2

The Physical Base

An understanding of the physical geography of the Canadian North provides the essential background necessary to appreciate the delicate balance among the North's physical base, human population, resource development, and fragile environment. An important feature of the North's physical base is the interrelationship between its various physical elements, but especially between climate, natural vegetation, soils, and permafrost. The five geomorphic regions, which provide much diversity within the North, are another notable characteristic of northern geography. Finally, the Arctic Ocean, its ice cover, and its role in global oceanic circulation and climate change are considered in this chapter.

Climate change has turned the usually stable feature of physical geography into something much more dynamic. For centuries, ice shelves on Ellesmere Island were at an equilibrium state and thus represented stability. This has changed rather suddenly. As reported in August 2010 (Smith, 2010), Professor John England observed a large piece of ice, perhaps the size of Bermuda, breaking off from the Ward Hunt Ice Shelf on Ellesmere Island in Nunavut. England concluded that the ice shelf itself is badly fractured and rapidly failing.

Of all the regions of Canada, the North has the narrowest range of natural resources, the most demanding physical conditions for settlement and resource development, and the most delicate environment. Unusually warm summers in recent years have affected the North, causing glaciers and sea ice to melt and permafrost to thaw. If this warming trend continues into the rest of the twenty-first century, the North's physical base will be greatly modified, with much of the permafrost and Arctic ice pack disappearing, the boreal forest extending far northward, and the Northwest Passage becoming ice-free for much of the year.

Overview

The North is a vast area consisting of more than three-quarters of the land mass of Canada. Within this cold **land mass**, the latitude ranges from 50° to 83°N. Not surprisingly, the North's physical character varies from place to place. To appreciate and at the same time to simplify these variations, our attention is focused on the broad spatial

Figure 2.1 Northern Edge of the Boreal Forest in the Mackenzie Delta

At the northern verge of the boreal forest, wetlands (lakes, muskeg, and peat bogs) are interspersed with black and white spruce trees. Under a warmer climate induced by global warming, longer and warmer summers could, by the end of the twenty-first century, change this forest/tundra transition zone into a closed boreal forest zone and extend the forest/tundra transition zone into some of the islands of the Arctic Archipelago.

Source: Staffan Widstrand/Nature Picture Library.

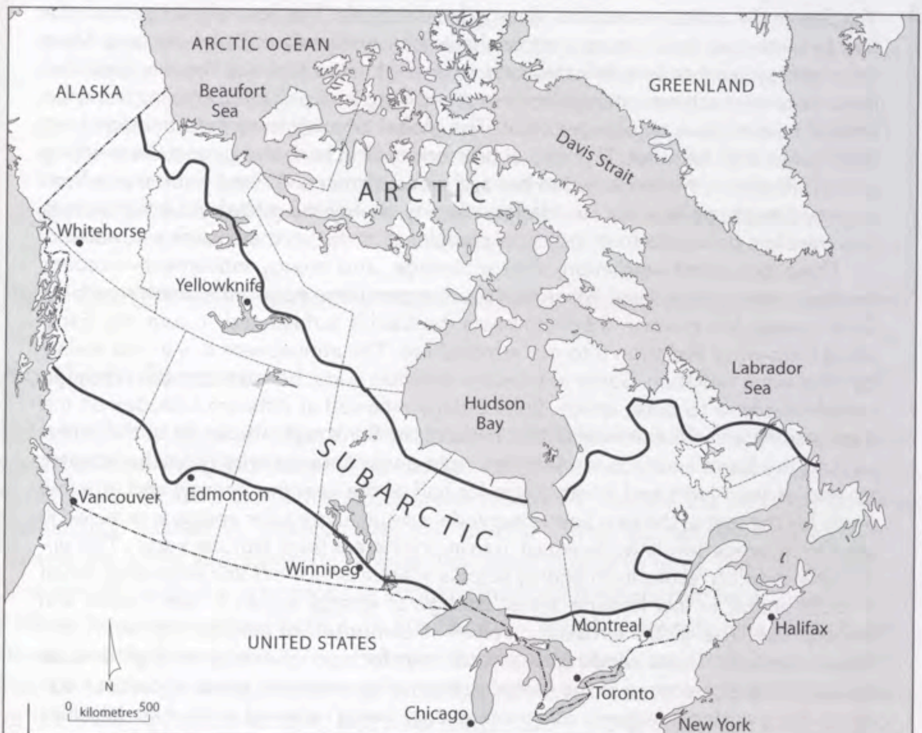
Vignette 2.1 Climate Change and Global Warming

Global warming refers to higher average annual temperatures that are leading to the warming of the planet and these higher temperatures are caused by the increase in greenhouse gases in the atmosphere. Known as the **greenhouse effect**, these gases, which trap solar energy and thus warm the Earth, are increasing due to the burning of fossil fuels. **Climate change** is a much broader term that encompasses all aspects of weather. Global warming, if sustained, could result in dramatic climatic changes. For example, higher temperatures could alter the global energy balance (see Vignette 2.2). By doing so, global warming could cause climatic change because, as the Earth's average temperature increases, winds and ocean currents move that heat around the globe, triggering long-term changes in weather conditions and, eventually, altering the geographic extent of natural vegetation zones, permafrost, and sea ice. Predictions of much warmer global temperatures for the late twenty-first century suggest a dramatic climatic change perhaps exceeding temperatures thought to have occurred in Climatic Optimum some 5,000 to 9,000 BP (Table 2.2).

patterns making up the North's physical base. These broad spatial patterns are represented by two natural regions or biomes, the Arctic and Subarctic (Figure 2.2), and these two biomes provide a context for discussing the complexities and diversity of the physical geography of the North. But first we must consider the basic natural characteristics of the North. Without a doubt, its polar climate dominates and shapes other northern elements. This climate is split into Arctic and Subarctic components that are associated with the Arctic and Subarctic biomes. Within each biome, natural vegetation, soils, wildlife, and humans have had centuries to adapt to the relatively stable climatic conditions. One challenge facing scientists and northerners is the impact that global warming will have on the biophysical nature of the North and the geographic extent of the Arctic and Subarctic biomes.

