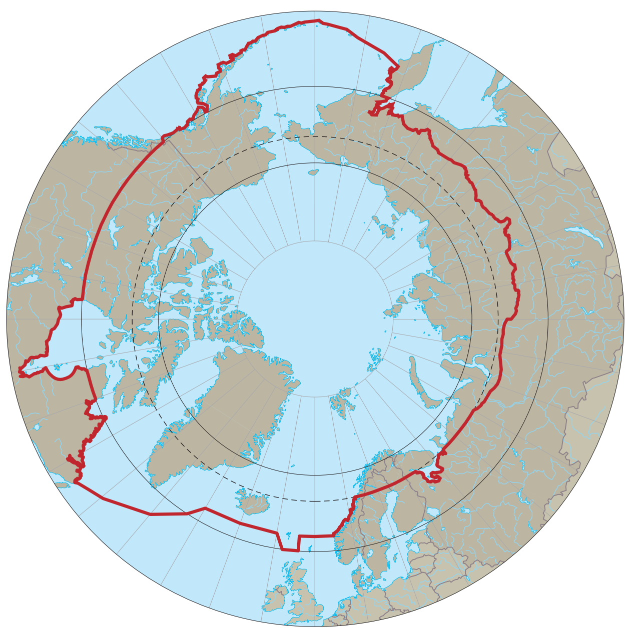
MANITOBA ENVIROTHON

THINKTREES
MANITOBA FORESTRY ASSOCIATION

# Climate Change in the North

2018 Manitoba Envirothon Study Guide

*The Arctic is still a cold place, but it is warming faster than any other region on Earth. Over the past 50 years, the Arctic's temperature has risen by more than twice the global average. Increasing concentrations of greenhouse gases in the atmosphere are the primary underlying cause: the heat trapped by greenhouse gases triggers a cascade of feedbacks that collectively amplify Arctic warming.*



***The Arctic***

*as defined by*
*the Arctic Monitoring and Assessment Programme*

# Preface

The Manitoba Envirothon is an annual hands-on environmental education competition for high school students, designed to encourage team work, problem-solving skills, and public speaking skills while fostering an appreciation for current environmental issues. Manitoba Envirothon combines the exhilaration of team competition, the challenge of learning about environmental issues, and the experience of using this knowledge in hands-on activities. This approach to environmental education helps students develop skills necessary to address environmental issues, such as team work, problem-solving, critical thinking, and public debate. Please see our website for more information: https://www.thinktrees.org/programs/envirothon

The editors of this study guide (made for high school students in Manitoba, Canada) were responsible for amalgamating highlights from these materials and some specific editing but were not responsible and do not take credit for any of the writing or primary research. Materials were amalgamated in this form for ease of studying for Manitoba Envirothon participants. See below for author information.

*Words in **bold** are defined in *Key Definitions* section

*Resources taken from:*

U.S. Global Change Research Program (www.globalchange.gov)

Furgal, C., and Prowse, T.D. (2008): Northern Canada; in From Impacts to Adaptation: Canada in a Changing Climate 2007, edited by D.S. Lemmen, F.J. Warren, J. Lacroix and E. Bush; Government of Canada, Ottawa, ON, p. 57-118.

AMAP, 2017. Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2017. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. xiv + 269 pp.

# Note to Teachers and Students

The study of climate change is a very dynamic field, full of statistics and predictions based on the most recent model and study. As such, writing and teaching about the subject often becomes very technical and involves describing temperature approximations, precipitation estimates, predictions, date ranges etc. However, at the end of the day, it is most important to understand the general trends, scientific principles, and issues surrounding these changes, rather than focus on the exact numbers. As you are using this guide to prepare for Envirothon, please keep in mind that the general concepts are our focus and goal, not memorizing exact figures, tables, and diagrams.

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# Climate Changes

Throughout its history, Earth's **climate** has varied, reflecting the complex interactions and dependencies of the solar, oceanic, terrestrial, atmospheric, and living components that make up planet Earth's systems. For at least the last million years, our world has experienced cycles of warming and cooling that take approximately 100,000 years to complete. Over the course of each cycle, global average temperatures have fallen and then risen again by about 5°C, each time taking Earth into an ice age and then warming it again. This cycle is believed to be associated with regular changes in Earth's orbit that alter the intensity of solar energy the planet receives. Earth's climate has also been influenced on very long timescales by changes in ocean circulation that result from plate tectonic movements. Earth's climate has changed abruptly at times, sometimes as a result of slower natural processes such as shifts in ocean circulation, sometimes due to sudden events such as massive volcanic eruptions. Species and ecosystems have either adapted to these past climate variations or perished.

While global climate has been relatively stable over the last 10,000 years—the span of human civilization— regional variations in climate patterns have influenced human history in profound ways, playing an integral role in whether societies thrived or failed. We now know that the opposite is also true: human activities— burning fossil fuels and deforesting large areas of land, for instance—have had a profound influence on Earth's climate. In its 2007 Fourth assessment, the Intergovernmental Panel on climate change (IPCC) stated that it had

> *"very high confidence that the global average net effect of human activities since 1750 has been one of warming."*

The IPCC attributes humanity's global warming influence primarily to the increase in three key heat-trapping gases in the atmosphere: carbon dioxide, methane, and nitrous oxide. The U.S. climate change Science Program published findings in agreement with the IPCC report, stating that

> *"studies to detect climate change and attribute its causes using patterns of observed temperature change in space and time show clear evidence of human influences on the climate system (due to changes in greenhouse gases, aerosols, and stratospheric ozone)."* (Karl et al. 2006)

To protect fragile ecosystems and to build sustainable communities that are resilient to climate change— including extreme **weather** and climate events—a climate-literate citizenry is essential. This climate science literacy guide identifies the essential principles and fundamental concepts that individuals and communities should understand about Earth's climate system. Such understanding improves our ability to make decisions about activities that increase vulnerability to the impacts of climate change and to take precautionary steps in our lives and livelihoods that would reduce those vulnerabilities.

## *Informed Climate Decisions*

In the coming decades, scientists expect climate change to have an increasing impact on human and natural systems. In a warmer world, accessibility to food, water, raw materials, and energy are likely to change. Human health, biodiversity, economic stability, and national security are also expected to be affected by climate change. Climate model projections suggest that negative effects of climate change will significantly outweigh positive ones. The nation's ability to prepare for and adapt to new conditions may be exceeded as the rate of climate change increases.

Reducing our vulnerability to these impacts depends not only upon our ability to understand climate science and the implications of climate change, but also upon our ability to integrate and use that knowledge effectively. Changes in our economy and infrastructure as well as individual attitudes, societal values, and government policies will be required to alter the current trajectory of climate's impact on human lives. The resolve of individuals, communities, and countries to identify and implement effective management strategies for critical institutional and natural resources will be necessary to ensure the stability of both human and natural systems as temperatures rise.

## *Guiding principles for informed climate decisions*

A. Climate information can be used to reduce vulnerabilities or enhance the resilience of communities and ecosystems affected by climate change. Continuing to improve scientific understanding of the climate system and the quality of reports to policy and decision- makers is crucial.

B. Reducing human vulnerability to the impacts of climate change depends not only upon our ability to understand climate science, but also upon our ability to integrate that knowledge into human society. Decisions that involve Earth's climate must be made with an understanding of the complex inter-connections among the physical and biological components of the Earth system as well as the consequences of such decisions on social, economic, and cultural systems.

C. The impacts of climate change may affect the security of nations. Reduced availability of water, food, and land can lead to competition and conflict among humans, potentially resulting in large groups of climate refugees.

D. Humans may be able to mitigate climate change or lessen its severity by reducing greenhouse gas concentrations through processes that move carbon out of the atmosphere or reduce greenhouse gas emissions.

E. A combination of strategies is needed to reduce greenhouse gas emissions. The most immediate strategy is conservation of oil, gas, and coal, which we rely on as fuels for most of our transportation, heating, cooling, agriculture, and electricity. Short-term strategies involve switching from carbon-intensive to renewable energy sources, which also requires building new infrastructure for alternative energy sources. Long-term strategies involve innovative research and a fundamental change in the way humans use energy.

F. Humans can adapt to climate change by reducing their vulnerability to its impacts. Actions such as moving to higher ground to avoid rising sea levels, planting new crops that will thrive under new climate conditions, or using new building technologies represent adaptation strategies. Adaptation often requires financial investment in new or enhanced research, technology, and infrastructure.

G. Actions taken by individuals, communities, states, and countries all influence climate. Practices and policies followed in homes, schools, businesses, and governments can affect climate. Climate-related decisions made by one generation can provide opportunities as well as limit the range of possibilities open to the next generation. Steps toward reducing the impact of climate change may influence the present generation by providing other benefits such as improved public health infrastructure and sustainable built environments.

# Climate Science

The Sun is the primary source of energy for earth's climate system:

A. Sunlight reaching the Earth can heat the land, ocean, and atmosphere. Some of that sunlight is reflected back to space by the surface, clouds, or ice. Much of the sunlight that reaches Earth is absorbed and warms the planet.

B. When Earth emits the same amount of energy as it absorbs, its energy budget is in balance, and its average temperature remains stable.

C. The tilt of Earth's axis relative to its orbit around the Sun results in predictable changes in the duration of daylight and the amount of sunlight received at any latitude throughout a year. These changes cause the annual cycle of seasons and associated temperature changes.

D. Gradual changes in Earth's rotation and orbit around the Sun change the intensity of sunlight received in our planet's polar and equatorial regions. For at least the last 1 million years, these changes occurred in 100,000-year cycles that produced ice ages and the shorter warm periods between them

E. A significant increase or decrease in the Sun's energy output would cause Earth to warm or cool. Satellite measurements taken over the past 30 years show that the Sun's energy output has changed only slightly and in both directions. These changes in the Sun's energy are thought to be too small to be the cause of the recent warming observed on Earth.

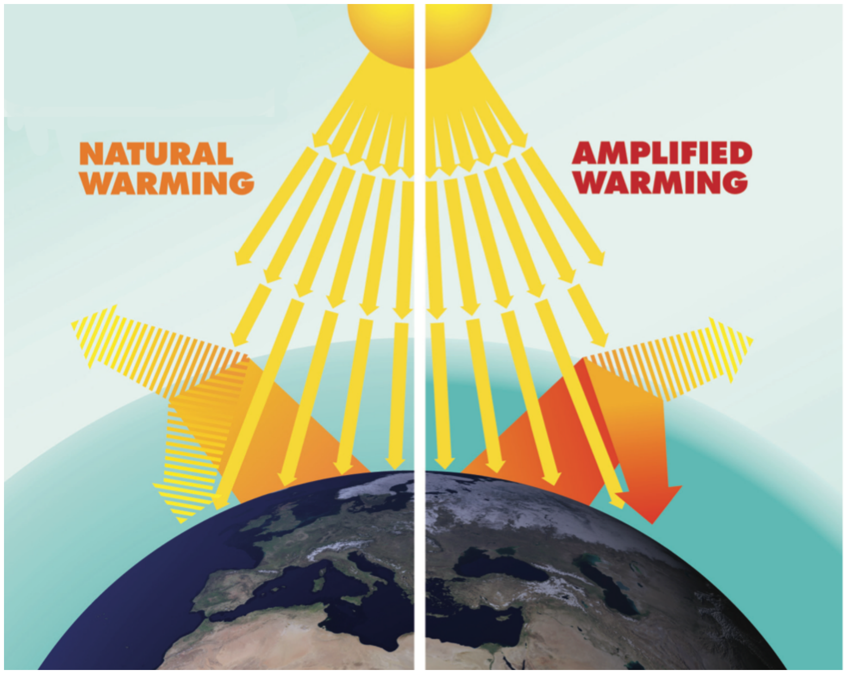



**Figure 1.** The greenhouse effect is a natural phenomenon whereby heat-trapping gases in the atmosphere, primarily water vapor, keep the Earth's surface warm. Human activities, primarily burning fossil fuels and changing land cover patterns, are increasing the concentrations of some of these gases, amplifying the natural greenhouse effect. ***Source:*** *Modified from the Koshland 2004*

## *Complex Climate Interactions*

Climate is regulated by complex interactions among components of the earth systems. Solar power drives Earth's climate. Energy from the sun heats the surface, warms the atmosphere, and powers the ocean currents.

A. Earth's climate is influenced by interactions involving the sun, ocean, atmosphere, clouds, ice, land, and life. Climate varies by region as a result of local differences in these interactions.

B. Covering 70% of Earth's surface, the ocean exerts a major control on climate by dominating Earth's energy and water cycles. It has the capacity to absorb large amounts of solar energy. Heat and water vapor are redistributed globally through density-driven ocean currents and atmospheric circulation. Changes in ocean circulation caused by tectonic movements or large influxes of fresh water from melting polar ice can lead to significant and even abrupt changes in climate, both locally and on global scales.

C. The amount of solar energy absorbed or radiated by Earth is modulated by the atmosphere and depends on its composition. Greenhouse gases—such as water vapor, carbon dioxide, and methane—occur naturally in small amounts and absorb and release heat energy more efficiently than abundant atmospheric gases like nitrogen and oxygen. Small increases in carbon dioxide concentration have a large effect on the climate system.

D. The abundance of greenhouse gases in the atmosphere is controlled by biogeochemical cycles that continually move these components between their ocean, land, life, and atmosphere reservoirs. The abundance of carbon in the atmosphere is reduced through seafloor accumulation of marine sediments and accumulation of plant biomass and is increased through deforestation and the burning of fossil fuels as well as through other processes.

E. Airborne particulates, called "aerosols," have a complex effect on Earth's energy balance: they can cause both cooling, by reflecting incoming sunlight back out to space, and warming, by absorbing and releasing heat energy in the atmosphere. Small solid and liquid particles can be lofted into the atmosphere through a variety of natural and man-made processes, including volcanic eruptions, sea spray, forest fires, and emissions generated through human activities.

F. The interconnectedness of Earth's systems means that a significant change in any one component of the climate system can influence the equilibrium of the entire Earth system. Positive feedback loops can amplify these effects and trigger abrupt changes in the climate system. These complex interactions may result in climate change that is more rapid and on a larger scale than projected by current climate models.

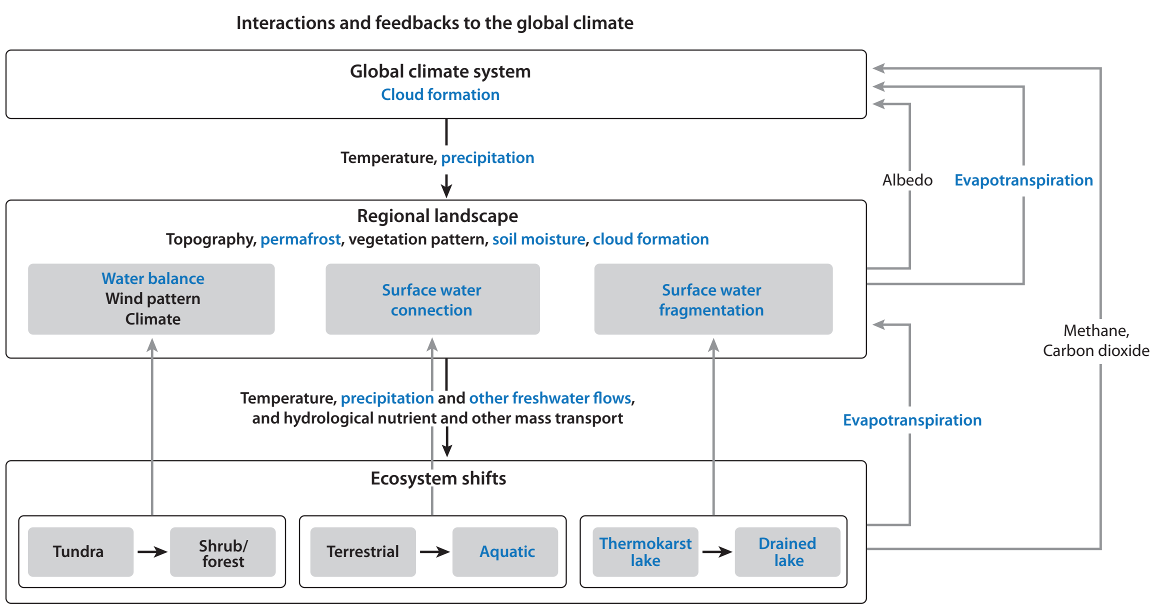



**Figure 2.** Interactions and feedbacks from three general types of ecosystem (from AMAP 2017, Wrona et al., 2016 – adapted from Karlsson et al., 2011)

# Northern Regional Overview

## *Physical Geography*

Northern Canada includes five major physiographic regions: Canadian Shield, Interior Plains, Arctic Lowlands, Cordillera, and Innuitian Region (see Figure 3).

## *Climate*

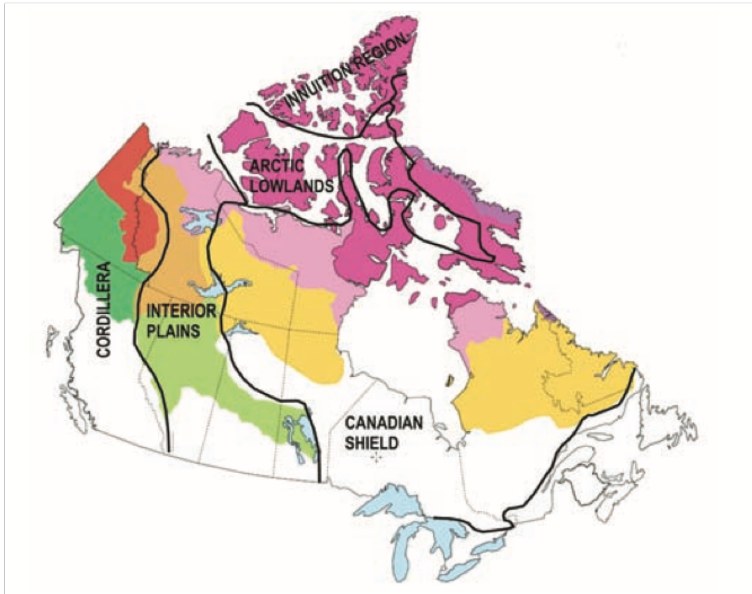
Northern Canada is characterized by long cold winters interrupted by short cool summers. Precipitation is light and concentrated in the warmer months. Mean annual temperatures (1971–2000) range from approximately –1 to –5°C in more southerly regions of the Canadian Arctic to near –18°C in the islands of the high Arctic. On a seasonal basis, average winter temperatures range from around –37°C in the north to –18°C in the south, and summer values from +6 to +16°C . Within these averages, there exists a high degree of variability on intraseasonal, interannual and interdecadal scales.

Northern Canada receives relatively low amounts of precipitation, particularly at very high latitudes. Annual values typically range from 100 to 200 mm over the islands of the high Arctic to nearly 450 mm in the southern Northwest Territories.

## *Permafrost*

The term '**permafrost**' refers to earth materials that remain below 0°C for two consecutive summers. The permafrost region covers about half of the Canadian landmass. In more northerly areas, permafrost is continuous and may be several hundred metres thick. Southward, its distribution becomes discontinuous and patchy, and it is only a few metres thick at the southern fringe of the permafrost region. Subsea permafrost is also found offshore in parts of the Canadian Arctic.

The presence of permafrost and associated ground ice strongly influence the properties and performance of earth materials, landscape processes and surface and subsurface hydrology, and also control much land and property development. Permafrost restricts infiltration of water and has led to the formation of extensive wetlands and peatlands in areas of low relief. Differential thawing of ice-rich permafrost results in hummocky or thermokarst topography. Runoff response in permafrost regions is controlled by the depth of the seasonal thaw (active) layer, which may exist for as little as 2 months.




| Ecozone | Landforms | Climate | Vegetation | Wildlife |
|---|---|---|---|---|
| **Arctic Cordillera** | Massive icefields and glaciers cap the rugged mountains | Very cold and arid | Largely absent due to permanent ice and snow | Polar bear, walrus, seals, narwhal, whales |
| **Northern Arctic** | Lowland plains with glacial moraines in the West, and uplands in the East | Very dry and cold | Dominated by herbs and lichen | Caribou, muskox, wolf, arctic hare, lemmings |
| **Southern Arctic** | Broadly rolling upland and lowland plains | Long, cold winters, and short cold summers | Dwarf shrubs that decrease in size in the North | Muskox, wolf, arctic fox, grizzly and polar bear, caribou |
| **Taiga Plains** | Broad lowlands and plateaus, incised by major rivers | Semi-arid and cold | Dwarf birch, Labrador tea, willows and mosses | Moose, woodland caribou, wolf, black bear, marten |
| **Taiga Shield** | Rolling terrain with uplands, wetlands and innumerable lakes | Subarctic continental climate, with low precipitation | Open forests and arctic tundra | Caribou, moose, wolf, snowshoe hare, black and grizzly bears |
| **Taiga Cordillera** | Steep, mountainous topography with sharp ridges and narrow valleys | Dry, cold winters and short, cool summers | Shrubs, mosses, lichens, dwarf birches, willows | Dall's sheep, caribou, lynx, wolverine |
| **Boreal Plains** | Level to gently rolling plain | Moist climate with cold winters and warm moderate summers | Spruce, tamarack, jack pine, white birch, balsam, poplar | Woodland caribou, mule deer, coyote, boreal owl |
| **Boreal Cordillera** | Mountain ranges with high peaks and extensive plateaus | Long, cold, dry winters and short, warm summers | Spruce, alpine fir, trembling aspen, white birch | Woodland caribou, Dall's sheep, mountain goat, marten, ptarmigan |

**Figure 3.** Physiographic regions (from Fulton, 1989) and ecoregions of the Canadian North (Furgal et al., 2003). ***Please note, students are only responsible for Taiga Shield row***.

