming of the Arctic and resulting in increasing methane emissions will require global responses in the near and foreseeable future. Recent analyses suggest that the transition to a more efficient and low-carbon energy system could provide substantial economic opportunities and have a minimal or very modest effect on gross domestic product at the global scale (IPCC 2007, Stern 2006). The ability to integrate economic incentives into global climate policy responses will play a key role in engaging and energizing the best in our institutions of government, industry, and society and across the emerging economies, the developing world, and industrialized nations.

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