Climate determines the particular natural rhythm of the North, including the spring migration of the caribou herds to the tundra, the extreme variation in amount of daylight from summer to winter, and the dramatic release of water from ice-locked lakes and rivers every spring. Climate, too, determines the location of the treeline, beyond which summer growing conditions are too cold for tree growth. The treeline marks the natural boundary separating the Arctic and Subarctic biomes.

Figure 2.2 Arctic and Subarctic Biomes



The natural division of the Canadian North into the Arctic and Subarctic biomes has biological, economic, and cultural implications. These implications focus on biodiversity and ecozones, the impact of resource companies on the environment, and the concept of traditional homelands for Indians and Inuit.

But the North's physical geography was also affected by past climates. Some 16,000 to 25,000 years ago, extremely low world temperatures associated with the Late Wisconsin ice advance dramatically altered the North's physical geography by freezing the ground to great depths, thus creating permafrost; by covering land with a continental ice sheet whose enormous weight depressed the Earth's crust; and, as the huge ice sheet slowly advanced, by scraping and scouring the landforms beneath the ice sheet. From this extremely cold climate, unique natural features emerged, such as patterned ground, permafrost, the polar ice cap, and pingos. With the post-ice age climate warming over the last 15,000 years, the Arctic and Subarctic biomes gradually expanded and eventually reached their present geographic arrangement.

The Arctic and Subarctic form the broad natural framework within which ecosystems and ecozones are found and, combined, constitute the northern environment. As a natural hierarchical structure, the two biomes provide the first division of the cold environment, followed by ecosystems and ecozones, which are simply smaller and more precise natural units. These natural units took hundreds, if not thousands, of years to develop their unique biological communities that interact with one another within a

Vignette 2.2 The Global Energy Balance

The Sun is the primary source of energy for the Earth. The flow of energy from the Sun to Earth and then into our atmosphere is an extremely complex process. Most solar energy reaches low latitude areas while high latitude areas like the Canadian North receive much less energy. The former are described as having an energy surplus while the latter have an energy deficit. The **global circulation system** transfers heat from low to high latitudes. This spatial differentiation in solar energy and the resulting global circulation system form the basis of world climates. Air and water move from tropical areas to polar areas. Besides transferring energy, the global circulation system also transfers pollutants from industrial complexes to the northern lands and water.

Three processes—radiation, energy storage, and energy movement—account for the variation in annual mean surface temperatures across the Earth's surface. Solar energy (short-wave radiation) heats the Earth's surface and, in turn, the Earth emits long-wave radiation into our atmosphere. The atmosphere is warmed mainly by long-wave radiation. Some long-wave radiation is lost because it passes through our atmosphere to outer space. Solar energy received at different latitudes on the Earth's surface varies because of the angle of the Sun's rays. The angle of these rays striking the Earth's surface ranges from right-angle (intense energy) at the equator to zero at the North and South poles for half of the year (no energy) and at a low angle for the rest of the year (low energy). As a result, more solar energy is received in equatorial areas (low latitude areas) than in polar areas (high latitude areas). This differential heating results in an energy surplus in equatorial areas and an energy deficit in polar areas. In low latitude areas, storage of energy occurs in the oceans and atmosphere. The global circulation system is comprised of atmospheric winds and ocean currents. These winds and currents transfer surplus energy to high latitude areas. However, because of the global pattern of atmospheric winds and ocean currents, this transfer is uneven, with more energy being received in the high latitudes of the west coasts of North America and Europe. At the same time, cold deepwater flows from the Arctic Ocean into the North Atlantic Ocean.

particular geographic area. Another important factor related to the northern environments is that, over this long time period, the number and variety of species inhabiting a particular geographic area or habitat have increased. Known as **biodiversity**, this has become one of the major environmental issues of our time, with the fear being that change—induced by human and natural causes—could reduce the region's biodiversity. Human causes are related to resource development and the growth of settlements, both of which have a negative impact on the North's fragile environment and therefore on its biodiversity (Vignette 2.3). Among the principal human impacts are clear-cut logging in the boreal forest, mining activities that introduced toxic wastes to the environment, and hydroelectric projects that result in an industrial landscape by creating reservoirs and altering the seasonal flow of rivers. Natural causes, which, indirectly, are also largely of human origin, are related primarily to global warming, which may see the Arctic environment greatly reduced in size and its species, such as the polar bear, threatened.