### *Water*

Eighteen per cent of Canada's fresh water is found north of latitude 60°N, primarily in lakes (e.g. Great Bear and Great Slave lakes) on the mainland Canadian Shield of the Northwest Territories and Nunavut. This percentage does not include the extensive glacierized areas that total in excess of 150 000 $km^2$ on the islands of the Arctic Archipelago and 15 000 $km^2$ on the territorial mainland. Twenty per cent of Canada's wetland area is found in the Arctic. Runoff in the North is strongly influenced by snowmelt and/or glacier **ablation**.

Freshwater ice seasonally covers all lakes and rivers in the Northern Canada, with mean thickness in excess of 2 m on lakes at the highest latitudes. Duration of river-ice coverage is less than that of lake ice because rivers freeze up later in the year and are first to break up in the spring. Complete clearance of lake ice does not always occur in the far North, and multi-year ice develops on some lakes because of the brevity of the melt season. Multi-year ice accretions can also be found in the extreme North, where groundwater flow has contributed to the development of exceedingly thick surface ice.

Northern rivers are a major source of fresh water to the Arctic Ocean and contribute to the **thermohaline** circulation of the world's oceans, a regulator of global climate. The dominant hydrological system in the North is the Mackenzie River, the largest river basin in Canada (1 805 200 $km^2$). The Yukon River drains approximately three-quarters of the Yukon as it flows northwest into Alaska.

### *Marine Environment*

Canada's northern seas consist of the Arctic Ocean, Beaufort Sea, Hudson Bay, Foxe Basin, Baffin Bay and various channels and straits between the islands of the Arctic Archipelago. The most striking characteristic of these waters is the seasonal to multi-year cover of sea ice, often several metres thick. Permanent pack ice occurs in the central Arctic Ocean. Open water develops in the late summer off the west coast of Banks Island and in the Beaufort Sea. Farther south, Hudson Bay freezes by the end of December and begins to clear in July. Overall, the distribution and thickness of sea ice are extremely variable. Of ecological importance are open-water areas during the winter, called polynas, that occur in the Beaufort Sea, Arctic Archipelago and northern Baffin Bay.

The Arctic Ocean is connected to the Atlantic Ocean via the Greenland and Norwegian seas, as well as by numerous channels through the Arctic Archipelago to Baffin Bay and the Labrador Sea. A dominant influence on the circulation of the Arctic Ocean and pack-ice cover is the Beaufort Gyre, which results in clockwise circulation and ice movement in the Canada Basin of the Arctic Ocean. Apart from landfast ice within archipelagos and along coastlines, the sea ice is in constant motion. The movement of the marine waters and presence of extensive ice packs exert a strong influence on the climate of Canada's northern landmass.

### *The Arctic's Role in the Global Climate System*

Compared with mid-latitudes and the tropics, the Arctic receives relatively little energy from the Sun. Because most of the Arctic's surface is covered in snow and ice, much of the energy that it does receive is reflected back to space. These factors account for the Arctic's cold climate.

The Arctic acts as a global refrigerator by drawing warm ocean water from the south, cooling it, and ultimately sinking it toward the ocean bottom. Surface water moves in to replace the sinking water, creating ocean currents. The movement of warmer ocean waters to the north has a major influence on climate; it accounts for northern Europe's relatively mild climate compared with that of Canadian provinces at the same latitude, for example, and it keeps the tropics cooler than they would be otherwise.

Meltwater from Arctic glaciers, ice caps, and the Greenland ice sheet also influences climate by flooding the ocean with freshwater, affecting ocean circulation and weather patterns. The Arctic is both a source and sink for greenhouse gases. Changes in the quantities of greenhouse gases such as carbon dioxide and methane stored or released in the Arctic can have a long-term impact on global climate.

### *Demographics*

A little more than 100 000 people live in Northern Canada. Nearly two-thirds of northern communities are located along coastlines. The majority of Arctic communities (inland and coastal) have less than 500 residents, and these small communities together represent only 11% of the total northern population. Only the three territorial capitals, Whitehorse, Yellowknife and Iqaluit, have populations exceeding 5000. Although Whitehorse (population 23 511 in 2005) accounts for approximately 73% of the total population of the Yukon, more than two-thirds of people in Nunavut live in communities of less than 1000 people.

The region has experienced significant demographic, social, economic and political change in recent decades, with maximum growth associated with an increase in the non-Aboriginal population, related primarily to resource development and the increase in public administration. Most growth since the establishment of communities has occurred in the three main urban centers. Over the next 25 years, greatest growth is projected in the Northwest Territories, partly as a result of industrial development associated with the Mackenzie Valley pipeline project and new mining developments.

The average age of northern residents is younger than for Canada as a whole, and more than 50% of residents in Nunavut are less than 15 years old. Projections for the next 25 years indicate that the population in Northern Canada will remain young, but have a growing proportion of people over the age of 65, increasing dependency ratios across the territories.

Just over half of northern residents are Aboriginal and represent diverse cultural and language groups, from the fourteen Yukon First Nations in the west to the Inuit of Nunavut in the east, many of whom have been in these regions for thousands of years. Non-Aboriginal residents account for 15 and 78% of the total population in Nunavut and the Yukon, respectively. The majority of small communities are predominantly Aboriginal in composition and are places where various aspects of traditional ways are still strong components of daily life.

### *Health Status*

The health status of northern Canadians is lower than the national average, as measured by a number of health indicators. All territories report lower life expectancy and higher infant mortality rates than the national averages, and these disparities are particularly pronounced in Nunavut. The health status of Aboriginal northerners is, for many indicators, significantly below that of non-Aboriginal northern residents and the national average. Higher rates of mortality from suicide, lung cancer, drowning and unintentional injuries (i.e. accidents) associated with motor vehicle accidents occur in the North relative to the rest of the country. Accidental deaths and injuries are likely associated, in part, with the increased exposure associated with the amount of time spent 'on the land' and the high level of dependence on various modes of transport for hunting, fishing and collection of other resources, which are a strong part of livelihoods and life in the North.

### *Socioeconomic Status*

The economies of many northern communities are a mix of traditional land-based renewable resource–subsistence activities and formal wage-earning activities. Estimates of Nunavut's land-based economy are between $40 and 60 million per year, with an estimated $30 million attributed to all food-oriented economic activity.

However, the true value of such activities is difficult to measure, as they are significant contributions to the social fabric of communities and provide more than monetary benefits. The traditional economy is similarly important in other northern regions. For example, more than 70% of northern Aboriginal adults reported harvesting natural resources via hunting and fishing and, of those, more than 96% did so for subsistence purposes.

Food insecurity in Canada is highest in the three territories, where there are significantly higher numbers of female single parent households and the cost of a standard list of grocery items can be up to three times higher than in southern Canada. In communities, not accessible by road (e.g. Nunavut, Nunavik and Nunatisavut and some smaller regions and communities in the Northwest Territories and Yukon), access to market food items is reliant upon shipment via air or sea, which significantly increases the price. Data from 2001 show that 68% of households in Nunavut, 49% of those in the Northwest Territories and 30% of those in the Yukon had at least one occasion in the previous year when they did not have the financial resources for sufficient food.

Despite the physical, economic and administrative challenges to health for some residents in the North, the deterioration of cultural ties to land-based and subsistence activities among Aboriginal people is the most serious cause of decline in well-being within circumpolar regions. The loss of connection to the land through changes in ways of life, loss of language and dominance of non-Aboriginal education systems are impacting health and well-being in various and long-lasting ways.

## Climatic Conditions, Past and Future

Climate varies over space and time through both natural and man-made processes.

A. Climate is determined by the long-term pattern of temperature and precipitation averages and extremes at a location. Climate descriptions can refer to areas that are local, regional, or global in extent. Climate can be described for different time intervals, such as decades, years, seasons, months, or specific dates of the year.

B. *Climate is not the same thing as weather*. Weather is the minute-by-minute variable condition of the atmosphere on a local scale. Climate is a conceptual description of an area's average weather conditions and the extent to which those conditions vary over long time intervals.

C. Climate change is a significant and persistent change in an area's average climate conditions or their extremes. Seasonal variations and multi-year cycles (for example, the El Niño Southern Oscillation) that produce warm, cool, wet, or dry periods across different regions are a natural part of climate variability. They do not represent climate change.

D. Scientific observations indicate that global climate has changed in the past, is changing now, and will change in the future. The magnitude and direction of this change is not the same at all locations on Earth.

E. Based on evidence from tree rings, other natural records, and scientific observations made around the world, Earth's average temperature is now warmer than it has been for at least the past 1,300 years. Average temperatures have increased markedly in the past 50 years, especially in the North Polar Region.

F. Natural processes driving Earth's long-term climate variability do not explain the rapid climate change observed in recent decades. The only explanation that is consistent with all available evidence is that human impacts are playing an increasing role in climate change. Future changes in climate may be rapid compared to historical changes.

G. Natural processes that remove carbon dioxide from the atmosphere operate slowly when compared to the processes that are now adding it to the atmosphere. Thus, carbon dioxide introduced into the atmosphere today may remain there for a century or more. Other greenhouse gases, including some created by humans, may remain in the atmosphere for thousands of years.

**Figure 4.** Muir Glacier, 1891 compared to 2005, taken from the same location. (Mid-1890s picture by L.V. Winter and P.E. Pond. 2005 picture by Bruce F. Molnia, USGS)

The high natural climate variability of the Arctic, together with the relatively sparse observational data sets, make it difficult to distinguish with confidence a climate change signal in the trends observed in the instrumental period of record. As few stations have data prior to 1950, estimates of trends and variability are limited to the second half of the twentieth century. For the period 1950 to 1998, there is a west to east gradient in mean annual temperature trends, with significant warming of 1.5°C to 2.0°C in the western Arctic and significant cooling (–1.0°C to –1.5°C) in the extreme northeast. During more recent periods, all regions show warming. Trends were strongest in winter and spring. Annual and winter temperature anomalies and annual precipitation departures over four northern regions from 1948 to 2005 show greatest warming in the Yukon and Mackenzie District (2.2°C and 2.0°C, respectively

Annual precipitation totals (1948–2005) increased throughout all of northern Canada, with the largest increases over the more northerly Arctic Tundra (+25%) and Arctic Mountain (+16%) regions. The increase in high Arctic regions is evident during all seasons, with strongest trends in fall, winter and spring. The magnitude of heavy precipitation events increased during the period of record and there has been a marked decadal increase in heavy snowfall events in northern Canada.

The observed trends and variability in temperature and precipitation over northern Canada are consistent with those for the entire Arctic. Throughout the circumpolar Arctic annual air temperatures during the twentieth century increased by 0.09°C per decade.

Climate of the last 400 years has been characterized by warming and related changes over most of the Arctic, including retreat of glaciers, reduction in sea-ice extent, **permafrost** melting, and alteration of terrestrial and aquatic ecosystems. During the past approximately 150 years, however, it is evident that the rate and nature of change are unprecedented since the abrupt warming at the onset of the current interglacial period more than 10 000 years ago. This rapid acceleration in temperature increase over the Arctic is projected to continue throughout the twenty-first century.

## Implications of Changing Climate for the Arctic Environment

The Arctic is still a cold place, but it is warming faster than any other region on Earth. Over the past 50 years, the Arctic's temperature has risen by more than twice the global average. Increasing concentrations of greenhouse gases in the atmosphere are the primary underlying cause: the heat trapped by greenhouse gases triggers a cascade of feedbacks that collectively amplify Arctic warming.

As a result, the Arctic of today is different in many respects from the Arctic of the past century, or even the Arctic of 20 years ago. Many of the changes underway are due to a simple fact: ice, snow, and frozen ground—the components of the Arctic **cryosphere**—are sensitive to heat. As the cryosphere changes, so do the Arctic's physical, chemical, and biological systems, with complex consequences within and beyond the region.

Since 2011, evidence for the Arctic's evolution toward a new state has grown stronger. Additional years of data show continued or accelerating trends in record warm temperatures, changes in sea ice and snow, melting of glaciers and ice sheets, freshening and warming of the Arctic Ocean, thawing of permafrost, and widespread ecological changes.

Beyond the trends, new data also show stronger evidence for fundamental shifts in some elements of the cryosphere, the ocean, and ecosystems. Sea ice in the Arctic is entering a new regime in which vast areas of ocean that used to be covered by ice throughout the year are now seasonally ice-free and dominated by younger, thinner ice. The composition of many boreal forests is changing: coniferous trees are increasingly being replaced by deciduous species normally found farther south.

Together, these findings portray a system whose component parts are changing at different speeds, affecting the Arctic's role as a regulator of global temperature and its influence on Northern Hemisphere weather, its contribution to sea-level rise, the livelihoods of those who live and work in the Arctic, and the habitats of Arctic species. Today's Arctic is a new environment, evolving rapidly and in unexpected ways.

*The impacts of Arctic changes reach beyond the Arctic.* In addition to the Arctic's role in global sea-level rise and greenhouse gas emissions, the changes underway appear to be affecting weather patterns in lower latitudes, even influencing Southeast Asian monsoons.

## *Temperatures and Weather*

*Arctic temperatures are rising faster than the global average*. The Arctic was warmer from 2011 to 2015 than at any time since instrumental records began in around 1900, and has been warming more than twice as rapidly as the world as a whole for the past 50 years. January 2016 in the Arctic was 5°C warmer than the 1981–2010 average for the region, a full 2°C higher than the previous record set in 2008, and monthly mean

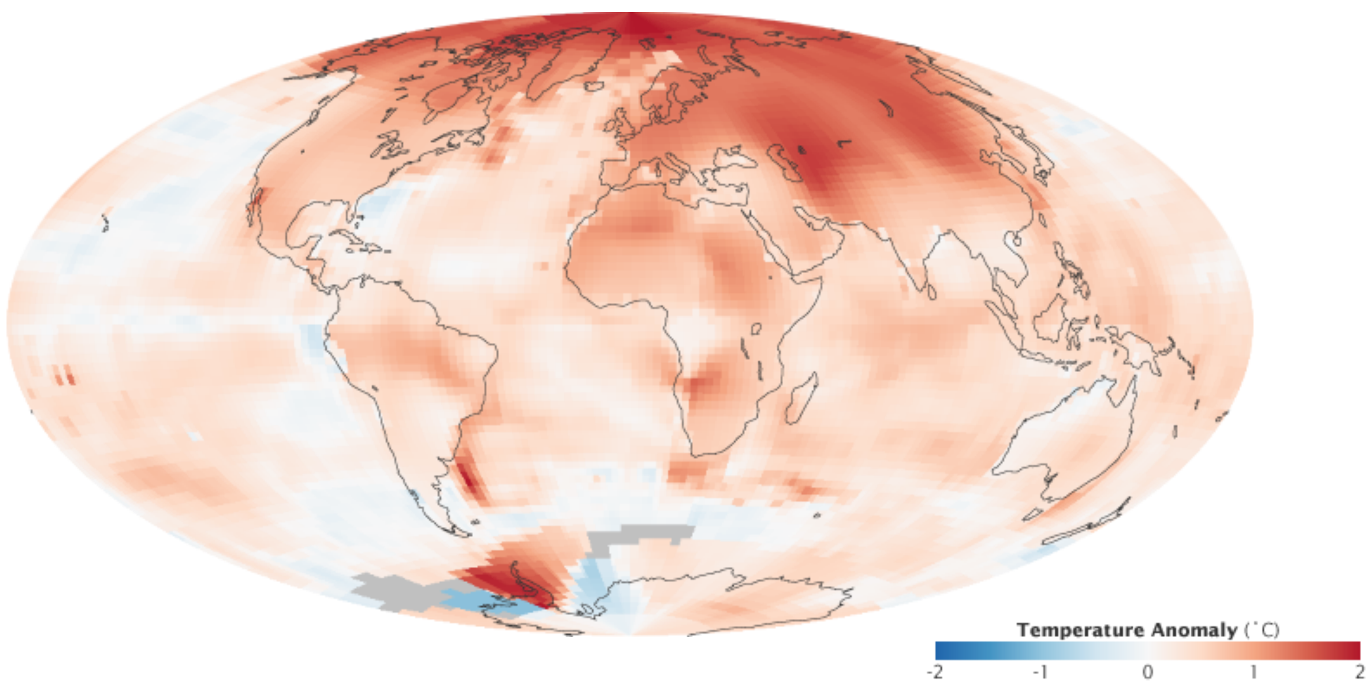



**Figure 5**. The map above shows global temperature anomalies for 2000 to 2009. It does not depict absolute temperature, but rather how much warmer or colder a region is compared to the norm for that region from 1951 to 1980. Global temperatures from 2000–2009 were on average about 0.6°C higher than they were from 1951–1980. The Arctic, however, was about 2°C warmer (NASA)

temperatures in October through December 2016 were 6°C higher than average for these months. Sea temperatures are also increasing, both near the surface and in deeper water.

Even several years of cold weather due to natural variations are unlikely to affect the long-term trend, and efforts to reduce greenhouse gas emissions will not affect projected temperatures until the latter half of this century. The warming climate will increase the amount of freshwater in the Arctic, with important implications for people, industries, ecosystems, and infrastructure.

*The frequency of some extreme events is changing*. Recent observations include a widespread decline in periods of extreme cold during both winter and summer, and increases in extreme warm periods in some areas, such as northern Alaska and northeastern Russia in autumn and spring.

## Sea Ice

Historically, sea-ice areal coverage varies generally from 5 to 6 million $km^2$ at the end of the summer to 14 million $km^2$ at the end of the winter. Sea-ice thickness increases along the path of sea-ice drift and convergence from west to east.

The decline in sea ice continues, with variation from year to year. Sea ice thickness in the central Arctic Ocean declined by 65% over the period 1975–2012. Sea ice extent has varied widely in recent years, but continues a long-term downward trend. A record low minimum sea ice extent occurred in 2012 and a record low maximum sea ice extent occurred in 2016.

Older ice that has survived multiple summers is rapidly disappearing; most sea ice in the Arctic is now 'first year' ice that grows in the autumn and

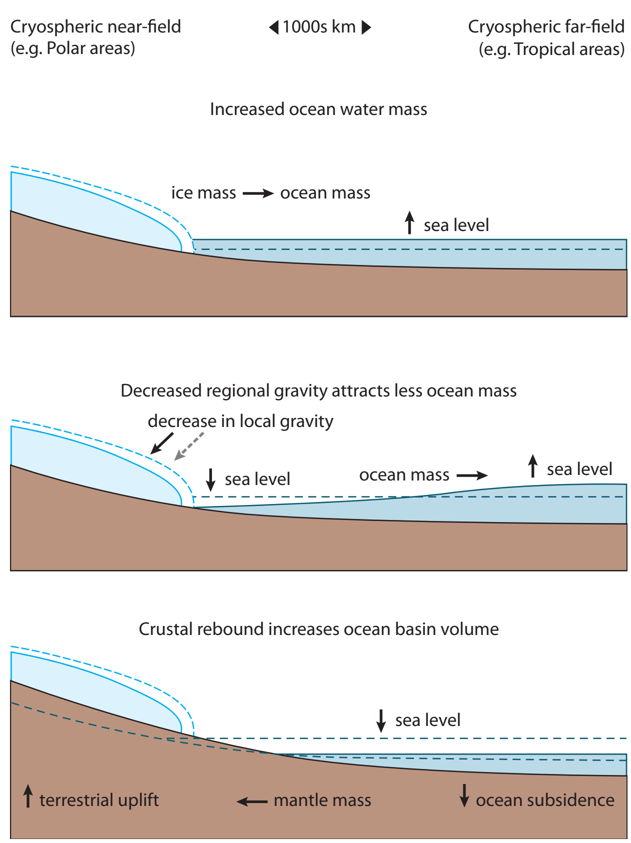



**Figure 6.** Schematic overview of cryospheric processes that influence absolute and relative sea level.

winter but melts during the spring and summer.