Vignette 2.3 A Fragile Environment

The northern environment is often described as fragile, meaning that the risk of anthropogenic damage is much higher in the North than in other regions of Canada. The primary reason for this regional variation is the much greater length of time required for nature to repair human damage to a northern environment compared to the time required in more temperate regions of the world. One illustration of the delicate nature of this cold environment is revealed by the relationship of temperature and precipitation to plant growth. Plant growth varies with temperature and precipitation. A combination of low temperatures and meagre precipitation results in very low levels of biological activity and, hence, a longer period of time is required for nature to heal itself. The same rule applies within the North, where the Subarctic can recover more quickly from physical damage because it has a longer and warmer summer plus more precipitation than the Arctic.

Northern Biomes

The complexity of the northern environment is revealed in both the formation and nature of its northern biomes. With the retreat of the last great ice sheets covering much of North America, plants and animals advanced towards the North, gradually establishing habitat in northern regions. In time, these former ice-covered lands became the Arctic and Subarctic biomes. For these biomes to form, the climate has to be relatively stable, i.e., variations in temperatures and precipitation have to fall within a relatively narrow range (Table 2.2). For example, the black spruce, one of the hardiest trees of the boreal forest, requires specific growing conditions to permit regeneration. Generally speaking, the average summer temperature must reach 10°C or higher for the black spruce to survive. Not surprisingly, then, the geographic position of the treeline has shifted in accordance with climate changes. For example, in the 400 or so years of the **Little Ice Age** (*c.* 1450–1850), the treeline retreated southward, thus expanding the area of the Arctic.

Another indicator of the complexity of the northern environment is found in ecosystems. Environment Canada (2007) has classified Canada's ecosystems, which include the Arctic and boreal ecosystems or biomes, into 20 terrestrial and marine ecozones. Ten of the 15 terrestrial ecozones and three of the marine ecozones are found in the North. So many ecozones are in the North for the simple reason that the North occupies over three-quarters of the land mass of Canada. These ecozones are subunits within the much larger Arctic and Subarctic ecosystems or biomes. A biome is a broad, continental type of ecosystem characterized by distinctive climate and soil conditions and a distinctive kind of biological community adapted to those physical conditions. Natural vegetation in the form of tundra and boreal forest serves to distinguish the Arctic and Subarctic biomes, though the biological complexity and diversity of each biome goes well beyond natural vegetation (Vignette 2.4).

Vignette 2.4 Ecology, Ecosystems, and Ecozones

Ecology is the study of the interactions of living organisms with one another and their physical environment. One of the characteristics of biological life is its high degree of complexity and interrelationship. For example, a group of individuals of the same species living and interacting in the same geographic area is defined as a population. Many populations may exist in the same geographic area or habitat and, collectively, these populations form a biological community. Ecosystems or biomes represent large, continental units while ecozones represent smaller units within ecosystems. Both units express the spatial extent of this complexity and interrelationship. In Canada, there are 15 terrestrial and five marine ecozones. A map of Canada's ecozones is found at an Environment Canada website (www.ec.gc.ca/subsnouvelles-newsubs/0C1F54C7-6D14-9CE1-44D3-6F01FE67498B/f2-en.gif).

The Arctic

Lying north of the treeline, the Arctic is the coldest biome in Canada. Its cool summers and permafrost control the type of natural vegetation and soil development. Tundra is found over much of the Arctic, while extremely thin and immature **cryosolic soils** are associated with continuous permafrost. In this zone of permafrost, frozen ground remains close to the surface in the short summer, thus inhibiting soil development.

The Arctic is found primarily in Nunavut and the Northwest Territories, but the Arctic also exists in Quebec, Newfoundland and Labrador, Ontario, Yukon, and Manitoba. The Arctic Ocean is part of the Arctic, though the ownership of these waters is still unsettled. Much of the Arctic Ocean is covered by a permanent ice cap. Since 1979 (the date of the NASA satellite photograph shown in Figure 2.5), the minimum geographic extent of the Arctic ice cap has decreased, replaced by open water (Figure 2.5 and Figures 8.2 and 8.3). The implications of more open water for Arctic sovereignty are discussed in Chapter 8.

The Arctic is characterized by a very cold climate where the warmest month has a mean temperature of less than 10°C. Under such climatic conditions, normal tree growth and soil formation are not possible. Instead, tundra vegetation and thin soils known as cryosols (soils formed in areas of permafrost that have a shallow active layer in the summer) are found in the Arctic. Even when summer air temperatures thaw the top few centimetres of the ground, the presence of permafrost beneath this thin active layer acts not only as a cooling agent but also as a barrier to water. In such a cold landscape, soil-forming processes only work in the short summer when soil temperatures are often just above the freezing point.

Harsh Arctic climatic and soil conditions permit only a few varieties of plants, but the ones that do survive are true marvels of adaptability that can withstand long periods without sunlight. Arctic vegetation is divided into two subzones—Low Arctic and High Arctic. The Low Arctic occupies the mainland while the High Arctic is found in the northern reaches of the mainland and the Arctic Archipelago. The Low Arctic is associated with tundra vegetation. This subzone is characterized by nearly complete plant cover, including many shrubs, such as dwarf birch and willow, and sedges that appear in imperfectly drained lowlands. Tussock sedge and ground-hugging shrubs provide summer grazing for caribou, which are still a major source of food for Aboriginal peoples. Heath, herbs, and lichen are the typical plants. Reindeer moss, a grey-green, sponge-like lichen, is an important source of food for caribou, muskox, and other herbivores. While trees such as willows do grow, they reach a height of only a few centimetres. In the High Arctic zone, by contrast, little vegetation exists, though lichens are found on rock surfaces. Most of the land surface in the High Arctic consists of rock and unconsolidated material. Such barren Arctic lowlands are called polar deserts (Vignette 2.5).