Except for the coldest northern regions of the Arctic Ocean, the average number of days with sea ice cover in the Arctic declined at a rate of 10–20 days per decade over the period 1979–2013, with some areas seeing much larger declines. Warm winds during the autumn of 2016 substantially delayed the formation of sea ice.

Sea ice is becoming more mobile as its extent and thickness decrease, increasing ice-related hazards. More open water occurs in all months of the year compared with observations reported in 2011.

*The Arctic Ocean may be ice-free sooner than expected.* The Arctic is expected to be largely free of sea ice in late summer within the next few decades, possibly as early as the 2030s, although natural variability and other factors make it impossible to make precise predictions. The ice that appears in winter will be thinner, more salty, less rigid, and more mobile than today's sea ice. More open water is expected in winter, affecting temperature and the exchange of moisture between the atmosphere and ocean, leading to more extreme weather locally and at lower latitudes. Sea ice is currently thinning and shrinking more rapidly than projected by most models.

## *Snow Cover*

In the Arctic regions, snow can account for up to 80% of annual precipitation. Snow insulates the ground, affecting the ground thermal regime and permafrost distribution. Snow also influences surface radiation balances and water budgets, and

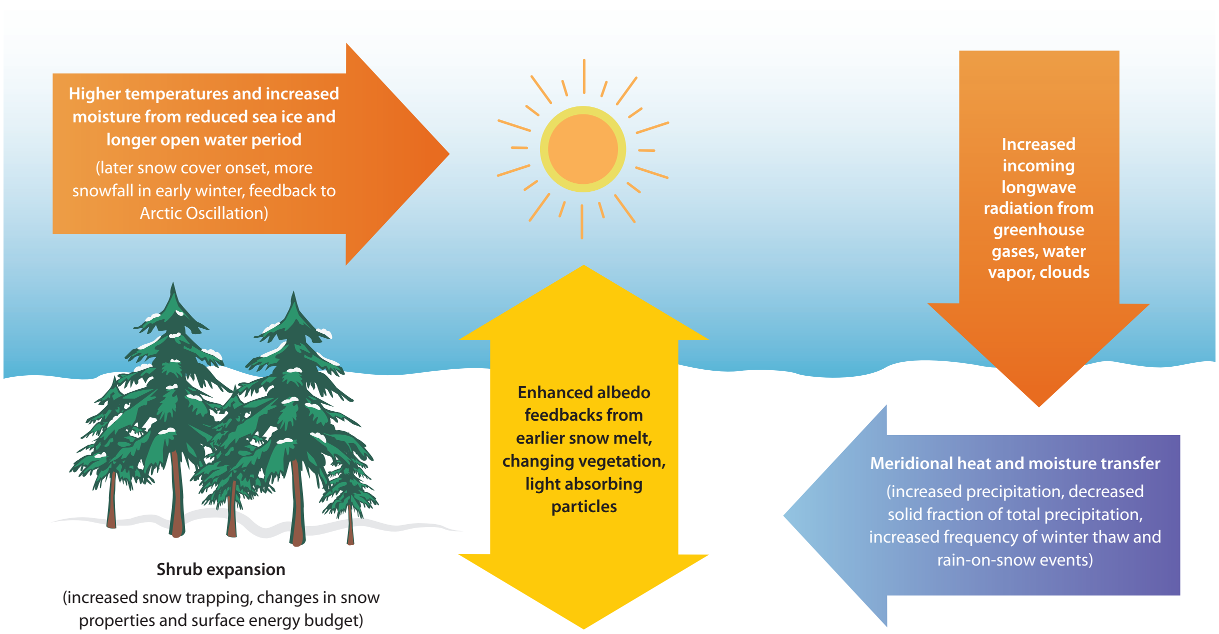



**Figure 7.** Schematic illustration of some of the important drivers influencing Arctic snow cover (AMAP 2017)

affects the habitat of terrestrial and aquatic biota.

The area and duration of snow cover are decreasing. Snow cover has continued to decline in the Arctic, with its annual duration decreasing by 2–4 days per decade. In recent years, June snow area in the North American and Eurasian Arctic has typically been about 50% below values observed before 2000.

### *Glaciers and Ice Sheets*

Canada has major glaciers and ice caps in the high Arctic and Yukon. In general, glaciers and ice caps across the Arctic (apart from the Greenland Ice Sheet) show a retreat in glacier fronts and volume decreases since about 1920, although there are large regional variations. The mass balance for all ice caps in the Canadian Arctic Archipelago over a five-year period at the end of the last century is estimated to be –25 km3/a of ice, which corresponds to a global sea-level rise of 0.064 mm/a. Although this is significant, more pronounced **ablation** has been recorded for the Yukon-Alaska glacier network, where accelerated melting of 1.5 ± 0.5 mm/a has contributed almost 9% of the observed global sea-level rise during the past 50 years, and possibly as much as 3.2 mm/a during the past decade or so. Glacier ablation also affects the magnitude and timing of river flows and drainage patterns.

*The melting of land-based ice will contribute significantly to sea-level rise.* If increases in greenhouse gas concentrations continue at current rates, the melting of Arctic land-based ice would contribute an estimated 25 centimeters to sea-level rise between 2006 and 2100. Many of the smallest glaciers across the Arctic would disappear entirely by mid-century.

### *Permafrost*

Active layer and permafrost thermal-monitoring activities during the last two to three decades indicate that warming of permafrost has occurred in many regions of the Canadian permafrost zone and that summer thaw penetration has increased. The magnitude of permafrost warming has varied both regionally and temporally, with generally greater warming occurring in the western Arctic and later warming occurring in the eastern and high Arctic. The response of the active layer to extreme warm conditions is consistent with that observed for other components of the cryosphere.

Approximately half of the area underlain by permafrost in Canada contains permafrost warmer than –2°C that could ultimately disappear under projected climate warming. Near-surface permafrost in the High Arctic and other very cold areas has warmed by more than 0.5°C since 2007–2009, and the layer of the ground that thaws in summer has deepened in most areas where permafrost is monitored. Where permafrost is thicker and colder, thickening of the active layer and warming and thinning of permafrost will likely occur.

The area of near-surface permafrost in the Northern Hemisphere is projected to decline by 20% relative to today's area by 2040, and could be reduced by as much as two-thirds by 2080 under a scenario of high greenhouse gas emissions. Impacts will vary widely at regional and local scales, but local effects are difficult to project given the lack of fine-scale detail in models.

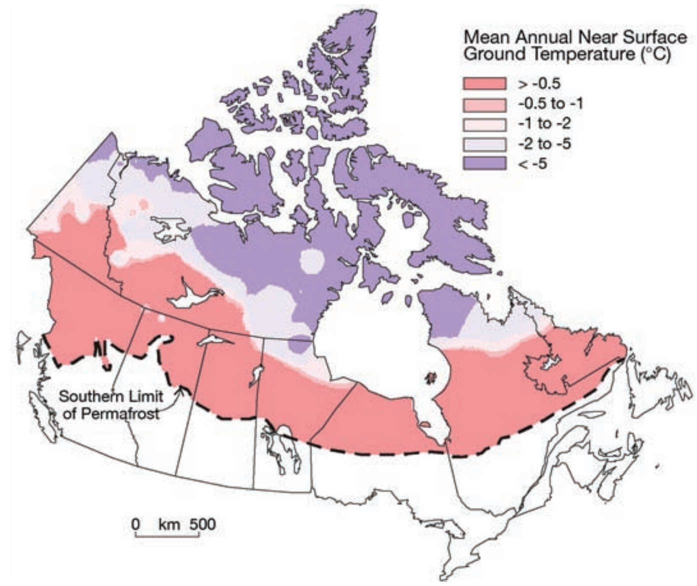


**Figure 8.** Variation in mean annual near surface ground temperature for the Canadian permafrost zone (Smith and Burgess, 2004)

Thawing of permafrost has the potential to release large pools of carbon, which can act as feedback to the climate system. New estimates indicate that Arctic soils hold about 50% of the world's soil carbon. While thawing permafrost is expected to contribute significantly to future greenhouse gas emissions, the amount released over the past 60 years has been relatively small.

Frozen ground plays an important role in northern hydrology through its influence on infiltration, runoff and groundwater storage and flow. Active-layer thickening and permafrost degradation in response to climate warming can lead to increased infiltration, greater groundwater storage, lower spring runoff and increase in base flow. As a result, groundwater will play a greater role in future streamflow, with implications for surface-water quality. As ground ice thaws, differential settlement and ponding may occur, leading to changes in drainage and the distribution of surface water. Thawing of ice-rich permafrost may also cause some lakes and wetlands to drain, leading to loss of fish and wildlife habitat.

## Soil and Land Use

**Figure 9.** Canadian System of Soil Classification, 1998

*Cryosolic Soil Order - Permafrost and Peatlands*

Soil Order: Cryosolic soils are soils whose formation is affected by **permafrost** within the soil control section (1-2 meters). This order is commonly known as permafrost.

Cryoturbation (cryo: freezing, turbation: mixing) is the mixing of the soil layers in response to repeated freeze-thaw cycles. This can redistribute organic carbon from the surface into lower layers of the soil profile. The most common being mixing from frost heave. In areas of permafrost, freezing can occur from top and bottom of the soil layers.

Soils of the Cryosolic order occupy much of the northern third of Canada (Arctic, Subarctic and Boreal regions) where permafrost exists close to the surface of both mineral and organic deposits. Cryosolic soils predominate north of the tree line, are common in the subarctic forest area in fine-textured soils, and extend into the boreal forest in some organic materials and into some alpine areas of mountainous regions. Cryoturbation of these soils is common and may be indicated by patterned ground features such as sorted and nonsorted nets,


**Figure 10.** Map of Canada showing the extent of the boreal, subarctic, and cordillera regions. Outlines of the cordillera and subarctic regions follow that defined for ecoclimactic provinces (Ecoregions Working Group, 1989). The extent of the boreal region on the figure is confined to high boreal ecoclimactic regions where Cryosols are known to occur.

**Figure 11.** Example of cryoturbation effect on frozen soil profile (Agriculture Canada)

*Permafrost is largely defined by temperature. This controls the organic pool, rate of release of carbon to the atmosphere.*

Cryosolic soils are formed in either mineral or organic materials that have permafrost either within 1 m of the surface or within 2 m if the pedon has been strongly cryoturbated laterally within the active layer, as indicated by disrupted, mixed, or broken horizons. They have a mean annual temperature ≤0°C. Differentiation of Cryosolic soils from soils of other orders involves either determining or estimating the depth to permafrost.

Canada contains significant permafrost, but a much larger extent is found in Northern Russia. There is permafrost in the Antarctic, but the carbon content is low, unlike the frozen peatlands of the Arctic regions.

Permafrost temperature, thickness and geographic continuity are controlled to a large extent by the surface energy balance, so vary widely with latitude. Thickness typically ranges from 350 to 650 meters, and over double that in some areas of northern Siberia. In the southern Boreal Region where it is discontinuous, it could be less than a meter. In the discontinuous zone, it is largely controlled by local factors such as topography, hydrology, vegetation, snow cover, and subsurface materials.

The subsurface ground layer that thaws during summer and refreezes completely in winter is known as the active layer. This could be a few centimeters to more than 2 meters.

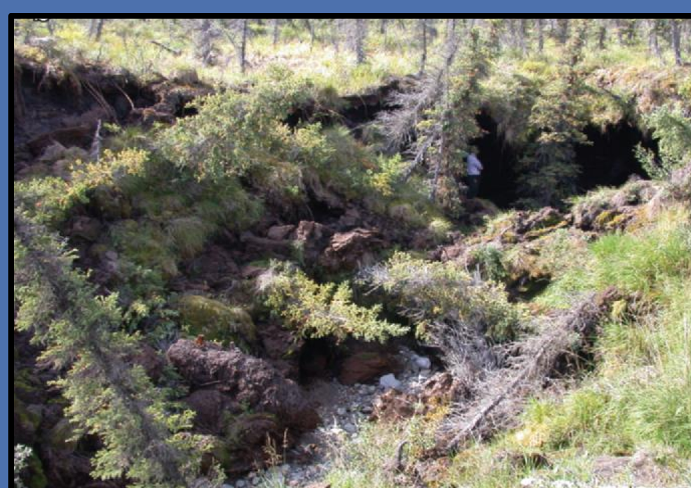



**Figure 10.** Drunken Forest effect, with trees collapsing as ground thaws (from Schuur et al. 2008)

This active layer controls such things as rooting depth, organic matter exposed to above freezing temperatures, and hydrologic water processes.

Figure 11. Example of northern peatlands with frozen ice lenses

*Permafrost is Thawing*

Global warming of the Arctic regions has become evident already, as permafrost has started to thaw. Evidence of this is seen in coastline erosion, where the permafrost along the ocean's edge has melted, making the shoreline much more susceptible to the impact of wave action. In some northern communities, building have become unstable, and trees have started to fall over, as the ground beneath them thaws, resulting in the "drunken forest" effect.

**Organic Soils (Northern Peatlands)**

Peatlands cover 12% of the land area of Canada, with most (97%) of this area found in the Boreal and Subarctic regions, and 37% being perennial frozen permafrost. Climate change is predicted to seriously impact all peatlands with 87% of the perennially frozen areas to be impacted. Because peatlands are an important carbon sink (storage area), the warming climate is predicted to decrease the amount of carbon being stored, and increase the amount being released as carbon dioxide and methane. This will further increase global warming.

Frozen organic soils (peatlands) in the boreal and subarctic regions contain considerable amounts of carbon, more than twice the amount currently in the atmosphere. Permafrost thawing will expose previously frozen carbon to microbial degradation and will release gases such as carbon dioxide and methane. Permafrost thawing can also seriously alter the landscape, vegetation and infrastructure built on the once frozen ground.

The greatest impact of global warming will be in the Boreal, Subarctic, and Arctic regions. The most significant impact will be on the perennially frozen peatlands, especially in the Boreal region, as these peatlands have ground temperatures just slightly below 0°C. The slightest increase in ground temperature will has the ability to cause thawing of the permafrost on a widespread basis.

The amount of soil organic carbon contained in Canadian peatlands is very significant, being accumulated over the last 9,000 years. Very little or no decomposition has occurred due to cold temperatures and waterlogged acidic conditions. As temperatures increase, the ability to store carbon will become less, and microbial decomposition will increase.

The major concern is the melting of ice locked into the perennially frozen peatlands, leading to waterlogged conditions. The thawing of the perennially frozen peatlands will result in water saturated conditions. In combination with higher temperatures, this will result in anaerobic conditions, and microbial decomposition with release of methane ($CH_4$) (21 times more effective as a greenhouse gas than carbon dioxide ($CO_2$)). In the southern boreal region, higher air temperatures will raise ground temperatures, increase evapotranspiration and drying of peatlands due to drought. Increased oxygen in the organic soil will speed microbial decomposition releasing $CO_2$. Drier conditions will also lead to increased wildfires, and burning of peat, resulting in more $CO_2$ loss to the atmosphere.

*Other effects of thawing permafrost:*

A. Release of water from organic material could release dangerous chemicals such as persistent organic pollutants which have been stored by the frozen plant material.
B. Erosion: Thawing **permafrost** and channeling water can thaw and move significant areas of previously frozen ground, in shorter time.
C. Landscape changes: in some areas, **permafrost** can occupy a large portion of the soil volume, thus thawing can trigger major changes in surface topography and ecosystem dynamics. In areas of the Arctic, lakes and ponds are increasing in areas, due to thawing.
D. Increased drying and fires along southern boreal areas. This could remove surface organic matter, decrease reflectivity, which can increase heat flux into soil and further increase thawing.
E. Significant losses of carbon from thawing **permafrost** peatlands is one of the most significant potential feedbacks from terrestrial systems to the atmosphere. This could trigger strong feedback mechanisms.

*Permafrost Carbon Feedback*

Degrading **permafrost** can alter ecosystems, damage infrastructure, and release enough $CO_2$ and $CH_4$ to influence global **climate.** The **permafrost** carbon feedback is the amplification of surface warming due to $CO_2$ and $CH_4$ emissions from thawing permafrost. The impact is yet unknown with no good estimates available.

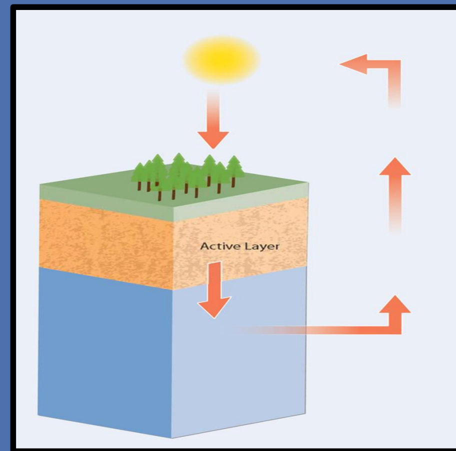



**Figure 12.** From Schaefer et al. 2014

## *River and Lake Ice*

Freshwater ice is responsible for the timing and severity of many hydrological extremes in northern systems, such as low flows and floods that are experienced during freeze-up and break-up periods. River ice is also a major factor in river ecology. Canadian data for the period 1947–1996 show that western sites have a predominant trend towards earlier break-up dates, and that there has been a nationwide trend towards earlier freeze-up dates.

*The loss of land-based ice has accelerated in recent decades.* Seventy percent of the Arctic's contribution to sea-level rise comes from Greenland, which on average lost 375 gigatons of ice per year—equivalent to a block of ice measuring 7.5 kilometers or 4.6 miles on all sides—from 2011 to 2014. This is close to twice the rate over the period 2003–2008.

Although changes are difficult to predict, future warming will likely lead to a shortened ice season and thinner lake- and river-ice covers, and cover composition (i.e. proportion of white ice) might be altered by increases in winter snowfall. Changes in winter snowfall will be a major factor in determining whether the severity of river-ice events, such as ice-jam flooding, increase or decrease.

# Climate Impacts on Arctic Lake Ecosystems

*Introduction*

Lakes and ponds are major features of the Arctic landscape, and span a diverse range of environmental conditions, from dilute, glacier-fed meltwaters to nutrient-rich tundra ponds and perennially ice-capped, stratified lakes with anoxic bottom waters. The most abundant freshwater ecosystems in the north are small and shallow but have a large total area and volume. Therefor they may influence biogeochemical dynamics at a global scale. In parts of the Arctic, these numerous shallow waters can account for up to 90% of the total land surface area. Large lakes >500 km2 are also found throughout the circumpolar Arctic. Many of these high arctic lakes are formed through thermokarst processes (permafrost thawing and erosion).

There is lots of variation in lake size, type, and composition but northern lakes also have a number of features in common. Firstly, as a result of their high latitude location, these ecosystems experience extreme seasonal variations in incident solar radiation. Above the Arctic Circle, this translates into three months of continuous winter darkness and three months of continuous light in summer, which in turn give rise to high fluctuations in primary production and all related food-web processes. Secondly, these seasonal effects are compounded by snow and ice, which cover these lakes for at least six months each year. For a small and decreasing number of extreme Arctic lakes, thick perennial ice persists throughout the year. The solid ice cap over the lakes influences all aspects of their limnology, including the availability of light for photosynthesis, rates of gas exchange with the atmosphere, interactions with the surrounding watershed, and their stratification and mixing regimes. Thirdly, persistent low temperatures strongly affect physiological and ecological processes within high latitude lakes and their surrounding catchments. This effect on chemical and biochemical reaction rates result in slow rates of soil-weathering in the Arctic. Because of this, lakes receive only sparse inputs of nutrients, which maintain their water columns in an oligotrophic status of low algal biomass. As a result of all of these constraints, the remoteness of the area, northern ecosystems often have low biodiversity of aquatic plants and animals. Many of the organism that are present are specialized towards extreme cold, low energy supply, and low nutrient availability (oligotrophy).

There is now compelling evidence of rising atmospheric temperatures at a planetary scale, with the most severe changes recorded at high northern latitudes.