The treeline represents the place where the last trees are able to grow and thus serves as the boundary between the Arctic and the Subarctic. Like many other natural features, the treeline in fact is a transitional zone between the closed boreal forest and exclusively tundra vegetation. While the treeline closely corresponds to the isotherm representing a 10°C monthly mean temperature for July, other natural factors, such as the depth of the active layer of permafrost, topography that protects trees from wind, south-slope radiation, and well-drained land, may result in patches of trees growing north of this isotherm or, conversely, tundra occurring south of it. All of these factors have produced a transition zone at the northern edge of the Subarctic that can be described as 'wooded tundra' and 'lichen woodland'. In this transition zone, the proportion of tundra to forest varies, but towards the southern edge of the Arctic the wooded tundra zone exists. Here, patches of bush-size spruce and larch are found in sheltered, low-lying areas while high, more exposed lands are treeless. Towards the south, the lichen woodland emerges, with stands of more mature trees mixed with open areas consisting of a thick ground cover of lichens (see Figure 2.4). This transition zone of the wooded tundra and the lichen woodland also represents a biological and cultural boundary. Polar bears and Arctic foxes prevail in the Arctic, while beaver and moose are restricted to the forest lands of the Subarctic.

The treeline (and therefore the Arctic) does not follow a latitudinal direction, but has a distinct northwest to southeast direction due to two factors. First, the continental effect causes the interior of the North to warm in the summer, thus allowing the treeline to reach the mouth of the Mackenzie River, well north of the **Arctic Circle**, which

Vignette 2.5 Polar Desert

Polar desert exists in the higher latitudes of the Arctic where extremely cold, arid conditions occur throughout the year. Low summer temperatures combined with permanently frozen ground greatly limit biological activity. For that reason, little vegetation is found in polar deserts. Lichens are by far the most important group of primitive plants found in polar deserts. Since the principal geomorphic process is a freeze/thaw cycle, a sterile, barren-looking landscape consisting of shattered bedrock, patterned ground, and unconsolidated materials prevails. An example of polar desert is provided in the photograph below of a barren landscape with no visible vegetation. Located on Melville Peninsula (around 69°N), frost action has produced a rugged surface of shattered rock fragments.

Figure 2.3 Polar Desert

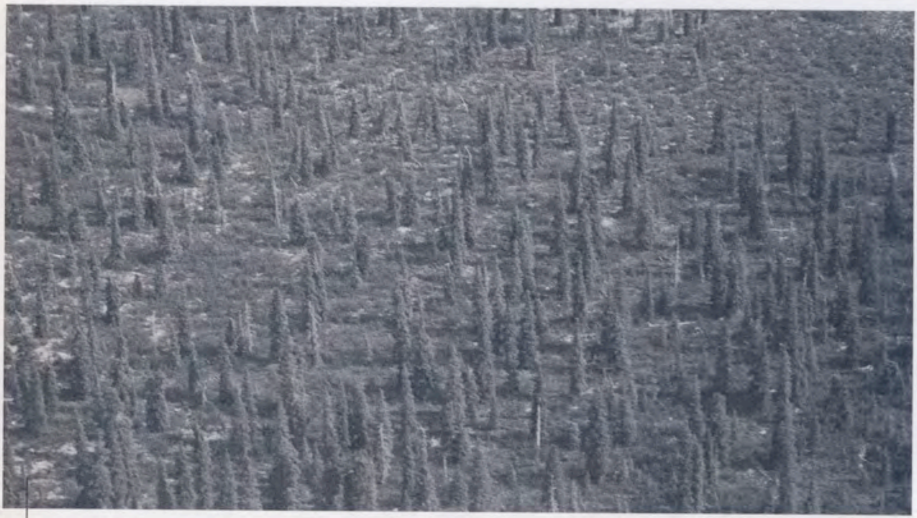
Frost-heaved rock fragments along jointing sites, near Hall Beach, Melville Peninsula, Nunavut.

Source: Natural Resources Canada. 2010. 'Canadian Landscape s Photo Collection', Geological Survey of Canada, 2010, at: <gsc.nrcan.gc.ca/landscapes/details_e.php?photoID=807>.

Source: Reproduced with the permission of Natural Resources Canada 2011, courtesy of the Geological Survey of Canada (Photo 2002-552 by Dredge, Lynda).

is located at 66° 33'N and shown on Figure 1.3. Second, the cold waters of Hudson Bay and the Labrador Sea prevent tree growth along its coastline. The latitudes of three communities just south of the treeline are Aklavik (68° 13'N), Churchill (58° 48'N), and Cartwright (53° 36'N). Aklavik, located on a deltaic island at the mouth of the Mackenzie River, has a warmest-month average mean temperature of 14°C; Churchill, situated near the shore of Hudson Bay, has an average July temperature of 11.8°C; and Cartwright, lying along the Labrador coast, has a mean July figure of 12°.

Figure 2.4 Lichen Woodland Landscape



Close to the treeline, this transition zone between the Arctic and Subarctic consists of a sparse stand of black and white spruce with a lichen understory consisting of lichen, dwarf birch, dwarf willow, and labrador tea.

Source: Northwest Territories (2004). Photo: Dave Downey and Department of Environment and Natural Resources, Government of the Northwest Territories.

Figure 2.5 The Arctic Ice Cap, September 1979

The Arctic ice cap consists of pack ice and new ice. By September, the maximum ice melt has taken place with two critical areas containing open water. These areas are Lancaster Sound and the southern part of the Beaufort Sea. In September 1979, the section of the Northwest Passage between Lancaster Sound and the Beaufort Sea was blocked by thick ice. The data for the period 2002 to 2010 (Figure 8.2) indicated much more open water in September than was found in 1979, but the amount of open water, and therefore the retreat of the ice cap, varies from year to year.

Source: NASA (1979).

Figure 2.6 Arctic Ice Extent, September 2007

NASA satellite images reveal that, over the last 25 years, the Arctic ice cap has shrunk. Its extent on 25 September 2007 is shown in white while a dark line shows the median September monthly position based on data from 1979 to 2000. The change is remarkable. Compared with the NASA satellite image of September 1979 (Figure 2.5), the Northwest Passage from Lancaster Sound to the Beaufort Sea was open water in September 2007 but solid ice in 1979.

Source: NSIDC (2007b).

The Subarctic

The Subarctic is the largest natural region in North America. Its natural vegetation, the boreal forest or taiga, provides a clear indication of its geographic extent. The boreal forest extends in a continuous belt from the Rocky Mountains to Labrador. While its long winters are cold, summers are short but warm, allowing for a much richer vegetation cover than that found in the Arctic. Coniferous trees predominate. Variation in the size and density of forest cover south of the natural vegetation transition zone in the Subarctic is defined by two subzones: closed boreal forest and forest parkland. The closed boreal forest, a dense forest of mature fir, spruce, and pine, is found in southern Yukon, a small part of the Northwest Territories (principally the upper Mackenzie Valley), and the northern areas of the seven provinces. An example of this forest in the Northwest Territories is shown in Figure 2.7. Within this huge zone, the forest cover is broken by a variety of wetlands, including lakes, **muskeg**, and peat bogs. In this wet environment, black spruce and larch are the most common species. On well-drained

Figure 2.7 Boreal Forest in the Northwest Territories

The boreal forest extends across Canada in a green swath, reaching into high latitudes in the Northwest Territories. Just south of the Arctic Circle in the vicinity of Great Bear Lake and the Mackenzie River Valley, the boreal forest consists of mature stands of black and white spruce. In this photograph, the boreal forest extends to the shore of Oscar Lake.

Source: The Boreal Songbird Initiative, at: <www.borealbirds.org/>. © Ducks Unlimited, Canada.

land, species of spruce, fir, pine, and larch are common along with stands of poplar and birch. Towards its southern limits, broadleaf trees, particularly aspen and birch, are found. The forest parkland, a narrow transition area adjacent to the Canadian Prairies, is a combination of forest and mid-latitude grasslands. Small bushes, including blueberries, and grasses form the ground cover.

Podzolic and gleysolic soils are common in the Subarctic. In the Canadian North, thin, acidic **podzolic soils** are best formed under cool, wet growing conditions where the principal vegetative litter is derived from a coniferous forest. **Gleysolic soils** are associated with extremely poorly drained and often waterlogged land such as marshes and bogs. A low evaporation rate, immature drainage, and permafrost ensure an excess of ground moisture, resulting in severely leached soils and the widespread occurrence of ponds, lakes, and bogs. Yet, the longer summer temperatures in the Subarctic allow the better drained ground to thaw to a depth of several metres, promoting biological activity, plant growth, and chemical action. Unlike the cryosolic soils in areas of continuous permafrost, podzolic soils are associated with discontinuous and sporadic permafrost, both of which have relatively thick active layers (for more on the types of permafrost and their geographic extent, see the subsection on permafrost in this chapter).

The boreal forest is a rich zone of biodiversity with different types of wildlife: moose, deer, martens, rabbits, beaver, foxes, wolves, bears, eagles, and various birds.

Local medicinal plants for treating colds, diabetes, and heart and skin problems are known and used by First Nations and Métis. The biological diversity of the boreal forest includes thick layers of moss, soil, and peat that store huge amounts of organic carbon and thus play a significant role in regulating the Earth's climate. Boreal wetlands also filter millions of gallons of water each day that fill Canada's northern rivers, lakes, and streams.

Polar Climate

In the classification of climates throughout the world, the polar climate is the coldest climatic type. The polar climate is divided into four climatic subtypes: the Arctic, Subarctic, mountain, and ice cap climates. In this text, however, the mountainous areas of northern British Columbia, Yukon, and the Northwest Territories are treated as part of the Subarctic (Vignette 2.6). Similarly, the ice cap climatic type is merged with the Arctic climatic type. The ice cap climate is associated with glaciers found on Baffin, Devon, and Ellesmere islands. This climate has a mean temperature below freezing for all months. Those small areas covered by glaciers are considered part of the Arctic climate. Each climatic type is associated with an **air mass** that reflects the weather characteristics of that type. As these air masses move across the continent, they affect weather in other regions

Unlike other climatic types, the polar climate is characterized by extreme seasonal variations in the amount of solar energy. Summer days, for example, are long while winter days receive little to no sunlight. The Arctic Circle marks the latitude where the Sun remains above the horizon for one summer day (21 June, the summer solstice) each year and it remains below the horizon for one winter day (21 December, the winter solstice) each year. At latitudes well beyond the Arctic Circle, summer days and winter nights can last for months. At the North Pole, the Sun is above the horizon for six months and below the horizon for the rest of the year. A day of continuous darkness is referred to as a 'polar night' (Vignette 2.7).