These changes will have drastic effects on Arctic freshwater ecosystems, given that many of their limnological features are dependent on prolonged sub-zero air temperatures each year. Direct physical impacts of climate warming, range from loss of ice cover, to complete loss of freshwater ecosystems by drainage or evaporation. Biogeochemical impacts include shifts in organic matter loading, changes in oxygen levels and the formation and release of microbial methane from thermokarst lakes associated with permafrost thaw. Some biological impacts include loss of cold-adapted organisms and arrival of invasive species.

*Physical impacts of climate change*

The most drastic limnological impact of climate change is the complete loss of certain aquatic ecosystems. This may occur through geomorphological effects such as the breaching of an ice dam, or erosion of permafrost soils. For example, epishelf lakes are freshwater lakes underlain by seawater and dammed by ice shelves. The warming and break-up of the northern ice shelves has resulted in their drainage and loss. Thaw lakes appear to have natural cycles of expansion, erosion, drainage, and reformation which may accelerate under warmer climate conditions. Over the past 50 years there has been an overall trend of increasing snow precipitation in the Arctic. Global climate models predict that precipitation trends will differ among regions, with decreases in snow water equivalent over Scandinavia and Alaska, little to no change over the boreal forest region, and increased precipitation over northern Siberia and the Canadian Arctic Archipelago. However, these trends are offset by warmer temperatures in summer and decreased duration of ice cover, both of which favor water loss by evaporation. Lakes at several locations appear to have shifted to a negative net precipitation-evaporation balance (more evaporation than precipitation), and for some ponds and small lakes this has led to complete drying up.

Many high Arctic wetlands are dependent on perennial snow banks and glaciers, and are vulnerable to rapid warming. Increased evaporation and drainage in northern wetlands and lakes may result in the release of methane from Arctic permafrost. The decrease in ice cover has many effects on limnology in the north. The increased availability of light for photosynthesis may enhance primary production, and may also result in an enlarged photic zone, allowing a greater portion of the lake to be available for net primary production. For example, photosynthesis may be greater under conditions of decreased snow and ice cover. The absence of ice also allows wind-induced mixing that may entrain nutrients from deeper in the water column.

For phytoplankton communities in the surface waters of Arctic lakes, loss of snow and ice cover may also result in damage by increase of ultraviolet radiation in the water column.

Earlier breakup dates for ice cover and increased duration of exposure of the water column to sunlight will also result in radiative heating, causing the water columns to have more time to heat up. Even a slight warming can shift a lake that stratifies during winter but not summer (cold monomictic) to one that stratifies during both seasons, with periods of mixing in fall and spring (dimictic). For deep windswept lakes that are only weakly stratified and readily mixed by storms during summer, the decrease in water density with warming may result in less frequent summer mixing or shorter mixing periods. Changes in stratification have a variety of effects, including increased warming of the surface layer, possible increases in phytoplankton and zooplankton growth rates, and a greater risk of oxygen depletion. They can also potentially result in the increased retention of contaminants within Arctic food webs.

*Biogeochemical impacts of climate change*

Climate warming affects the biogeochemistry of lake ecosystems, directly by increasing the reaction rates of all chemical and biochemical processes, and indirectly through a variety of effects on water column and catchment processes. Changes to oxygen concentration under conditions of increased stratification is a result of less exchange of gases between the bottom waters of the lake and the atmosphere during stratified periods. Under extreme conditions these bottom waters may be driven to anoxia. This can be caused by increased nutrient and organic carbon inputs such as the release of inorganic phosphorus, iron and manganese from the sediments, stimulating additional biological production. Increased thawing of the permafrost results in increased erosion and transport of tundra soils and organic carbon to lakes, increases the microbial production of carbon dioxide and methane. An area of great concern in the arctic is the mobilization of organic carbon trapped in permafrost below lakes. This thawing also results in the rapid production and emission of methane and carbon dioxide. Given the tremendous size of the permafrost carbon pool (more than twice the size of the atmospheric carbon pool), permafrost thaw could result in the release more than ten times the amount of methane in the current atmosphere. The release of this potent greenhouse gas could create a positive feedback cycle in which methane causes global climate warming, which in turn causes permafrost to thaw, and more methane to be formed and released.

Arctic warming is leading to increased plant growth across the tundra, with the northward expansion of shrubs and trees. This is likely to cause increased soil weathering during higher temperatures, the expansion of root biomass, and increased microbial activity in the rhizosphere. An increase of shrubs and trees in the landscape can also result in a substantial increase in terrestrial organic carbon production and its export to lakes as dissolved and particulate organic matter. Depending on the acid-neutralizing capacity (alkalinity) of the lake waters, such changes could also result in decreased pH.

*Biological impacts of climate change*

The warming of northern ecosystems is likely to impair cold-adapted specialist organisms and can lead to a complete regime shift in food-web structure. This may be worsened by the invasion of generalist species from the South. The local biodiversity of northern lakes may increase in terms of species richness, but at the expense of Arctic native species that may be driven to extinction by competition, parasitism or direct thermal stress. There is also evidence of changes in community structure at all trophic levels among all different sectors of the Arctic. The displacement of native fish in northern lakes is of particular concern to Inuit and First Nations communities, and will be an increasing priority of research and monitoring. For example, smallmouth bass showed that it could potentially invade some additional 25 000 northern lakes and, because of its strongly negative effects on other fish, cause the extirpation of four native cyprinid species from these lakes.

*Human impacts of climate change*

Northern lakes provide a variety of key ecosystem services including transport routes, drinking-water supplies, habitats for aquatic wildlife, traditional value to northern communities, and water for industries including hydroelectricity, recreational fishing, eco-tourism and mining. The influence of climate change on water supply and quality is increasingly viewed with concern by Inuit and other indigenous communities. Warmer temperatures may allow invading species to survive and reproduce, causing the extinction of native biota and serious impairment of traditional hunting and fishing practices. Lake and river ice in the north provide winter transport routes that are important to northern indigenous people for access to their traditional hunting and fishing areas, as well as for the heavy transport of goods to remote communities and industries such as mining centers. Both ice roads and traditional routes are now subject to earlier break-up and unseasonal warming, which reduces their economic value and creates dangerous conditions for freight haulers and northern communities.

Several climate-related effects may influence the future quality of drinking water in the North. Ongoing permafrost degradation may cause a rise in turbidity and dissolved organic matter levels in the raw source waters. High-latitude freshwaters are mostly free of toxic bloom-forming cyanobacteria that create a broad spectrum of water quality problems in the temperate zone, but ongoing warming and stratification of Arctic and subarctic lakes combined with climate-related increases in nutrient loading may encourage the development of these taxa. Arctic char (*Salvelinus alpinus*) is a key element of the traditional diet of Inuit and other northern indigenous people, and changes in this and other fish species associated with climate change may have impacts on northern culture and health. Arctic char appears are especially sensitive to high temperatures relative to other salmonids, and is also the most tolerant of low temperatures. With ongoing climate change, Arctic char will be unlikely to survive in the warmer surface and littoral waters of many northern lakes. The arrival of southern species such as Atlantic salmon (*Salmo salar*) and brook trout (*Salvelinus fontinalis*) could reduce or replace Arctic char. The current expansion of economic and resource extraction activities in the Arctic will require increasing vigilance and appropriate water management strategies to avoid and minimize such impacts in the future.

*Conclusions*

As a result of climate change, the northern landscape has now entered a state of rapid transition, and Arctic freshwater ecosystems are beginning to show shifts in their physical, biogeochemical and biological properties. These ongoing changes will affect the ecosystem services that they are able to provide to northern residents, industries and society at large. Many of these impacts are interconnected. Changes in climate affect water temperature and stratification, which may lead to anoxia, and changes to community composition. The Arctic Ocean is predicted to be seasonally ice-free within decades, and this could be a tipping point that triggers widespread degradation of permafrost, with implications for lake water quality, mobilization of permafrost organic carbon, and accelerated methane release. The potential arrival of invasive species will create particularly challenging problems for ecosystem management, including fisheries, and will require increased surveillance and prevention measures as road access to the north continues to develop.

# Impacts of climate change on fish species and aquatic ecosystems: a compilation of reports

Rising mean annual air temperatures are expected to affect abiotic processes governing these ecosystems resulting in changes in water temperatures, precipitation and flow regimes, dissolved oxygen and ice cover which will directly impact fish biodiversity in the regions. These abiotic changes, in turn, cause changes in biological interactions between species, especially the dynamics of ecological invasions and disease which will further impact fish communities and food webs in these regions.

Climate change is expected to modify patterns of precipitation, runoff and evaporation at a global scale. These changes may lead to a shift in peak stream flows from spring to late winter in snowmelt regions, affecting reproductive cycles of riverine fishes. Inter and intra-annual flow variation can affect the connectivity of intermittent streams, influencing dispersal, reproduction and population characteristics of fish species. As future thermal environments will likely exist within the optimum range of temperatures for these species, warm water fishes are predicted to experience an increase in thermal habitat as a result of rising temperatures

Declining lake levels can negatively impact biodiversity, as shorelines provide important nursery habitat for many fish species. Increasing water temperatures are expected to greatly influence the composition of freshwater fish communities. Considering that the majority of these species occur in Northern latitudes, which are expected to undergo the greatest increase in mean annual air temperatures globally, cold water fish species are predicted to experience local extinctions and extirpations at a large scale. This is especially true for species at the southern boundary range where these species are maintained within a few degrees of their thermal limits.

The consequences of changes in water temperature over the freshwater lakes (and its organisms) will be mediated by alterations in thermal stratification. The warming of non-stratified lakes would will move the distribution boundary of many warm and cool water species northward, at the same time excluding them from small lakes with now deeper thermoclines and hypoxic hypolimnion. In stratified lakes, the declining oxygen level below the thermocline will degrade the habitat for cold water fishes and organisms.

Besides obvious reductions in water availability, other indirect effects may complicate the predictions about responses of productivity to climate change, including:

A. Increasing eutrophication and thermal stratification can exacerbate hypoxia for many organisms

B. A shift in phytoplankton composition towards toxic algae (cyanobacteria) can compromise production at higher trophic levels

C. Changes in ice cover may decrease or increase productivity, depending on ice characteristics

D. Increasing input of nutrients may be accompanied by increasing pollutant concentrations and water turbidity, compromising light penetration and photosynthesis

E. Although photosynthesis is benefited by increasing light penetration, it may be accompanied by increasing UV penetration, which can damage organisms and compromise production.

### *Freshwater Discharge*

Rivers flowing into the Arctic Ocean have low winter runoff, high spring flow rates (driven by snowmelt) and rain-induced floods in the summer and autumn. Snowmelt accounts for most of the flow in high-Arctic rivers and streams. Flow of large rivers is strongly influenced by the hydrological regimes in their non-Arctic southern headwaters.

*In the past decade, freshwater storage in the Arctic Ocean has increased.* Compared with the 1980–2000 average, the volume of freshwater in the upper layer of the Arctic Ocean has increased by 8,000 cubic kilometers, or more than 11%. This volume equals the combined annual discharge of the Amazon and Ganges rivers, and could—if it escapes the confines of the Arctic Ocean—affect circulation in the Nordic Seas and the North Atlantic. Broadly speaking, projections of future climate suggest that total annual discharge to the Arctic Ocean from Arctic land areas could increase 20% by about 2050, with winter discharge likely to increase between 50 and 80%.

### *Sea-level Rise and Coastal Stability*

Climate change will lead to rising sea levels in the Arctic Ocean and other northern seas. Climate warming affects global sea level through ocean thermal expansion and additional water transfers to the ocean basins from melting glaciers and ice sheets. The rise in sea level will not be uniform throughout the globe and some areas, including parts of the Arctic, may be subject to more rapid rates. In addition, the relative sea-level change along any coast (the trend measured by a tide gauge) is a combination of sea-level change and any vertical motion of the land surface. Vertical motion in the Arctic is dominated by ongoing postglacial **isostatic rebound**, with uplift in some places being as high as about 1 m per century.

Sea-level rise increases the risk of flooding and erosion on Arctic coasts and may exacerbate other coastal hazards, such as ice ride- up and pile-up. In the western Arctic, sea-level rise and coastal erosion threaten cultural heritage sites (e.g. former habitations and burial sites) on the Yukon coast (e.g. Herschel Island), seasonal settlements (e.g. Shingle Point, YT) and coastal communities (e.g. Tuktoyaktuk, NT).

Reduced sea ice, more open water, and more energetic waves may be important in a number of places, where postglacial uplift and coastal emergence are ongoing. The most severe flooding risks in low-lying communities are associated with large storm surges, which may reach more than 2 m above global mean sea level. Storm waves during severe surges can cause rapid coastal retreat of 10 m or more in a single event. Sea-level rise will increase the upper limit of potential storm-surge flooding, and also increase the frequency of flooding at lower levels. Storm frequency in the Canadian Arctic shows no clear trends during the past 50 years. Erosion rates may be accentuated by warmer ground temperatures, deeper summer thaw and volume loss on melting of excess and massive ground ice where exposed in coastal cliffs. Despite some suggestions of increased erosion rates in the western Arctic, including the Yukon and Alaska coast, a regional analysis for the southern Beaufort Sea detected no significant trend in areas of rapid erosion for the 1972–2000 time interval. However, further warming, combined with sea-level rise and reduced sea ice, can be expected to maintain or increase the already rapid rates of coastal retreat along this coast.

### *Ecosystems and Biodiversity*

The extreme temperature gradients of the Arctic mean that plant communities will likely show a quick and strong response to temperature change. For currently widespread grass, sedge and flowering species, continued temperature increase will result in higher productivity and abundance, and an expansion in range to the north. Other species found exclusively (hyperarctic; e.g. grasses) or primarily (euarctic; e.g.

polar willow) at high northern latitudes, on the other hand, will likely respond to climate warming with a narrowing of their ecological niche.

Latitude and light regimes currently limit the distribution of some plant species, so these will not be able to migrate northward in response to increasing temperatures. Other important factors to be considered when projecting a whole-system response to climate change include: 1) the importance of carbon-nutrient interactions; 2) the interactions of carbon and nutrient cycles with temperature, water and snow cover; 3) the magnitude of dissolved organic and inorganic carbon losses in soil water; and 4) the magnitude and role of wintertime processes. The cumulative impacts of climate change on these factors will likely result in new communities, with different structures and species composition.

Increased disturbances, such as pest outbreaks and fire, will locally affect the direction of treeline response. In general, the treeline will show many different responses depending on the magnitude of temperature change, as well as changes in precipitation, permafrost conditions, forest composition and land use.

*In the past decade we have seen that, as predicted, ecosystems are already changing*. The decline in sea ice thickness and extent, along with changes in the timing of ice melt, are already affecting marine ecosystems and biodiversity; changing the ranges of Arctic species; increasing the occurrence of algal blooms; leading to changes in diet among marine mammals; and altering predator-prey relationships, habitat uses, and migration patterns. Terrestrial ecosystems are feeling the effects of changes in precipitation, snow cover, and the frequency or severity of wildfires. The occurrence of rain-on-snow and winter thaw/refreezing events affects grazing animals such as caribou, reindeer, and muskox by creating an ice barrier over lichens and mosses. While many tundra regions have become greener over the past 30 years, reflecting an increase in plant growth and productivity, recent satellite data show shifts toward browning (indicating a decrease in plant cover and productivity) over large areas of the Arctic, particularly in Eurasia.

### *Freshwater Ecosystems*

Climate change will affect the structure and function of Arctic freshwater ecosystems. Community and ecosystem attributes, including species richness, biodiversity, range and distribution, will be affected by changes in physical and chemical environmental parameters, and will consequently affect food-web structures and production levels.

General knowledge of the biology of aquatic biota is low, particularly with respect to understanding potential connections with climate drivers and ecosystem responses. Although large uncertainties remain in projecting species- and system-specific responses, it is likely that locally adapted Arctic species will disappear from certain areas when environmental conditions begin to exceed their physiological tolerances and/or ecological optima. The most vulnerable species are those with limited climatic ranges. Extinctions of Arctic species across their entire range are not expected, although some species will be marginalized geographically and/or ecologically.

Changing climate will also result in alterations to the geographic ranges of freshwater species due to loss of optimal habitat for 'native' Arctic species and the northward expansion of more southerly species. Ecological observations by trappers on the Peace-Athabasca Delta of the Mackenzie River system indicate that muskrat abundance is likely to increase in high-latitude lakes, ponds and wetlands due to the expected increases in the abundance of aquatic vegetation.

### *Follow the water: The changing interactions between cryosphere and hydrosphere*

The amplifiers of warming described above have contributed to an intensified water cycle in the Arctic, in which flows of freshwater between the land, the atmosphere, and the ocean are increasing. This pattern has important implications for human populations and ecosystems in the Arctic, as well as weather at lower latitudes.

For example, when precipitation increases in a warmer climate, much of that water ends up in rivers. As does the meltwater from snow, glaciers, and ice caps. The Arctic's rivers account for roughly 10% of the world's total river discharge, pouring enormous quantities of freshwater, sediment, nutrients, and organic carbon into the Arctic Ocean every year. Non-Arctic rivers, such as the St. Lawrence River in Canada, also contribute freshwater that ends up in the Arctic. Increases in freshwater flow into the ocean affect ocean circulation, ocean acidification, and biological productivity, and affect weather patterns far to the south. Melting sea ice also contributes to freshening of the ocean's surface. As the sea ice thins and shrinks, it also becomes more mobile, creating hazards to shipping and other activities, while increasing the risk that currents will push it to warmer waters where it will melt. Following the path of water through the hydrological cycle reveals many complex interactions between water and the cryosphere.

### *The Importance of Feedbacks*

A number of feedback mechanisms, some of them unique to the Arctic, are responsible for the more rapid warming observed over the Arctic compared with the rest of the world. These feedbacks amplify warming well beyond the effects caused by increasing greenhouse gas concentrations alone. By analyzing climate models, scientists have identified the relative contribution of the different feedbacks to warming in the Arctic.

The largest feedbacks, according to climate models, are related to the Arctic's inefficiency at radiating heat. Cold regions radiate heat slowly, so the warmth trapped by greenhouse gases tends to build up. Furthermore, warming in the Arctic is concentrated close to the Earth's surface, slowing the rate at which heat is lost to space from the top of the atmosphere.

The next-largest warming feedback comes from changes in surface reflectivity due to the melting of snow and ice. As reflective surfaces are replaced by darker surfaces such as open water or land, less energy is radiated back to space and the region warms further, leading to still more melting. Water vapor (a powerful greenhouse gas) also provides a warming feedback. Warmer temperatures increase evaporation, and a warmer atmosphere can hold more water vapor.

## Studying Climate Change

Our understanding of the climate system is improved through observations, theoretical studies, and modeling.

A. The components and processes of Earth's climate system are subject to the same physical laws as the rest of the Universe. Therefore, the behavior of the climate system can be understood and predicted through careful, systematic study.

B. Environmental observations are the foundation for understanding the climate system. From the bottom of the ocean to the surface of the Sun, instruments on weather stations, buoys, satellites, and other platforms collect climate data. To learn about past climates, scientists use natural records, such as tree rings, ice cores, and sedimentary layers. Historical observations, such as native knowledge and personal journals, also document past climate change.

C. Observations, experiments, and theory are used to construct and refine computer models that represent the climate system and make predictions about its future behavior. Results from these models lead to better understanding of the linkages between the atmosphere-ocean system and climate conditions and inspire more observations and experiments. Over time, this iterative process will result in more reliable projections of future climate conditions.

D. Our understanding of climate differs in important ways from our understanding of weather. Climate scientists' ability to predict climate patterns months, years, or decades into the future is constrained by different limitations than those faced by meteorologists in forecasting weather days to weeks into the future.

E. Scientists have conducted extensive research on the fundamental characteristics of the climate system and their understanding will continue to improve. Current climate change projections are reliable enough to help humans evaluate potential decisions and actions in response to climate change.

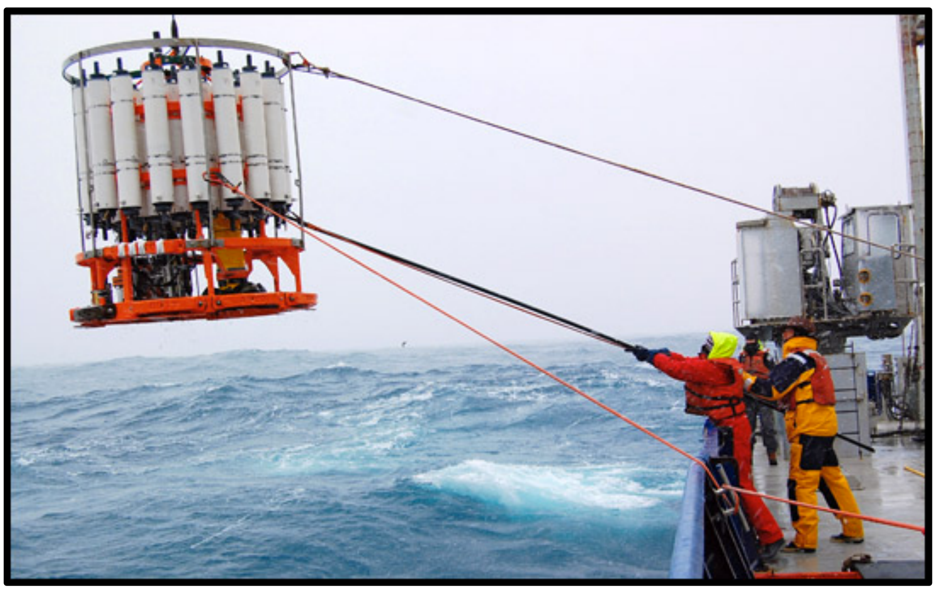


**Figure 13.** A rosette device containing 36 seawater samples is retrieved in the Southern Ocean. Seawater samples from various depths are analyzed to measure the ocean's carbon balance.

# Implications for Economic Development

## *Hydroelectric Development*

Demand for electricity is rising in all three territories, due to increasing population and heavy industry, such as diamond mines in the Northwest Territories and Nunavut. Alternative renewable energy sources, such as solar, wind, wood and even geothermal power, could help to meet some of the increasing demands for electricity, and territorial government agencies have indicated that they are committed to increasing renewable energy supply. There is already a significant dependence on hydroelectric generation, with seven large (>10 m in height) hydroelectric dams operating in the Yukon and Northwest Territories, along with a range of small, often privately owned, micro-hydro facilities. Further expansion of micro-hydro facilities is under consideration, but the major northern rivers still offer some of the largest potential.

Changing climate will affect the capacity and operations of current and future hydroelectric developments, as well as affecting the demand for electricity. Projected increases in winter runoff from rainfall and enhanced winter snowmelt will lead to a decline in winter snow storage. Reservoir capacities on current and future developments may need to be expanded to offset this loss in natural storage. The gradual loss of meltwater contributions from glaciers as they ablate and retreat will also need to be factored into future calculations of capacity.

## *Oil and Gas*

The oil and gas industry involves exploration, extraction, production and delivery. Although changes in climate need to be considered for all four, exploration activities are likely to be most affected. Some of the largest future potential reserves exist within the Canadian Arctic Archipelago, and projected decreases in sea-ice cover may result in this area becoming a focus of additional exploration activity.

Thawing of permafrost and changes in snow cover will necessitate an increased focus on low-impact vehicles and/or changes in seasonal scheduling of exploration activities. The unpredictability of the winter season and the winter ice-road system will necessitate greater flexibility in scheduling of exploration and extraction activities. The greatest impact of changing climate on exploration, however, may relate to the use of in-ground sumps for drilling wastes. Disposal in sumps relies on the presence of permafrost to prevent subsurface movement of drilling wastes into the surrounding environment. Increased ground temperatures resulting from increases in air temperature and/or snow depth will increase the likelihood of contaminant transport. Alternate drilling-waste practices, including remote sumps, central processing facilities, down-hole injection or transportation of waste to outside the territories, represent potential adaptations to climate change.

### *Mining*

There are currently three major mines operating in the northern territories (as of 2008): two diamond mines in the Northwest Territories and one diamond mine in Nunavut. Other projects have recently been approved or are in the advanced stages of environmental assessment and regulatory process in all three territories. Moreover, development of integrated land and marine transportation networks in response to projected declines in sea- ice cover is likely to stimulate further mine exploration and development. The principal mineral deposits include diamonds, gold, tungsten, silver, lead, iron, copper, zinc, nickel, coal, tantalum, niobium, lithium, cobalt, bismuth, uranium, beryllium and barium.

Resupply of existing mines is generally limited to winter periods and the availability of ice roads, whereas exploration activities are usually restricted to short summer periods, with access by air. Climate-change should be considered in the engineering design, during operations and in final closure and abandonment of mines, a planning process termed “designing for closure”. Of particular concern for mine access is the expected reduction in the availability of ice roads, which may necessitate development of all-season roads and/or water-based transportation systems. Another concern is the impact of climate change on permafrost and ground stability. The stability of waste-rock piles, tailings piles and tailings-containment impoundments often depends on maintenance of frozen conditions to ensure that contaminants and acid-metal leachate (or acid-rock drainage) are not discharged to the environment.

### *Infrastructure*

Permafrost and the ground ice it contains present challenges for the design, construction and operation of infrastructure in northern Canada and throughout the circumpolar region. Although ice-bonded frozen ground can provide a strong foundation for infrastructure, thawing of the ground leads to loss of strength, as well as to settlement and instability. The removal of insulating vegetation/organic cover and other disturbances of the ground surface that generally accompany construction can significantly alter the ground thermal regime, resulting in warming and thawing of permafrost. Additional warming may occur due to heat generated by the structure itself (e.g. heated buildings and buried water, sewage or hydrocarbon pipelines). For larger structures, particularly such linear structures as runways, roads and pipelines that cover large distances, concerns include differential settlement due to spatial variations in soil characteristics and ice content, and slope instability resulting from permafrost thawing.

Adaptation of northern infrastructure to climate change will largely involve approaches already in use to reduce the impacts of ground disturbance. These include the use of pile foundations (that may need to be deeper to account for climate change), insulation of the surface (which may require thicker gravel pads), clearance of snow (to promote colder winter ground temperatures), adjustable foundations for smaller structures, and increased use of artificial cooling to ensure that foundation soils remain frozen. Recently developed techniques, such as air-convection embankments, may also be utilized. Where permafrost is thin, frozen ice- rich material may be excavated and replaced with thaw-stable material, or intentionally thawed by clearing vegetation and postponing construction for several years until the permafrost has completely degraded and the ground has settled.

## *Marine Transportation*

The many different types of sea ice and glacier ice in Arctic marine environments, in addition to such conventional factors as storm waves and shoals, present unique risks to transport. In turn, marine transport presents potential risks to the Arctic environment, including the possibility of fuel and cargo spills, disturbance of wildlife via vessel presence and underwater and airborne noise, and destabilization of fast ice that can disrupt both animal and human travel. The Canadian Arctic provides three routes for marine shipping: to the port of Churchill and other communities in Hudson Bay via Hudson Strait; to the Beaufort Sea via Bering Strait or the Mackenzie River; and through the Arctic Archipelago via the Northwest Passage.

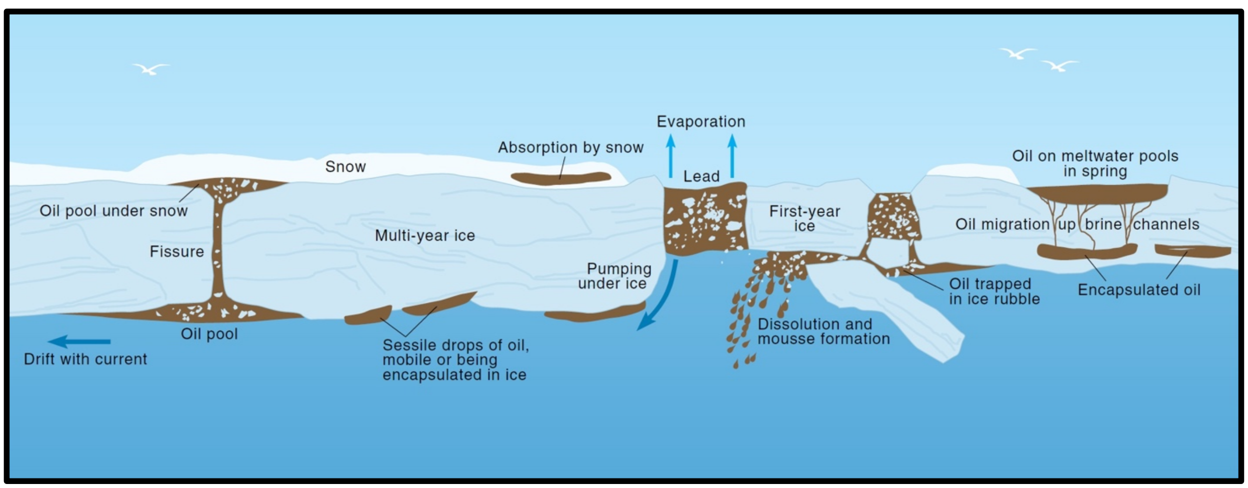



**Figure 14.** Possible interactions between oil and Arctic Sea Ice in the event of an oil-spill (Source: AMAP Assessment report: Arctic Pollution Issues (after original figure by Bobra and Fingas))

Arctic seaways are used for the resupply of communities, export of raw materials and cruises for sovereignty, tourism or science. Scientific cruises to the Arctic have increased dramatically since 1990, and are frequently multitasked on Canadian Coast

Guard (CCG) icebreakers that simultaneously serve other roles, such as navigational support and maintaining a Canadian government presence. In 2004, the CCGS Amundsen was outfitted specifically to support research on the impacts of climate change in the coastal Canadian Arctic, as part of the ArcticNet Network Centre of Excellence, and now regularly traverses the Northwest Passage. Similarly, tourist cruises through the passage are becoming increasingly common. Although international shipping represents another usage of marine waterways, initiatives by the tanker Manhattan in 1969 and 1970 revealed the serious challenges to safe, cost-effective and predictable transshipment through the Northwest Passage.

Arctic Canada has never seen year-round shipping. Resupply presently begins in July and ends in October, and frequently requires support from Canadian Coast Guard icebreakers even within that window. Winter shipping is difficult relative to summer shipping due to that fact that winter ice is colder, and therefore stronger, than summer ice. In addition, winter ice is consolidated from shore to shore, without the cracks (leads) that make it easier for a ship to pass through. Additionally, near-total darkness and bitter cold make winter navigation exceedingly hazardous. Multi-year ice, which does not soften much in summer, is a serious hazard to ships year-round. At high concentrations, multi-year ice is a barrier to all but the most powerful icebreakers, even in summer. In winter, it is effectively impenetrable. The Arctic Ocean's open water season has already increased by 1–3 months over much of the ocean since the late 1970s, creating more opportunities for marine shipping, commercial fisheries, tourism, and access to resources.

**Table 1.** Summary of projected changes in ocean conditions (Loeng et al., 2005, Furgal and Prowse 2008).

| | 2020 | 2050 | 2080 |
|---|---|---|---|
| **Sea ice:** | | | |
| *Duration* | Shorter by 10 days | Shorter by 15-20 | Shorter by 20-30 days |
| *Winter extent* | 6-10% reduction | 15-20% reduction | Probably open areas in high Arctic |
| *Summer extent* | Shelves likely to be ice free | 30-50% reduction from present | 50-100% reduction from present |
| *Export to North Atlantic* | No change | Reduction beginning | Strongly reduced |
| *Type* | Some reduction in multi-year ice, especially on shelves | Significant loss of multi-year ice, with no multi-year ice on shelves | Little or no multi-year ice |
| **Landfast ice:** | | | |
| *Type* | Possibly thinning and a retreat in southern regions | Probable thinning and further retreat in southern regions | Possible thinning and reduction in extent in all Arctic marine areas |

### *Winter Roads*

Although lake and river ice have historically served as natural transportation routes, and modern engineering has led to increasingly sophisticated methods of winter-road construction and expansion, little scientific literature exists about the effects of climate on these systems. Since the 1950s, the seasonal road network has evolved into a large suite of private and public lake and river crossings linking northern communities and all-season road systems. Ice roads and ice bridges that are constructed and maintained each winter provide a relatively inexpensive way to supply northern communities and industry, particularly the rapidly expanding mining sector that relies on ice roads to move heavy equipment, materials and fuel for the remainder of the year. Additionally, they form critical travel routes connecting communities and facilitating the ability to continue social and cultural activities during winter months.

Reductions in ice thickness associated with climate warming reduce the maximum loads that can be safely transported. Initially, modifications in ice-road construction (as described previously) may serve as an effective adaptation. At locations where transport capacity is not already maximized, it is possible to modify transport schedules to concentrate shipping into the core portion of the winter when ice thickness is maximized. A possibility also exists for transporting heavy loads over ice with the assistance of balloons, as suggested for the movement of oilfield equipment in Alaska and the Canadian Arctic. This combination of impacts associated with decreased length of the ice-road season and reduced ice thickness translates into increased difficulties in resupplying northern communities and industrial sites during winter months.

### *Forestry*

The cultural, spiritual, social and economic well-being of many First Nations is dependent on a healthy forest ecosystem. Gathering of food and the exercise of cultural practices are important uses of forest land. The mounting evidence of local ecological responses to recent climate change demonstrates the sensitivity of northern forested ecosystems to climate change. Indeed, many of the projected impacts of changing climate on the northern forest sector are already visible. Increased forest disturbances due to insect outbreaks are almost certain to result from continued climate warming. The spruce bark beetle infestation of southwestern Yukon, which has led to widespread mortality of white spruce, is the largest and most intense outbreak to affect Canadian trees and is a notable example of ecosystem response to recent warming. Climate change is also projected to increase the frequency, extent and severity of forest fires, thereby reducing mean fire return intervals, shifting age class distributions toward younger forests, triggering more frequent shifts from conifer- to deciduous-dominated successional trajectories, and decreasing the amount of terrestrial carbon stored in the boreal forest.

Depending on species, site type and region, warmer temperatures in the last several decades have either improved or decreased tree growth. In some areas where declines have been observed, drought stress has been identified as the cause, whereas declines in other areas remain unexplained. Drought stress is also impeding the re-establishment of spruce forests following fire in some areas of southwestern and south-central Yukon, which are highly vulnerable to climate change if trends towards drier conditions continue. Most projections of future climate result in conditions that are very likely to limit the growth of commercially valuable white spruce types and widespread black spruce types in large parts of Alaska and probably the western boreal forest of Canada. Climate-related changes in forest productivity will likely have significant impacts on northern forest-dependent communities.

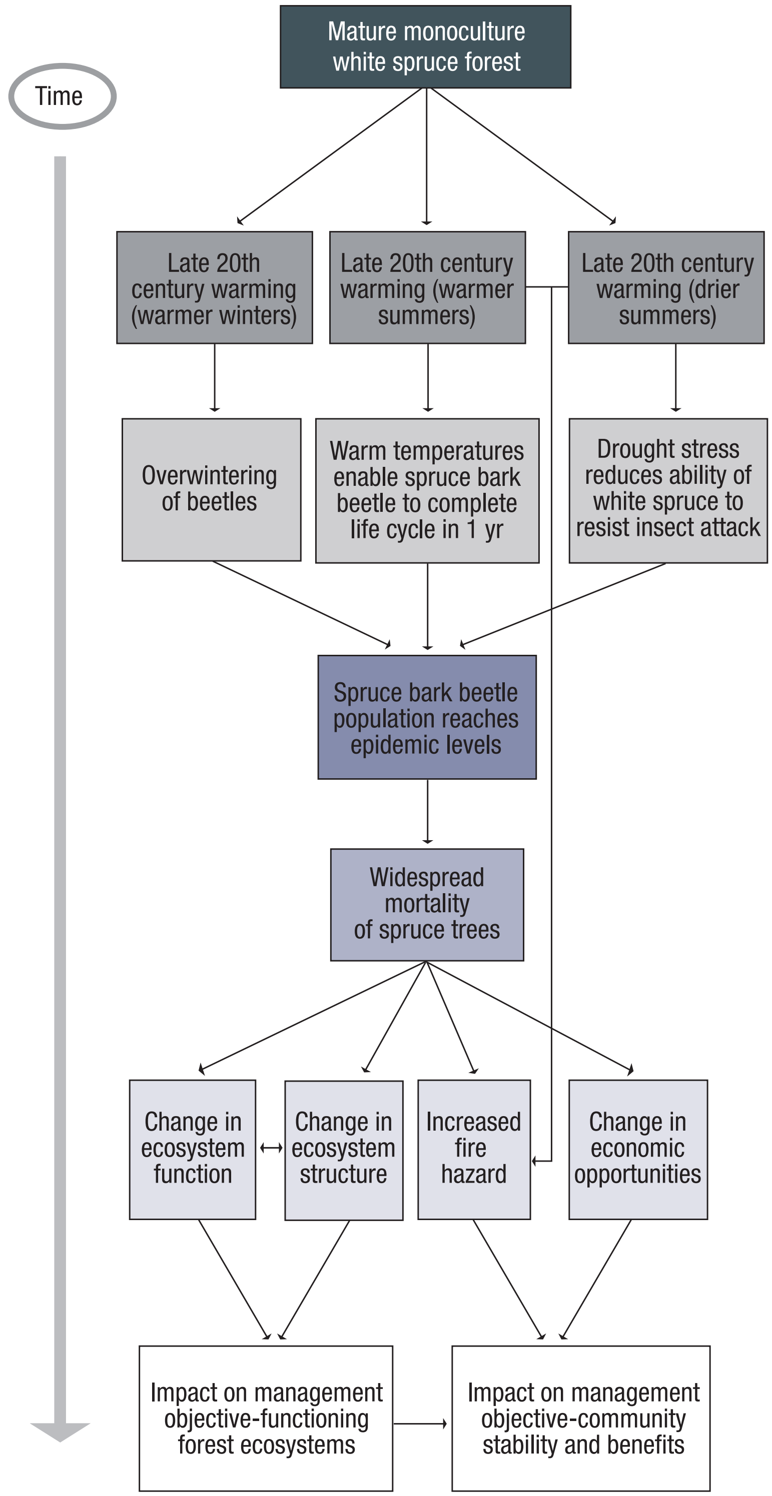



**Figure 15.** Influence of climate warming on spruce bark beetle populations in the southwest Yukon (Ogden, 2006)

### *Fisheries*

The northern fish fauna of Canada consists of an estimated 240 species. Additional fish species, not yet recorded due to poor sampling coverage, likely also occur in northern, particularly marine, waters. Adjacent regions contain additional species that may eventually be found in the North. Of the endemic species, northern fisheries target relatively few, most of which are salmonids (e.g. salmon, chars, whitefishes, grayling) captured in fresh, estuarine or nearshore waters.

The number of species present in the region is likely to rise as climate changes, especially along the southern margin of the North. Several southern species are known to occur as vagrants in the North, including three species of Pacific salmon in the western Arctic and Atlantic salmon in the east. Colonization could result in new opportunities for fisheries, but could also add to existing stressors as ecosystems restructure, new predators appear, competition ensues and/or parasites are introduced by the colonizing species. Experience with the vagrants in local fisheries enhances interest in future potential for fisheries based upon those species.

Freshwater and anadromous species can be divided into three groups, based on thermal associations and preferences:

- Arctic (thermal tolerance <10°C): species that are wholly or primarily distributed in the north (e.g. broad whitefish, an anadromous fish of the western Arctic)

- Northern cold-water–adapted (11–15°C): species that reach their limits of distribution somewhere in the North.

- Southern cool-water–adapted (21–25°C): many of these species (e.g. Atlantic salmon) reach the northern limit of their distribution near the extreme southern margin of the North. Changing climate will affect these three groups, and associated fisheries, differently. Arctic species will likely experience declining productivity, local extirpation along the southern margin of their distribution and overall range contraction as local conditions exceed thresholds and southern species colonize and compete with or prey upon them. Both northern cold-water and southern cool-water species will likely increase in abundance and local productivity, and perhaps also extend their geographic range farther northward as conditions allow.

Particular fish species are either stenothermal (i.e. adapted to a narrow range of temperatures) or eurythermal (i.e. adapted to wide thermal ranges). These species are often captured together in the same fishery. In many cases throughout the North, local climate change may be positive for one species and negative for another. Such variability in the response will substantially affect fishery structure, output and sustainability, and present challenges to those fishery managers who rely primarily upon single-species management approaches. Management structures and approaches that focus on the ecosystem level are likely to be more highly responsive to climate change impacts. An ecosystem approach involves attaching differential values to local species and enabling the setting of attainable goals for sustainable fisheries and their management.