Monthly receipts of solar energy vary widely throughout the year (Vignette 2.2). On a yearly average, the Earth's poles receive 40 per cent less radiation than the

Vignette 2.6 The Subarctic Climate in the Cordillera

Many factors, such as latitude, topography, the proximity of bodies of water, and the nature of the underlying surface, control climate. In Yukon, due to its mountainous nature, topography becomes very important. The territory benefits from Pacific airflows from the west, while high mountain ranges block Arctic air masses from the north. The mountain ranges also affect atmospheric circulation patterns, the amount, frequency, and type of precipitation, winds, atmospheric pressure, and the local radiation regime. Elevation in particular plays a major role in determining temperature. During the winter, a strong surface-based inversion develops in Yukon due to the net negative radiation balance. Thus, temperatures tend to increase with height, especially in the bottom 1,500 metres of the atmosphere.

Source: Adapted from Etkin (1989: 12).

Vignette 2.7 The Polar Night

The polar night is a period of continuous winter darkness. Twilight does not occur. Polar nights take place north of 72° 33′N, well beyond the Arctic Circle (66° 33′N). Why is this? We know that the Sun does not rise above the horizon at the Arctic Circle during the winter solstice. Yet there are not 24 hours of continuous darkness because diffused light from the sky is caused by the Sun's rays being reflected from a position below the horizon onto the atmosphere and then back down to the Earth. Twilight may last for an hour or more at the time when the Sun is below (but less than 6° below) the horizon, thus providing at that time sufficient light for outdoor activities. On 21 December, the latitude of 72° 33′N, not the Arctic Circle, marks the geographic point where 24 hours of continuous winter darkness occurs.

Sources: Burn (1995, 1996).

equator (Lawford, 1988: 144). Within the Canadian North, the major dividing line, the Arctic Circle, marks the point where solar radiation is reduced to zero for one day (21 December) and, at higher latitudes, for longer periods of time. Such low levels of radiation result in continuous cooling of the land and the buildup of masses of frigid Arctic air, which are associated with daily high temperatures of –40°C or lower and strong surface winds. In fact, the Arctic coast is one of Canada's windiest places, with annual average wind speeds exceeding 20 km/hr. Cold polar air is often associated with extreme wind-chill conditions that will freeze exposed flesh in a matter of seconds. Arctic winds drive frigid air masses southward, causing stormy and sometimes blizzard conditions in the Canadian Prairies, sub-zero temperatures in eastern Canada, and freezing temperatures in the southern United States. In the spring, solar radiation increases but much of its effect is lost due to snow-covered surface. In fact, up to 80 per cent of the spring solar radiation is reflected into space

Vignette 2.8 The North's Energy Deficit

The North is an area of energy deficit (Vignette 2.2). The length and intensity of winter in the North are indicative of its energy deficit. The principal factor is the low amount of solar energy received in high latitudes compared to that received in middle latitudes. Williams (1986: 6–7) defines a cold environment as having a negative annual heat balance due to a greater amount of long-wave radiation emitted to outer space than the amount of incoming short-wave radiation and energy transfer by global winds and ocean currents. Mean annual air temperature, defined as the total of daily mean temperatures for the year at one place divided by 365 days, provides one measure of the negative annual heat balance. Those areas with annual mean air temperatures of less than zero degrees Celsius have a negative heat balance. With the exception of a small area of the boreal forest that extends into the middle latitudes of Ontario and Quebec, the Canadian North has a negative energy balance (Figure 1.3).

by the snow-covered ground. Once the snow is gone, winter's grip is quickly broken. Temperatures recover rapidly and the ensuing warm weather quickly melts the ice from lakes, rivers, and the ocean. By early July, sea ice has disappeared from Hudson Bay, and a few weeks later the ice is gone from along the edge of the Arctic coast. The polar pack, no longer attached to the coastline, drifts around the Arctic Ocean. During the long summer days, massive amounts of solar radiation reach the northern lands, warming the ground. In response, plants quickly appear and flower. Daily summer temperatures in the Mackenzie Valley and southern Yukon can reach into the low thirties Celsius. By late August, however, summer is over. Within another month, ice has formed on lakes and rivers, marking a return to a frozen landscape.