### *Wildlife, Biodiversity, and Protected Areas*

A diverse range of wildlife has been critically important for Aboriginal people in the Canadian North for thousands of years. Today, wildlife continues to play a vital role in the diet, traditions and cultures of Aboriginal people, and also forms important components of local and regional economies. Many Arctic terrestrial and marine mammals and bird species have narrow habitat and niche requirements that make them particularly sensitive to climate change. Range-restricted wildlife species that occur near their ecological limit have been some of the first to exhibit impacts from changing climate. Previous assessments of projected climate change on circumpolar Arctic wildlife highlight changes in mortality rates, reduced reproductive capacity, increased competition for resources due to northward extension of southern species, and the emergence of new zoonotic diseases. Such changes will impact key traditional, subsistence and economic species in some regions, and their effects could be reduced by means of proactive adaptation to reduce the implications for human populations relying on these resources.

Projected warming and shifts towards a wetter Arctic are expected to affect the diversity and accessibility of vegetation critical to several foraging mammals, such as woodland and barren ground caribou (*Rangifer tarandus*) and muskox (*Ovibos moschatus*). Changes in ultraviolet radiation, precipitation and temperature will directly affect the nutritive content of forage, while changes in the composition of flora communities may result in the loss of nutritionally important plant species, which are chosen by caribou during important reproductive stages. Projected increases in winter temperature and precipitation will likely result in an increase in energy expended by caribou to dig for food through deeper snow pack.

Caribou are a key traditional and subsistence species for Aboriginal peoples of the Canadian Arctic, including Gwich'in, Tli cho, Denesuline and Inuit, and play an important role in local nutrition, economies, cultures and spirituality. The climate sensitivity of caribou highlights the need to monitor and better understand changes in small and genetically unique groups of animals, and to adjust wildlife management strategies accordingly. Adaptation measures will need to limit the chance of undetected large-scale herd die-offs and harvesting above sustainable levels, in order to protect species from declines to levels from which they cannot recover. Wildlife management boards in the Northwest Territories are currently considering implementing measures to reduce the non-resident and non-Aboriginal harvest of caribou. Adaptive co-management strategies, involving local Aboriginal harvesters and bringing together scientific and traditional knowledge, are becoming increasingly important.

The Arctic marine environment is home to a variety of large mammal species that have adapted to the unique conditions of this ecosystem. Ringed sea (*Phoca hispida*), walrus (*Odobenus rosmarus*), narwhal (*Monodon monocerus*), polar bear (*Ursus maritimus*) and beluga whale (*Delphinapterus leucas*) are widely found throughout Northern Canada and are commonly harvested by coastal Aboriginal populations, conveying important health, economic and cultural benefits. Many of these species are also central to important Arctic tourism and sport-hunting ventures. Changes in the distribution, stability and annual duration of sea ice and snow availability will have significant impacts on the populations of these mammals. Some species dependent on sea ice as a suitable platform for resting, pupping, moulting or feeding are already showing stress at their southern limits. Species that rely on the ice-edge environment, such as beluga, narwhal and walrus, are most vulnerable to the effects of projected decreases in sea-ice cover.

Decreased snow depth and earlier ice break-up in the spring have been shown to affect the survival and recruitment of ringed seal (*Phoca hispida*) pups in western Hudson Bay, while early spring warming and rainfall have been linked to the melting and destruction of ringed seal lairs in southeastern Baffin Island. For some other seal species, including harbour seals and grey seals, climate warming and decreases in sea-ice cover will mean a northward expansion of their distributions and an increase in their prevalence in Arctic waters.

The distribution of polar bears (*Ursus maritimus*) is partly a function of the ice conditions that allow them to most efficiently hunt and travel. This relationship is particularly strong in areas of moving ice, between foraging grounds and where they give birth to and rear their young. As polar bears feed almost exclusively on ringed seals, changes in ice distribution and extent that impact seal populations will also affect polar bear distribution and foraging success. A significant decline in the numbers and condition of southern populations of adult bears has been documented in western Hudson Bay, and is associated with changes in sea-ice conditions and seal populations. Such changes require bears to travel longer distances in search of seals, and to diversify their diet when possible, expending more energy and depleting adipose stores. Ultimately, this can lead to reproductive impairment in females and decreased health of cubs, as mothers have less fat stores during winter months. Changes in the proportions of different seal species in the diet of polar bears in Hudson Bay are further evidence of the cascading effects that changing climate and other stressors are likely having on bears in this region. It has also been suggested that changes in ice conditions, as well as specific intraspecies and interspecies competition, have resulted in some bear mortalities in the Beaufort Sea.

Projected climate change is likely to lead to improved habitat conditions for both seals and bears at higher latitudes in the near future, as multi-year ice is replaced with annual ice and more leads and pressure ridges are created. In the longer term, however, it is likely that impacts similar to those currently seen in Hudson Bay will also be experienced in high-latitude areas. The iconic nature of the polar bear as a symbol of the Canadian North has elevated discussion of its fate. Not only are polar bears an important component of the Arctic ecosystem, but they are also a key attraction for many visitors to the North each year, and play a significant role in the culture and economies of many Aboriginal communities. Their economic value in regions where high success is achieved in sport hunts, such as western Hudson Bay and Lancaster Sound, is significant for Nunavut communities, where a tag alone can attract as much as $20 000 from a non-resident hunter, with additional income obtained from guiding and outfitting fees garnered by residents in the community. Thus, the impacts on bears of shifting climate regimes also have implications for tourism, culture and local economies in many regions.

Climate change is expected to affect Arctic biodiversity through changes in the distribution of ranges and habitats of species, the abundance of species, the genetic diversity and behaviour of migratory species, and the introduction of non-native species. Current plans for parks and protected areas adopt a natural region or ecoregion representation approach, designed to protect specific natural features, species and communities of a site. These plans generally do not consider the landscape-level shifts in ecosystem distribution and structure that are likely to result from changing climate.

### *Climate and the Biotic Community*

Life on earth depends on, is shaped by, and affects climate.

A. Individual organisms survive within specific ranges of temperature, precipitation, humidity, and sunlight. Organisms exposed to climate conditions outside their normal range must adapt or migrate, or they will perish.

B. The presence of small amounts of heat-trapping greenhouse gases in the atmosphere warms Earth's surface, resulting in a planet that sustains liquid water and life.

C. Changes in climate conditions can affect the health and function of ecosystems and the survival of entire species. The distribution patterns of fossils show evidence of gradual as well as abrupt extinctions related to climate change in the past.

D. A range of natural records shows that the last 10,000 years have been an unusually stable period in Earth's climate history. Modern human societies developed during this time. The agricultural, economic, and transportation systems we rely upon are vulnerable if the climate changes significantly.

E. Life—including microbes, plants, and animals and humans—is a major driver of the global carbon cycle and can influence global climate by modifying the chemical makeup of the atmosphere. The geologic record shows that life has significantly altered the atmosphere during Earth's history.

# Wildlife in a Changing Climate

There are a number of ways that climate change is beginning to impact wildlife. Temperature increases and changes in precipitation can directly affect species depending on their physiology and tolerance of environmental changes. Climate change can also alter a species' food supply or its reproductive timing, indirectly affecting its fitness. Understanding these interactions is an important step in developing management strategies to help species survive the changing climate.

### *Amphibians and Climate Change*

Several factors contribute to the vulnerability of amphibians to the projected effects of climate change. First consider that for over 20 years, amphibians have been globally recognized as declining. Today, they are among the leading taxonomic groups threatened with losses: about 1/3 of amphibian species are already at risk of extinction. Leading threat factors include habitat loss, disease, invasive species, overexploitation, and chemical pollution. Next, consider their basic biology. Amphibians have been heralded as Canaries in the Coal Mine, being sentinels of a host of environmental changes due to their biphasic life style with life stages relying on both aquatic and terrestrial systems, their moist permeable skin which is a sensitive respiratory organ, and their central position in food webs.

Amphibian species with narrow tolerances for temperature and moisture regimes may be at heightened risk. Amphibians that rely on certain habitat types may be at most risk, for example those found in ephemeral ponds and streams which may dry before the annual reproductive cycle is complete. Many taxa are already experiencing occasional early drying of their habitats, with mass mortality of eggs, tadpoles, and metamorphosing animals resulting. Regions projected to have increasing fluctuations in climate conditions may experience reproductive "bust" years, or episodic mass mortality. Knowing that climate change predictions vary considerably with geographic locations, that there is uncertainty tied to all climate change models, and amphibians are an extremely diverse taxon -a single or simple answer of how amphibians are likely to respond to climate change is not possible.

Several types of likely changes may prove to be lethal to amphibians: altered hydroperiods (timing of water availability); altered seasons and phenology (cyclical timing of events); increased incidence of severe storms and storm surge; rise in sea level; fluctuating weather conditions; and warmer, drier conditions.

Phenology refers to the timing of life cycle events such as breeding and overwintering. Climate change may result in shifts in phenology, especially for species that breed early or late in the season. A shift to earlier breeding may leave amphibians exposed to fluctuating weather conditions. For example, a warm spell in late winter followed by a cold storm after breeding can freeze animals. A deep freeze may penetrate below the ground surface to affect animals emerging in spring, or overwintering hibernacula in winter. Also, survival of annual recruits may be tied to their size at metamorphosis, which may depend upon when breeding occurs.

(prepared by Olson and Saenz 2013a)

In a local example, studies by Bernard 2014 demonstrated that wood frogs breed earlier and produce fewer eggs after warmer winters. They also produce more eggs during winters with more rain and snow.

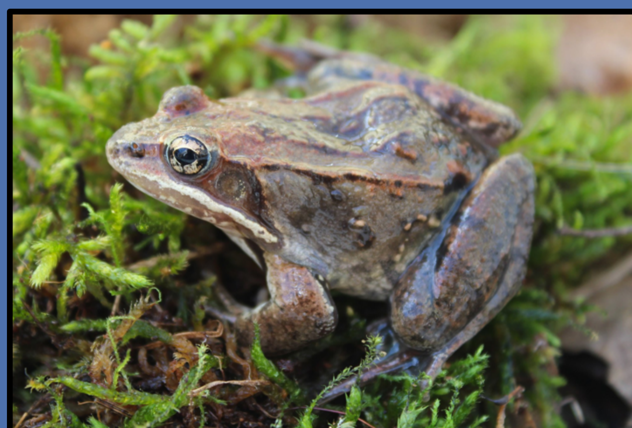


**Figure 16.** Wood frog (*Rana sylvatica*), a common amphibian species in Churchill, Manitoba

*Terrestrial Birds and Climate Change*

A discussion of avian responses to climate change is of interest for a number of reasons. First, because birds are relatively easy to identify and measure and their responses to environmental perturbation are relatively well known, they are useful as indicators of ecological change. Furthermore, birds are of conservation interest in their own right. Bird populations face global conservation challenges, with 1 in 8 species facing a high risk of extinction in the near future according to a recent report. Finally, birds perform significant ecosystem services with consequences for human health and well-being, including pest control, sanitation, seed dispersal and pollination.

Research on birds has shown that climate change affects birds both directly and indirectly. The distributions of birds are closely associated with both winter and summer temperatures, and increased temperatures due to climate change may directly affect birds by forcing them to use more energy for thermoregulation. This can disrupt their maintenance (the energy needed by organisms to maintain their basal levels of activity and condition), reproduction, timing of breeding and migration, and reduce survival or fitness. Birds may respond to these costs by shifting their ranges over time to areas with more suitable thermal conditions, but habitat and other resources may be insufficient or unsuitable for their needs.

Generally speaking, global temperatures decrease with increased latitude and elevation, so a fundamental prediction of climate scientists is that species will shift towards the poles and upward in elevation. Long-term changes in North American bird distributions show clear evidence of latitudinal shifts, with many species shifting their geographic distributions northwards over the past few decades. Elevational shifts have also been reported in long-term datasets, and these shifts appear to implicate changes in precipitation as well as temperature. In the Sierra Nevada mountains, data show that the majority of species ranges have shifted upwards in elevation since the 1940s, with some bird species more closely associated with temperature shifts and others with changes in precipitation.

Climate-related shifts in species distribution along latitudinal and elevation gradients have important implications for conservation. If shifts in temperature take place at a more rapid rate than vegetation responses, or occur beyond the boundaries of suitable potential vegetation, then bird populations could be forced into areas of marginal habitat where they are likely to experience decreased survival and reproduction.

In addition to these direct effects, increased temperatures associated with climate change have the potential to cause a myriad of indirect effects. One of the most widely reported is the de-synchronization of migrant bird reproduction with food resources. Many bird species synchronize their nesting cycle so the period of maximum food requirements of the young coincides with the maximum food availability. In the case of migratory birds, which comprise the majority of species and individuals in many temperate ecosystems, their departures from winter areas are related to photoperiod, whereas the availability of their largely insect food resources is affected by plant phenology.

Since plant phenology is related to climate and is advancing in most regions, migratory bird species are in some cases arriving and therefore breeding too late to keep pace with the timing of their food supply.

Other indirect effects are mediated by changes in the types and timing of disturbance. In parts of the western U.S., climate change is manifested by drought conditions that increase the frequency and severity of wildfires. These disturbances can impact birds directly by destroying nests and altering habitats. West Nile virus models also show climate's influence in this region, predicting disease spread to more western locations and states. This could impact vulnerable birds like the greater sage-grouse, which withdraws during droughts to water sources where it can be infected by mosquitos potentially carrying the virus. Finally, studies of high elevation birds in Arizona show that lower snowpack associated with climate change allows greater access to montane areas by elk, and recent declines in several species of migratory songbirds could be the result of decreased reproductive success resulting from habitat degradation from over-browsing.

There have been dramatic changes in global climate before, however the current challenge to species and ecosystems from climate is not only the degree of change but the rate. Rapid changes in environmental conditions are likely to exceed the ability of many bird species to adapt via natural selection. This concern has led to increased interest in identifying species characteristics associated with vulnerability to climate change. Analyses of data from the Breeding Bird Survey are underway to determine whether traits like migratory status, clutch size, or geographic range affect the vulnerability of bird species to climate change, as indicated by elevational and latitudinal shifts in their distributions. Because responses to climate change are largely species-specific it is expected that species will recombine into novel communities, which could present additional challenges as species are exposed to predators or competitors for whom they have no evolved defenses.

(prepared by King and Finch 2013)

The Grey Jay (*Perisoreus canadensis*), a social, non-migratory, scatter-hoarding resident of boreal and subalpine forests, including those around Churchill, Manitoba. It is an avian species that is likely vulnerable to the impacts of climatic warming. Grey Jays are known to hoard a broad range of perishable food items and , while they are not dependent upon a single food source, they do rely heavily upon reliable food-storage conditions (i.e., consistently cold temperatures).  Further, recent evidence has suggested that Gray Jays are showing a reduced reproductive performance after warmer winters (Whelan et al. 2016). Gray Jays rely on cold temperatures during autumn and winter seasons such that the effects of climate change pose a serious threat for their long-term survival.

**Figure 17.** Grey Jay (*Perisoreus canadensis*), a common bird species in Churchill, Manitoba (photo by Myrna Pearman)

*Mammals and Climate Change*

Climate change is expected to impact most parts of an ecosystem, and mammals are no exception. Some mammals have very specific climatic adaptations, such as requirements for snow, sea ice, or temperatures within a narrow range for hibernation. Some have distributions that are dependent on climate. Most mammals will not be able to avoid the effects of climate change, with both positive and negative effects possible. Mammals generally use a variety of often disjunct resources. They need places to hide, eat, drink, and breed, and in many cases these places are distinct and may change seasonally. Thus, there are many opportunities for climate change to disrupt mammalian life histories. In general, they will not be able to effectively hide in microhabitats; in contrast many plants can persist as rare endemics long after the climate has changed. Most mammals are also highly mobile and, compared to perennial plants, have relatively short (generally < 20 yrs) life spans. Thus, if climates become unsuitable, mammalian response can be expected to be rapid.

Mammals play dominant roles in many systems. They make up most of the terrestrial large-bodied predators in North America, and these large, high-trophic mammals have significant impacts on the ecosystems they inhabit. For example, gray wolf introduction in Yellowstone National Park has reduced the northern elk herd to approximately 1/3 of its former size, which has initiated a cascade of ecological effects. Rodents and lagomorphs (hares, pikas, and rabbits) are the primary prey for many mammalian, avian, and reptilian predators and rodents can affect the composition of vegetative communities through seed predation. Small terrestrial mammals, including rodents and insectivores (shrews), typically comprise the largest and most diverse group of mammals in many ecosystems; thus, most of the changes in mammal abundances and distributions resulting from climate change are expected to be in this group. Additionally, rodents host many diseases that can affect us. Many tick- and flea-borne pathogens that infect humans, including Lyme disease, Rocky Mountain spotted tick fever, Tularemia, plague, and Ehrlichiosis are carried by rodents or rodents serve as the reservoir hosts; the prevalence of these pathogens is often strongly linked to population size and density. Thus, changes in mammal communities will have profound impacts on ecosystems and may directly affect human societies.

The effects of climate changes on mammals can sometimes be ascertained directly through the study of their biology and physiology. For example, once it is understood that wolverines require snow to den and persistent spring snow defines the southern extent of their range, the likely effects of reduced snowpack are straightforward. There is no evidence that wolverines will be able to persist in areas that lose their snow as a consequence of climate change. For most mammals, however, climate broadly defines their ecological niche. Therefore, for many species, future distributions are estimated by correlating climatic factors with their current ranges and projecting these models into the future.

**Figure 18**. Snowshoe hare (*Lepus americanus*) is a common mammal species found around Churchill, Manitoba (photo by Sparky Stensaas)

The snowshoe hare (*Lepus americanus*) is a small lagomorph well-adapted to seasonally snowy environments. Its range includes most of Alaska and Canada, with montane extensions as far south as California and New Mexico in the western U.S. and West Virginia in the eastern U.S. It has oversized rear paws leading to low foot loadings and seasonally changes its pelage from mostly brown to white. Snowshoe hares are typically killed by predators (as opposed to dying of starvation, old age, etc.). Thus, predator avoidance is a critical aspect of snowshoe-hare behavior. Hares may be particularly vulnerable when their coloration does not match the background-a white hare on a brown background is more visible to predators. The period when the landscape is predictably snow covered is extremely sensitive to climate. With climate change, spring snowmelt is predicted to occur earlier and snow cover lost sooner in areas inhabited by the snow show hare. Hare pelage change has limited plasticity in the rate of the spring white-to-brown molt, but both initiation dates of color change and the rate of the fall brown-to-white molt are fixed; unless the timing of coat color change can be modified by natural selection, the reduced snowpack will increase periods of mismatch by 3 - 8 times (Mills et al. 2013).

(prepared by McKelvey et al. 2013)

*Non-Avian Reptiles and Climate Change*

Many reptiles are highly sensitive to the altered temperatures that may result from climate change due to their ectothermy which requires that they rely on ambient environmental temperatures to maintain critical physiological processes. Due to the variety of snakes, lizards, crocodilians, and turtles in our world (traditionally classified as reptiles), and because climate change data and projections vary with location, it will be important to consider each species and location separately when considering the potential effects of altered climate on these animals.

In temperate zones, lizards are thought to be highly vulnerable to climate change. Their reproduction is closely tied to narrow windows of time in the spring and summer when suitable temperature and moisture regimes are available for critical natural history activities, such as foraging and mating. Altered weather conditions during these seasons may result in frequently recurring "bust" years of reproductive failure. Other climate effects on lizard survival include mortality associated with warm spells in winter, interacting effects of altered vegetation communities, fire regimes and invasive species, and potentially disease/pathogens.

Snakes are very closely related to lizards, and these effects may hold true for them as well. Just as with lizards, new studies illustrate species differences: climatic niche models suggest that some rattlesnakes may have smaller ranges; while ratsnakes have increased activities due to warmer night temperatures.

Climate change concerns for turtles and crocodilians are three-fold. First, these mostly aquatic species may encounter altered habitats and increased habitat fragmentation with altered climate. In this regard, they share many concerns with amphibians, such as sensitivity to changes in water availability and its' thermal properties. Second, turtles and alligators have temperature-sensitive sex determination: cooler temperatures may produce nests of only males;

warmer temperatures may produce nests of only females. Temperature changes in a local area may have the effect of altering the sex ratios of populations - potentially affecting future reproduction and over time compromising their evolutionary fitness. Third, coastal species, such as the American Alligator and Crocodile, are susceptible to an increasing frequency or intensity of storms caused by increases in ocean temperatures. Storm surges can displace or drown animals, and dehydrate them by salt water intrusion into freshwater habitats.