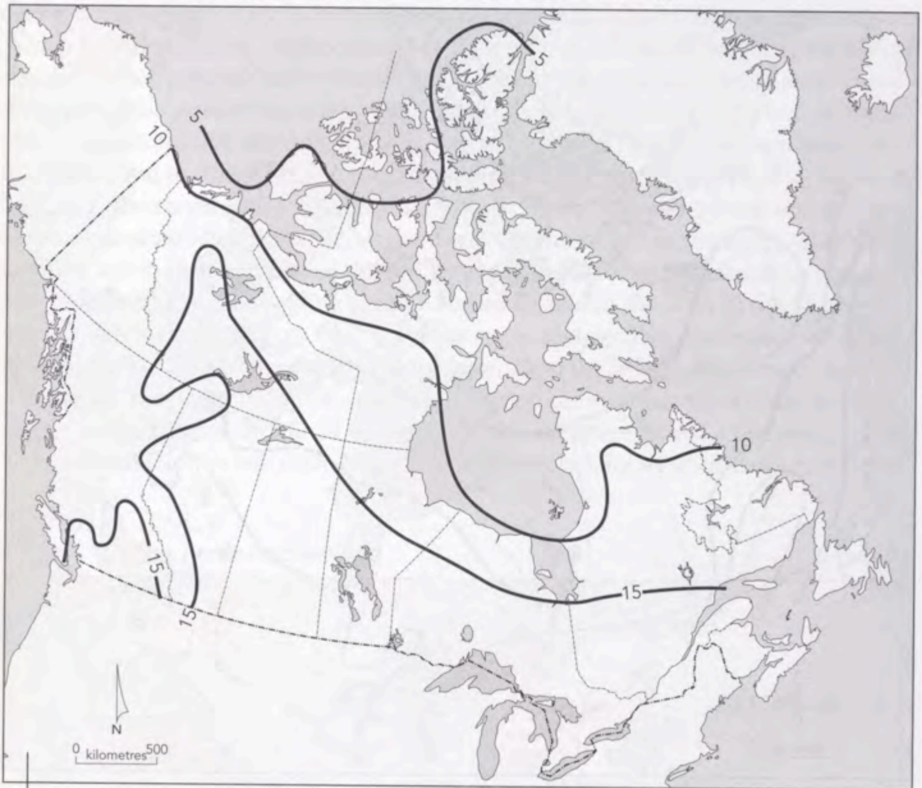
The sharp seasonal shift of air temperatures is illustrated in Figures 2.8 and 2.9. The winter regime has low mean monthly temperatures. The coldest January temperatures are found in two places—the northern extremes of Ellesmere and Axel Heiberg islands and just south of Boothia Peninsula. On the other hand, the mean

Figure 2.8 Mean Daily Temperatures in Degrees Celsius, January

The Pacific and Atlantic oceans have a temperature-moderating influence on near-coastal areas so that continental areas are colder in winter and warmer in summer than are areas closer to the Atlantic and Pacific coasts. The –20°C January isotherm reaches nearly 50°N in Ontario while the same isotherm is north of the sixtieth parallel in Yukon and Nunavut.

Source: After Hare and Thomas (1979: 37).

Figure 2.9 Mean Daily Temperatures in Degrees Celsius, July



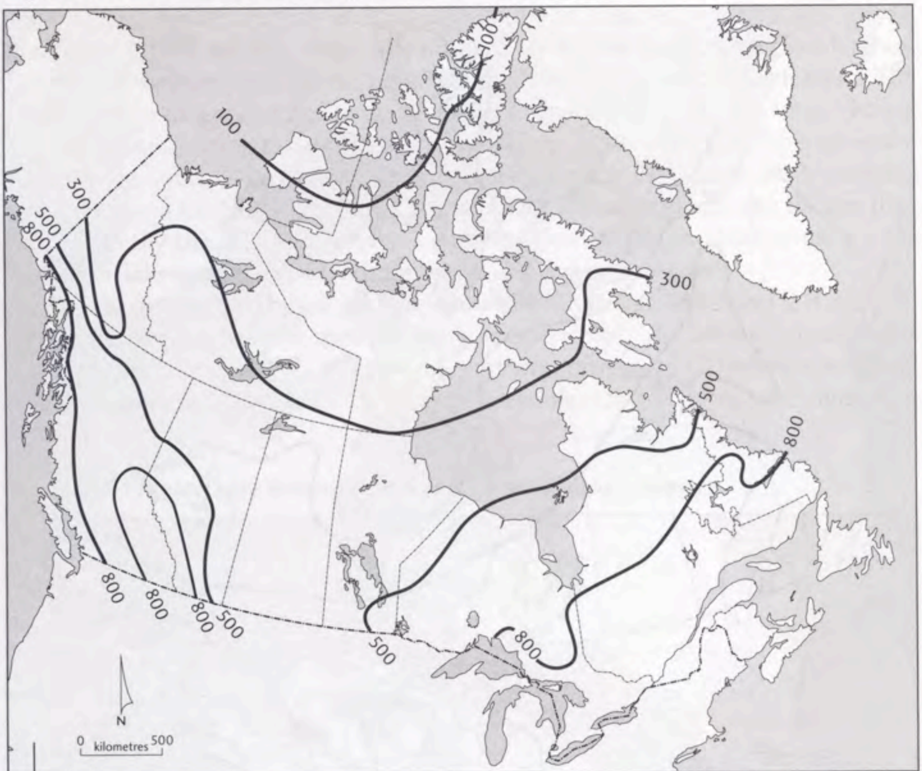
July isotherms indicate a northwest–southeast trend, with a warm corridor extending into the Mackenzie River Valley. This warm temperature corridor allows the treeline to reach the Mackenzie Delta (see Figure 2.1). The 15°C July isotherm reaches beyond 60°N in the interior of the Northwest Territories, indicating a continental warming effect.

Source: After Hare and Thomas (1979: 37).

daily temperature for July demonstrates both the warming effect of the northern land mass and the cooling effect of the Arctic Ocean, Hudson Bay, and the North Atlantic. A distinct northwest-to-southeast direction to the July isotherms exists. As well, a warm 'corridor' extends down the Mackenzie Valley to Norman Wells, where July temperatures are similar to those experienced in the Canadian Prairies.