The highest biodiversity of non-avian reptiles in the North America is in the southern areas, in desert and subtropical ecosystems. The northern distributions are constrained by latitude, with species richness dropping considerably as you go north. North boundaries of species ranges are often marginal habitats due to climate factors such as cool temperatures and weather variation. Altered thermal niches for non-avian reptiles in these zones due to climate change will be important to track. Briefly, to understand thermal niches, consider that there is a time-window during the day when there are suitable temperatures for non-avian reptile activities. It appears that this time-window is becoming smaller as climate changes are apparent in both tropical and temperate zone regions, reducing the activity times of non-avian reptiles, affecting their reproduction and survival. Although habitat may be marching northward or into mountains for some species, for other species, increased weather variation may alter the frequency or intensity of boom-bust reproductive cycles and cohort survival.

In Alberta, Canada, the Greater Short-horned Lizard, *Phrynosoma hernandesi*, overwinter survival relies on persistent snow cover to retain animals in insulated hibernation: lizards become active during warm spells in winter, and then they can be 'caught out' and die when it snows again.

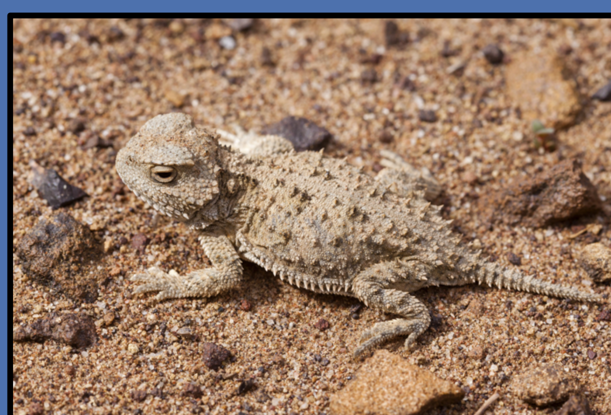


**Figure 19.** Greater Short-horned Lizard, (*Phrynosoma hernandesi*)

Vulnerability assessments and predictions of how habitat distributions will change abound for many taxa. Looming questions are where will suitable habitats occur in the future, and will organisms be able to get there? In our human-altered world, roads and urban-rural development are new hurdles to dispersing reptiles, added to a variety of natural geographic barriers.

(prepared by Olson and Saenz 2013b)

# Anthropogenic Impacts and Climate Change

Human activities (anthropogenic activities) are impacting the climate system.

A. The overwhelming consensus of scientific studies on climate indicates that most of the observed increase in global average temperatures since the latter part of the 20$^{th}$ century is very likely due to human activities, primarily from increases in greenhouse gas concentrations resulting from the burning of fossil fuels.

B. Emissions from the widespread burning of fossil fuels since the start of the Industrial Revolution have increased the concentration of greenhouse gases in the atmosphere. Because these gases can remain in the atmosphere for hundreds of years before being removed by natural processes, their warming influence is projected to persist into the next century.

C. Human activities have affected the land, oceans, and atmosphere, and these changes have altered global climate patterns. Burning fossil fuels, releasing chemicals into the atmosphere, reducing the amount of forest cover, and rapid expansion of farming, development, and industrial activities are releasing carbon dioxide into the atmosphere and changing the balance of the climate system.

D. Growing evidence shows that changes in many physical and biological systems are linked to human-caused global warming. Some changes resulting from human activities have decreased the capacity of the environment to support various species and have substantially reduced ecosystem biodiversity and ecological resilience.

E. Scientists and economists predict that there will be both positive and negative impacts from global climate change. If warming exceeds 2 to 3°C over the next century, the consequences of the negative impacts are likely to be much greater than the consequences of the positive impacts.

Climate change will have consequences for the earth system and human lives.

A. Melting of ice sheets and glaciers, combined with the thermal expansion of seawater as the oceans warm, is causing sea level to rise. Seawater is beginning to move onto low-lying land and to contaminate coastal fresh water sources and beginning to submerge coastal facilities and barrier islands. Sea-level rise increases the risk of damage to homes and buildings from storm surges such as those that accompany hurricanes.

B. Climate plays an important role in the global distribution of freshwater resources. Changing precipitation patterns and temperature conditions will alter the distribution and availability of freshwater resources, reducing reliable access to water for many people and their crops. Winter snowpack and mountain glaciers that provide water for human use are declining as a result of global warming.

C. Incidents of extreme weather are projected to increase as a result of climate change. Many locations will see a substantial increase in the number of heat waves they experience per year and a likely decrease in episodes of severe cold. Precipitation events are expected to become less frequent but more intense in many areas, and droughts will be more frequent and severe in areas where average precipitation is projected to decrease.

D. The chemistry of ocean water is changed by absorption of carbon dioxide from the atmosphere. Increasing carbon dioxide levels in the atmosphere is causing ocean water to become more acidic, threatening the survival of shell-building marine species and the entire food web of which they are a part.

E. Ecosystems on land and in the ocean, have been and will continue to be disturbed by climate change. Animals, plants, bacteria, and viruses will migrate to new areas with favorable climate conditions. Infectious diseases and certain species will be able to invade areas that they did not previously inhabit.

F. Human health and mortality rates will be affected to different degrees in specific regions of the world as a result of climate change. Although cold-related deaths are predicted to decrease, other risks are predicted to rise. The incidence and geographical range of climate- sensitive infectious diseases—such as malaria, dengue fever, and tick-borne diseases—will increase. Drought-reduced crop yields, degraded air and water quality, and increased hazards in coastal and low-lying areas will contribute to unhealthy conditions, particularly for the most vulnerable populations.

## Climate Change Impacts on Communities and Health

Communities throughout the North are already reporting impacts and challenges associated with climate change and variability. The distribution of economic, health, cultural and social impacts associated with changing climate will vary across regions and among segments of the population. Furthermore, climate is only one of several factors whose changes are influencing the nature of settlements and populations in the three Canadian territories. It is the interactions and effects of ongoing changes in human, economic and biophysical systems, exacerbated by changes in regional and local climate, that are disproportionately influencing the health and well-being of northern residents.

### *Direct impacts on health and well-being*

The direct influences of climate on human health and well-being in northern communities are primarily related to extreme weather and temperatures, and natural hazards.

Residents of small, predominantly Aboriginal communities in all regions of the Canadian Arctic have reported that the weather has become less predictable and, in some cases, that storm events progress more quickly today than in previous memory. This unpredictability limits participation in land-based and subsistence activities and travel, and increases the risks of being stranded or involved in accidents on the land. Some northern communities have found it harder to obtain wild sources of food due to the shorter snow cover season (which affects travel to hunting grounds as well as animal habitat). The thinning of sea ice and the lengthening melt season also affect access to resources.

Extremes of temperature, both cold and heat, influence health directly. The Council of Yukon First Nations has reported that 7% of injuries among youth are cold related, such as hypothermia and frostbite, and reports of heat-related stress are being recorded, predominantly among elderly residents, in a number of regions. Qualitative data suggest that the incidence of accident-related injuries attributable to weather conditions is increasing in smaller coastal communities throughout the North. Although preliminary analysis shows increased daily variability of weather in Nunavut, and climate models project an increase in the frequency and severity of extreme events (storms, floods, icing of snow layers, drought), the impacts of such events on health remain difficult to project.

In response to changing weather conditions, northern residents identified the need for improved infrastructure to communicate weather information, including cellular and improved citizens band radio service, and the need to construct more permanent shelters on the land as refuges from storms. People are also becoming more risk averse, with some residents curtailing hunting and travelling activities to avoid storms. Increased use of global positioning systems (GPS) for navigation, and of larger or faster vehicles, was reported among hunters in several communities to compensate for unpredictable or challenging weather. However, these adaptations can also increase exposure to risk by raising the sense of security among hunters and increasing the amount of travel in dangerous circumstances.

**Table 2.** Summary of potential, direct, climate related health impacts in northern regions (adapted from Furgal et al., 2002 and Furgal and Prowse 2008).

| Identified climate-related change | Potential direct health impacts |
|---|---|
| Increase in temperature extremes (magnitude and frequency) | Increased heat- and cold- related morbidity and mortality |
| Increase in frequency and intensity of extreme weather events (e.g., storms, etc.)<br>Increase in uncharacteristic weather patterns | Increased frequency and severity of accidents while hunting and travelling, resulting in injuries, death, and psychosocial stress |
| Increase in ultraviolet-B exposure | Increased risk of skin cancers, burns, infectious diseases, eye damage (cataracts), immunosuppression |

Documentation of experience with weather-related natural hazards, such as avalanches, is limited in northern regions. Fatal avalanches and property damage have been recorded in Nunavik (Arctic Quebec), Nunavut, the Northwest Territories and the Yukon, but they are far less common than in British Columbia and Alberta. Future climate change may bring higher risks of avalanches and floods from rapid melting in some regions of the Arctic.

### *Indirect impacts on health and well-being*

Indirect influences of changing climate on northern communities and residents' health and well-being result from shifts in ice conditions, changes in exposure to emerging diseases, changes and impacts to aspects of food security, implications of permafrost melting for community infrastructure, and the combined effects of environmental and other forms of change on northern residents.

**Table 3.** Summary of potential indirect climate-related health impacts in northern regions (adapted from Furgal et al., 2002 and Furgal and Prowse 2008).

| Identified climate related change | Potential indirect health impacts |
|---|---|
| Increase in temperature extremes (magnitude and frequency) | Increased incidence and transmission of infectious disease, psychosocial disruption |
| Decrease in ice distribution, stability, and duration of coverage | Increased frequency and severity of accidents while hunting and traveling, resulting in injuries, death and psychosocial stress<br>Decreased access to country food items, decreased food security, erosion of social and cultural values associated with country foods preparation, sharing and consumption |
| Change in snow composition (decrease in quality of snow for igloo construction with increased humidity) | Challenges to building shelters (igloo) for safety while on the land |
| Increase in range and activity of existing and new infective agents (e.g. biting flies) | Increased exposure to existing and new vector-borne diseases |
| Change in local ecology of water and food-borne infective agents (introduction of new parasites and perceived decrease in quality of natural sources) | Increased incidence of diarrheal and other infectious diseases<br>Emergence of new pathogens |
| Increase in permafrost melting, decrease in land surface stability | Negative impacts on stability of public health, housing and transportation infrastructure<br>Psychosocial disruption associated with community relocation (partial or complete) |
| Sea-level rise | Psychosocial disruption associated with infrastructure damage and community relocation (partial or complete) |
| Changes in air pollution (contaminants, pollens and spores) | Increased incidence of respiratory and cardiovascular diseases, increased exposure to environmental contaminants and subsequent impacts |

### *Ice Conditions and Safety*

Scientific studies and local Aboriginal observations have reported an increasing length of the ice-free season and decreasing ice thickness and extent of sea-ice cover. In addition to the implications of changes in ice conditions, as described above, such changes are also important for many traditional and subsistence activities. Sea-ice provides a stable travelling and hunting platform for northern residents and is critical to the reproduction and survival of several Arctic marine species. The increased mobility of sea ice, as well as the increased export of land ice into the ocean, lead to an increase in marine ice hazards.

Inuit residents have reported recent changes in ice characteristics, increasing danger and decreasing access to hunting areas and country/traditional foods throughout the territories. A perceived increase in the number of accidents and drownings associated with ice conditions may be reflected in statistics showing a higher incidence of accidental deaths and injuries in smaller settlements of the Northwest Territories. Increased velocity and volume of spring run-off from melting ice and snow create hazardous conditions for young children in northern communities. Economic impacts arising from changes in ice conditions include lost earnings from reduced seal or narwhal harvests, damage to equipment and loss of access to wildlife food resources. These changes also have a negative impact on social cohesion and mental well-being by disrupting the traditional cycle of land- based practice.

### *Food Security*

The diet of many northern residents is a combination of imported foodstuffs and locally harvested foods (country/traditional foods). These foods from the land and sea, including animal and plant species, contribute significant amounts of energy and protein to the total diet, help individuals meet or exceed daily requirements for several vitamins and essential elements, and provide protection from some forms of cardiovascular disease and, potentially, contaminant toxicity. The proportion of the total diet consisting of country/traditional foods is significantly higher among Aboriginal residents and older age groups.

Hunting, fishing and gathering also figure prominently in the cash economy of northern communities, and are important for maintaining social relationships and cultural identity among Aboriginal populations. The dependence on country/traditional foods is greater in more remote communities, where access to affordable, fresh market foods is significantly less. Despite their importance, there has been a shift away from country/traditional foods and an increase in the amount of store-bought foodstuffs in the diet of northern populations, especially among younger ages and residents of those communities with greater access to store foods.

Shifts in animal distributions and local ecology, and changes in northerners' access to country/traditional food species as a result of changing climate have significant implications for food security. Climate-related changes in terrestrial and marine species are reported to be affecting harvests of wildlife in some regions. For example, Inuvialuit residents have reported changes in fish and wildlife distributions in addition to the severe storms and changes in sea-ice and permafrost stability, all of which make harvesting more difficult. Many other northern communities have also reported impacts on country/traditional food security as a result of changing environmental conditions. These challenges are not limited to coastal communities.

Country/traditional food items are also the largest source of exposure to environmental contaminants for northern residents. Climate change will likely enhance transport, deposition and uptake into Arctic wildlife of contaminants, thereby influencing human exposures. These chemicals are known to adversely affect immune and neuromotor functioning in children. Current levels of exposure to mercury and organochlorine contaminants among some segments of the population in Nunavut already exceed recommended safety guidelines.

Increased temperatures and lengthening growing seasons present opportunities for the development and enhancement of small-scale northern agriculture, particularly in the western Arctic. Such opportunities would create additional and more cost-effective local sources of some food items. Increased warming will also lengthen the ice-free seasons and increase navigability of northern waters, and could therefore increase the frequency of transport to communities and reduce costs associated with some market items.

### *Water Quality*

There are significant concerns about access to, and quality of, freshwater resources in many northern communities. Climate-related impacts on the quantity, quality and accessibility of drinking water resources are expected to affect mainly smaller, remote northern communities, some of which face challenges in effectively utilizing municipal treatment systems. Increasing temperatures in the western Arctic have resulted in increased algal and plant growth, making untreated water sources less desirable.

Decreases in water quality and accessibility have resulted in northern residents becoming increasingly reliant on bottled water when hunting and fishing away from the community. Several communities have reported the need for more frequent water-quality testing of both municipal systems and untreated water sources to ensure safety and confidence in drinking water.

### *Community Infrastructure*

Communities and infrastructure built on frozen soils are significantly affected by thawing permafrost, one of the most economically costly impacts of climate change in the Arctic. The bearing capacity of building foundations has declined by 40–50% in some Siberian settlements since the 1960s, and the vast Bovanenkovo gas field in western Siberia has seen a recent increase in landslides related to thawing permafrost. Thawing permafrost may also contaminate freshwater resources when previously frozen industrial and municipal waste is released.

Low-lying coastal communities in areas of high risk of permafrost melting (i.e. areas with significant massive ground ice) are most vulnerable to infrastructure damage. Some communities in these regions are already reporting damage to community buildings from the combined forces of coastal erosion and permafrost degradation. Permafrost degradation and coastal erosion are also damaging important cultural sites and may mean partial or complete relocation of communities in the future. Although the shoreline in some communities has been reinforced to reduce coastal erosion associated with increased storm surges, decreasing sea-ice cover and increasing water levels, this is only a temporary solution. In many communities, residents are moving buildings back from the shoreline in response to erosion.

### *Multiple Stressors and Impacts*

Changes in environmental conditions also influence the mental health and well-being of many northern residents whose livelihood and ways of life are strongly connected to the local environment. This is especially the case for the approximately half of Arctic residents whose culture, language and identity are tied inextricably to the land and sea via their Aboriginal heritage and identity. Disruption of traditional hunting cycles and patterns, reduced ability of elders to predict weather and provide information to others in the community, and concern over losses of cemeteries and homes due to coastal erosion all represent forms of social disruption in communities already undergoing significant change as a result of both internal and external forces. These stresses resulting from these multiple changes have been associated with symptoms of psychosocial, mental and social distress, such as alcohol abuse, violence and suicide.

Each region in Northern Canada is unique with regards to the environmental, social, cultural, economic and political forces that influence change at the local and regional scales. This is very important for regions or communities undergoing various forms of rapid change in many sectors at the same time. For example, the increased growth of the wage economy in many regions has reduced both the necessity for, and time available for, hunting, fishing and gathering. This, in turn, has reduced the generation and transmission of traditional knowledge and environmental respect to younger generations, as well as diminishing the health benefits from the consumption of local foods. However, access to the cash economy provides resources for adaptation via the purchase of hunting equipment (e.g. boats, ATVs, snowmobiles) that, in turn, permits individuals to hunt more species over a larger geographic area. Dominant driving forces of change in any one community or region may be enhanced, reduced or altered by aspects of a changing climate. After reviewing key forces and their interactions, it has been reported that the deterioration of cultural ties to traditional and subsistence activities, and all they represent, is the most serious cause of decline in well-being among Aboriginal people in circumpolar Arctic regions today.

## Global Implications

Changes in the Arctic affect the rest of the world, not only in obvious ways (such as the Arctic's contribution to sea-level rise), but through the Arctic's role in the global climate system, its influence on ocean circulation, and its impacts on mid- latitude weather.

A. Coastal communities, low-lying islands, and ecosystems throughout the world will be affected by the melting of land ice (glaciers and ice sheets) in the Arctic, which is projected to increase the rate of global sea-level rise. Impacts include coastal flooding, erosion, damage to buildings and infrastructure, changes in ecosystems, and contamination of drinking water sources.
B. The implications mentioned above for shipping; access to oil, gas, and minerals; and impacts to fisheries have economic consequences outside the Arctic.
C. Changes in Arctic sea ice cover, marine ecosystems, and the water cycle affect the amount of carbon dioxide that the Arctic Ocean absorbs from the atmosphere. The ocean becomes more acidic as it absorbs more carbon dioxide, with potential implications for marine life. Changes in snow cover and permafrost also affect carbon and nitrogen cycling, as well as methane emissions.

## Climate Science Literacy

Climate science literacy is an ongoing process. No single person is expected to understand every detail about all of the fundamental climate science literacy concepts. Full comprehension of these interconnected concepts will require a systems-thinking approach, meaning the ability to understand complex interconnections among all of the components of the climate system. Moreover, as climate science progresses and as efforts to educate the people about climate's influence on them and their influence on the climate system mature, public understanding will continue to grow.

Climate is an ideal interdisciplinary theme for lifelong learning about the scientific process and the ways in which humans affect and are affected by the Earth's systems. This rich topic can be approached at many levels, from comparing the daily weather with long- term records to exploring abstract representations of climate in computer models to examining how climate change impacts human and ecosystem health. Learners of all ages can use data from their own experiments, data collected by satellites and other observation systems, or records from a range of physical, chemical, biological, geographical, social, economic, and historical sources to explore the impacts of climate and potential adaptation and mitigation strategies.

### *How do we know what is scientifically correct?*

Science is an on-going process of making observations and using evidence to test hypotheses. As new ideas are developed and new data are obtained, oftentimes enabled by new technologies, our understanding evolves. The scientific community uses a highly formalized version of peer review to validate research results and our understanding of their significance. Researchers describe their experiments, results, and interpretations in scientific manuscripts and submit them to a scientific journal that specializes in their field of science. Scientists who are experts in that field serve as "referees" for the journal: they read the manuscript carefully to judge the reliability of the research design and check that the interpretations are supported by the data. Based on the reviews, journal editors may accept or reject manuscripts or ask the authors to make revisions if the study has insufficient data or unsound interpretations. Through this process, only those concepts that have been described through well- documented research and subjected to the scrutiny of other experts in the field become published papers in science journals and accepted as current science knowledge. Although peer review does not guarantee that any particular published result is valid, it does provide a high assurance that the work has been carefully vetted for accuracy by informed experts prior to publication. The overwhelming majority of peer-reviewed papers about global climate change acknowledge that human activities are substantially contributing factors.

### *What is climate science literacy?*

Climate science literacy is an understanding of your influence on climate and climate's influence on you and society.

A climate-literate person:

A. Understands the essential principles of Earth's climate system,

B. Knows how to assess scientifically credible information about climate,

C. Communicates about climate and climate change in a meaningful way, and is able to make informed and responsible decisions with regard to actions that may affect climate.

### *Why does climate science literacy matter?*

- During the 20th century, Earth's globally averaged surface temperature rose by approximately 0.6°C, additional warming of more than 0.14°C has been measured since 2000. Though the total increase may seem small, it likely represents an extraordinarily rapid rate of change compared to changes in the previous 10,000 years.

- Over the 21$^{st}$ century, climate scientists expect Earth's temperature to continue increasing, very likely more than it did during the 20$^{th}$ century. Two anticipated results are rising global sea level and increasing frequency and intensity of heat waves, droughts, and floods. These changes will affect almost every aspect of human society, including economic prosperity, human and environmental health, and national security.

- Scientific observations and climate model results indicate that human activities are now the primary cause of most of the ongoing increase in Earth's globally averaged surface temperature

- Climate change will bring economic and environmental challenges as well as opportunities, and citizens who have an understanding of climate science will be better prepared to respond to both.

- Society needs citizens who understand the climate system and know how to apply that knowledge in their careers and in their engagement as active members of their communities.

- Climate change will continue to be a significant element of public discourse. Understanding the essential principles of climate science will enable all people to assess news stories and contribute to their everyday conversations as informed citizens.

## Climate Change Models and Changes in Canada's Climate

A new series of maps made by climatologists at the *Prairie Climate Centre* highlights just how vulnerable Canada is to continued climate changes. The maps illustrate how temperature and precipitation are likely to change in the future under two hypothetical warming scenarios: a 'low carbon' scenario that assumes the international community will get together very soon to drastically reduce greenhouse gas emissions (known in the scientific community as RCP4.5), and a 'high carbon' scenario which assumes the opposite – that humanity will continue to emit more and more greenhouse gases into the atmosphere well into the future (RCP8.5). Presently, we are trending very close to the high carbon scenario.

(1) **The maps show that all of Canada is projected to get warmer in the future, even under a low-carbon scenario**
- This result is important because it underscores the need for more climate change adaptation planning in Canada. It is of course urgently necessary that we reduce greenhouse gas emissions to prevent the most dire climate change consequences, but we must also accept the reality that at least some climate change impacts are all but guaranteed.

(2) **Canada's Arctic will warm much faster than Canada's South**
- At first blush, it may seem unimportant that Canada's vast Arctic is expected to become much warmer in the future – after all, temperatures in the high Arctic routinely dip below -40 °C. However, the Arctic is an important component of the global climate system. Sea ice and snow in particular help reflect unwanted solar energy back to space, so the continued loss of these shiny surfaces is amplifying planetary warming.

(3) **December and January are expected to warm much faster than the other months**
- Warmer winters may sound like a good thing. However cold winter days are vital. Cold temperatures help keep agricultural and forest pests and invasive species at bay. Cold winters are needed for winter roads, which are relied upon by tens of thousands of Canadians.

(4) **Southern Canada is projected to get much wetter throughout the spring, fall and winter months, but much drier in the summer**

- Wetter winters and springs will undoubtedly increase the risk of flooding in many areas, whereas drier summertime conditions can increase the risk of severe drought and wildfire.

*Data & Methods*

These maps were produced from a group of 12 global climate models supplied by the *Pacific Climate Impacts Consortium.* These maps are called 'delta' maps (delta means *change*). They are produced by first finding average climate condition for a specific month in the future and then *subtracting* the average values for that same month in the past. In other words, these maps show the difference between current climate conditions and projected, future climate conditions. We used two 30-year future periods (2021-2050 and 2051-2080). Our "current" period was set to 1976-2005.

*Important things to know about this climate model data*

The daily climate model data we used was *statistically* generated from monthly General Circulation Model outputs. As such, there are some limitations on how this data can be used and interpreted. Precipitation is much more difficult to model than temperature. The range of possible extreme precipitation events are (in many cases) much higher in real-life than in the modelled data. To address this problem, we rely on using an ensemble of 30-year averages, which should approximate this natural variability.

In meteorology, the mean temperature reflects the average of all temperature measurements made in a day (typically the average of 24 hourly measurements). Because we only had access to the daily max and daily min temperatures, we defined (as is very common in climatological research) mean temperature as the average of the daily max and daily min temperature.

The climate model data is *downscaled* to a 10 km by 10km grid by statistically meshing the climate model data through a set of *modeled and interpolated* observed data produced by Natural Resources Canada. Any errors or misrepresentations in the Natural Resources Canada gridded dataset, therefore, are transferred to the downscaled climate model data. Misrepresentations in the interpolated historical data are possible when

A. There are temporal gaps in the raw weather station data
B. There are large geographic distances between weather stations
C. There are mountains present
D. There are large contrasts in microclimate inside of a 10km by 10km region. In short, the climate model data we use is most prone to error over mountainous regions, rural regions across all of Canada, and all northern Canada.

**Please note, students are not responsible for remembering the entire figures below (Figure 22-26), just the general trends.**

(prepared by Ryan Smith, *Climate change researcher*, Prairie Climate Centre)

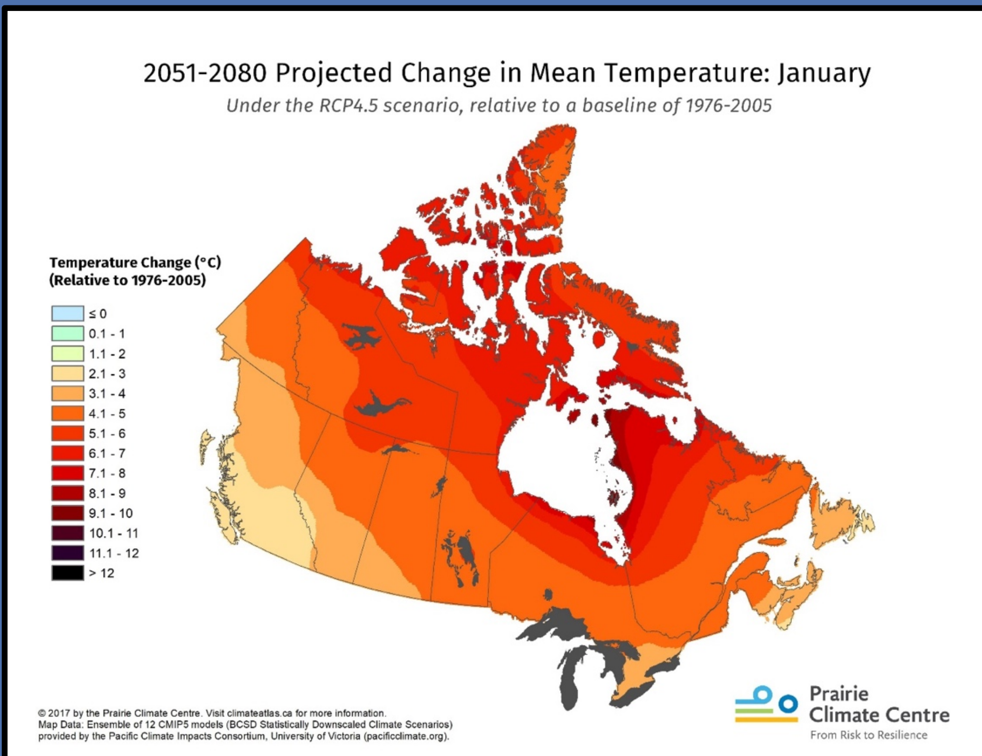



**Figure 20.** Darker red colours illustrate regions that are expected to warm fast. This particular map shows how January temperatures will likely change under a low-carbon emissions scenario

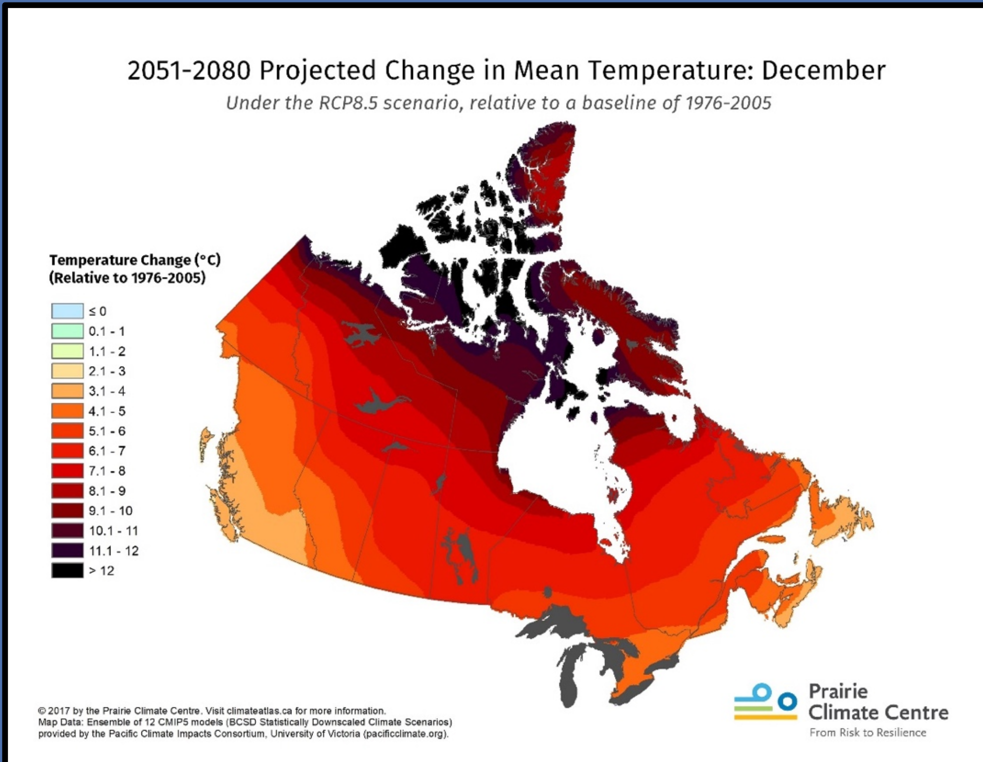



**Figure 22.** The month of June (below) is projected to warm much less than the month of December.

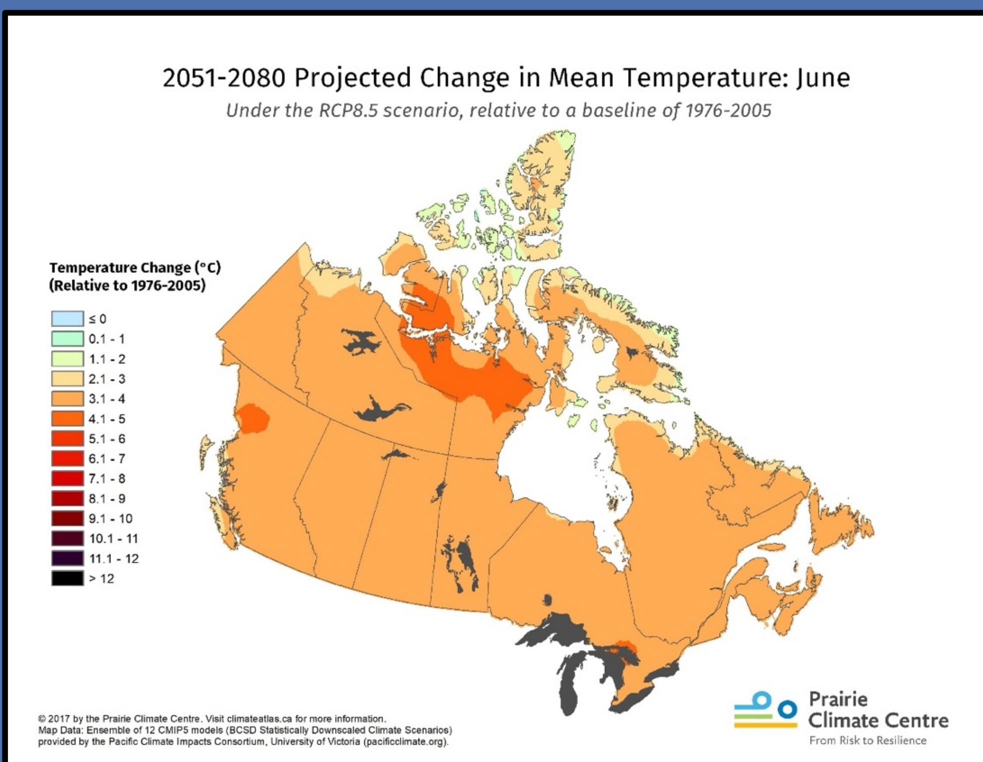



**Figure 21.** The month of December (above) is projected to warm much more than the month of June.

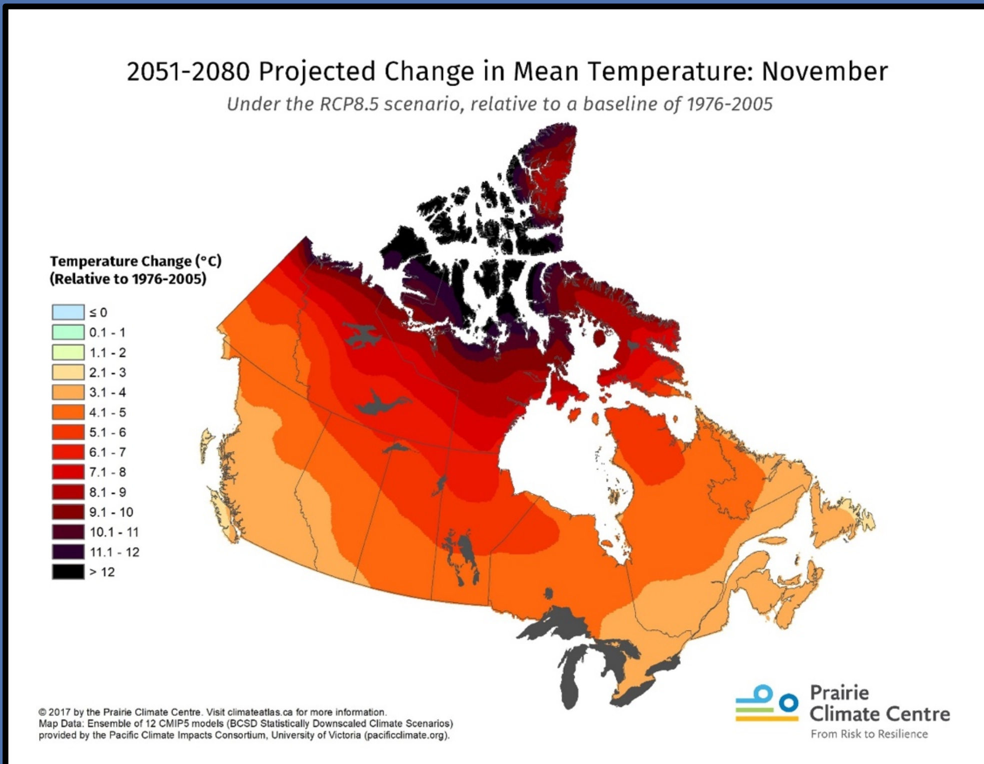
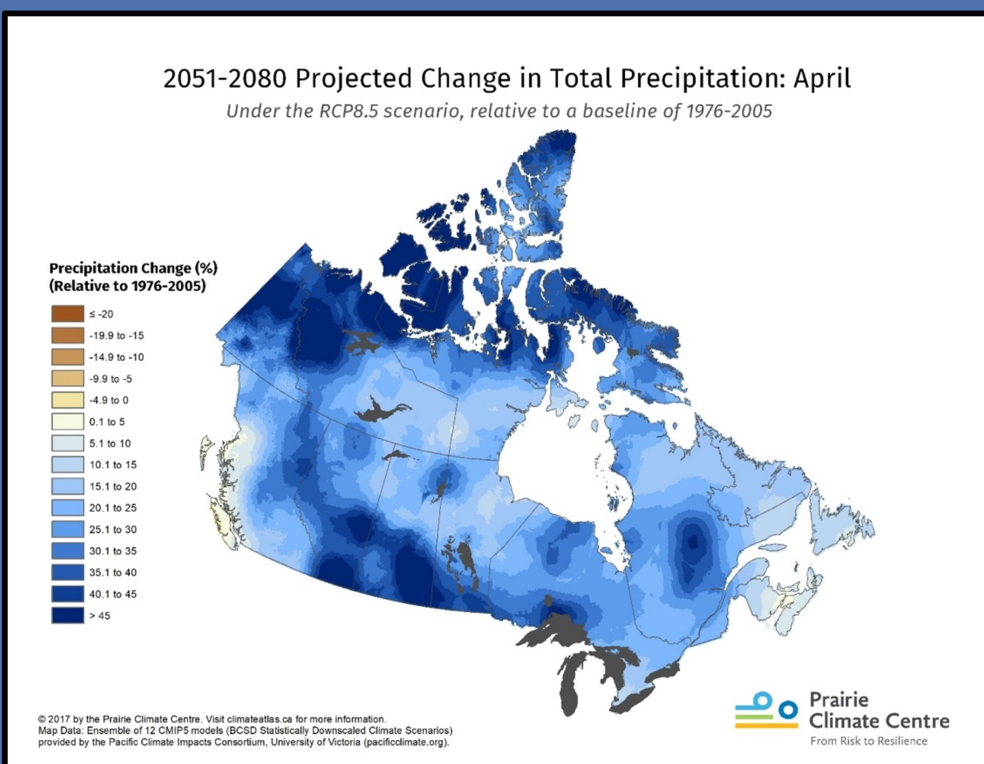



**Figure 23.** In some months, the Arctic is projected to warm by more than 12 °C by the end of this century. That's way higher than the global average



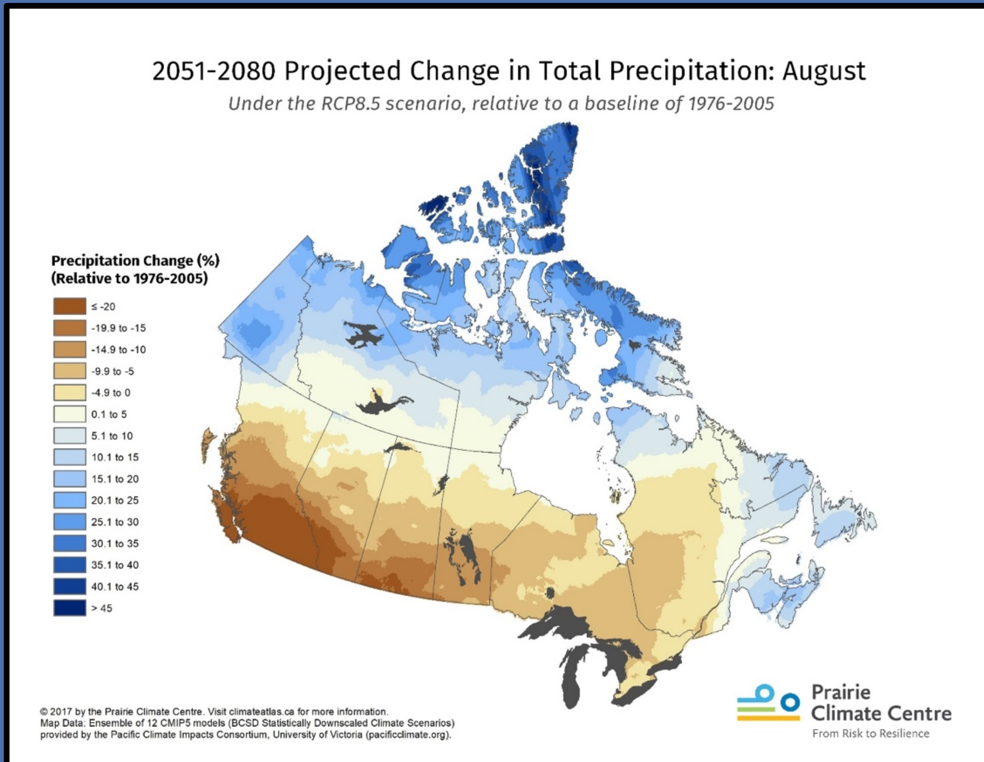



**Figure 24.** Differences in projected changes in precipitation between April and August in the same area for the same period of time (2051-2080) (see previous page).

## Key Definitions

**Ablation** - the removal of snow and ice by melting or evaporation, typically from a glacier or iceberg.

**Climate** - the long-term average of conditions in the atmosphere, ocean, and ice sheets and sea ice described by statistics, such as means and extremes.

**Cryosphere** – places where water is in its solid form, frozen into ice or snow.

**Isostatic rebound** - (also called continental rebound, post-glacial rebound, or isostatic adjustment) is the rise of land masses that were depressed by the huge weight of ice sheets during the last ice age

**Permafrost** - ground which remains frozen for at least two consecutive years.

**Thermohaline circulation** - Winds drive ocean currents in the upper 100 meters of the ocean's surface. However, ocean currents also flow thousands of meters below the surface. These deep-ocean currents are driven by differences in the water's density, which is controlled by temperature (thermo) and salinity (haline). This process is known as thermohaline circulation.

**Weather** - the specific conditions of the atmosphere at a particular place and time, measured in terms of variables that include temperature, precipitation, cloudiness, humidity, air pressure, and wind.

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