Precipitation in the North is generally light, with the least amount falling in the Arctic due to the inability of Arctic air masses to absorb moisture from cold bodies of water. The isohyets shown in Figure 2.10 clearly indicate that the lowest amounts of annual precipitation are found in the Arctic Archipelago, where some islands record less than 100 mm annually. The lowest annual precipitation occurs in the ice-locked islands of the Arctic Archipelago (Vignette 2.9). Victoria Island, for example, has such scant rain and snowfall (often less than 140 mm annually) that the island is described as a 'polar desert'. Towards the northern edge of the Subarctic, annual precipitation increases. At Yellowknife, the annual precipitation is around 250 mm. The Subarctic,

Figure 2.10 Mean Annual Precipitation in Millimetres



Air masses originating over the Atlantic and Pacific oceans bring most moisture to the North. Air masses forming over the cold Arctic Ocean usually contain little moisture. As a result, the highest levels of annual precipitation are found along the western and eastern edges of the North while the Arctic Archipelago is extremely dry, causing scientists to refer to this area as a polar desert (Vignette 2.5).

Source: After Hare and Thomas (1979: 41).

Vignette 2.9 Arctic Archipelago

The Canadian Arctic Archipelago (Figure 2.11) is a group of islands in the Arctic Ocean. Covering over 1.3 million km^2, they form the largest group of islands in the world. The largest islands are Baffin Island (507,451 km^2), Victoria Island (217,290 km^2), and Ellesmere Island (196,236 km^2). Most islands have elevations below 200 metres and few topographic features. Elevations do rise above 2,000 metres in the eastern islands of the Arctic Archipelago. Mount Barbeau on Ellesmere Island, for example, reaches an elevation of 2,616 metres. At these high elevations, glaciers exist. The geological history of the Arctic Archipelago began some 3 billion years ago and Precambrian rock exists at the surface on Baffin, Devon, and Ellesmere islands. Most of the Arctic islands were formed much later and contain sedimentary rocks. Within these sedimentary rocks, vast oil and gas deposits exist.

on the other hand, generally receives more precipitation, usually over 300 mm annually. Precipitation does vary, however. The greatest amount of precipitation occurs in the Cordillera and along the Atlantic coast. In these two areas, the high terrain results in orographic precipitation (rain or snow caused when warm, moisture-laden air is forced to rise over hills or mountains and is cooled in the process). The south coast of Baffin Island receives around 400 mm annually, while the annual total for the southern coast of Labrador and northern Quebec exceeds 800 mm. Most precipitation falls as snow. In the spring, the runoff peaks when melting snow and ice flow into the streams and rivers. Some communities along the Mackenzie River are subject to spring flooding. Fort Simpson, situated on an island at the confluence of the Liard and Mackenzie rivers, has been inundated a number of times, and Aklavik, located in the delta of the Mackenzie River, is threatened by flood waters almost every spring. The occurrence of spring flooding at Aklavik is so regular that, in the late 1950s, the federal government decided to create the new town of Inuvik rather than expand the community of Aklavik.

The Arctic climate is defined as one in which the average mean temperature for the warmest month is less than 10°C. It has extremely long winters and a brief, cool

Figure 2.11 The Arctic Archipelago

Source: Adapted from Infoplease, at: <www.infoplease.com/atlas/region/nunavut.html>.

summer. The Arctic climate lies north of the treeline and includes all of the Arctic Archipelago, the coastal zone stretching from the Beaufort Sea to the coast of Labrador, and much of the interior of the northern territories, known as the 'Barren Lands', which stretch from Hudson Bay in the east to Great Bear and Great Slave lakes to the west. While the Arctic climate is normally associated with high latitudes, it does reach into the middle latitudes along the Labrador coast. Here, the chilling effect of the cold Labrador Current keeps summer temperatures along the east coast of Canada low, allowing the Arctic climate to extend along the Labrador coast to the northern tip of Newfoundland. Resolute and Iqaluit have Arctic climates and their mean monthly temperature regimes are shown in Table 2.1.

Unlike its Arctic counterpart, the Subarctic climate has a distinct but short, warm summer. Normally, this climate is found in continental or inland locations and is characterized by a wide range in seasonal and daily temperatures. This continental effect results in record daily cold temperatures being set in Yukon rather than in the Arctic Archipelago. The coldest temperature recorded in Canada for the period 1971–2000 was –62.8°C at Snag, Yukon. In contrast to the cold winter temperatures, a number of hot summer days can occur. In July 1989, for example, during a 'heat wave' in the Mackenzie Valley, Norman Wells recorded an all-time maximum daily high of 35°C. The climatic regions for all of Canada are shown in Figure 2.12.

Winter is the dominant season, and although an occasional summer day may be extremely hot, summers in the Subarctic are short, usually less than three months.

Table 2.1 Mean Monthly Temperatures for Chibougamau, Prince George, Iqaluit, and Resolute

Centre	Latitude	Jan.	Feb.	Mar.	Apr.	May	June
Chibougamau	49° 55′	–18.4	–10.5	–1.0	6.4	13.3	15.8
Prince George	53° 53′	–9.6	–5.4	–0.3	5.2	9.9	13.3
Iqaluit	63° 45′	–25.6	–25.9	–22.7	–14.3	–3.2	3.4
Resolute	74° 43′	–32.4	–33.1	–30.7	–22.8	–10.9	–0.1
Centre	**July**	**Aug.**	**Sept.**	**Oct.**	**Nov.**	**Dec.**	**Year**
Chibougamau	15.8	14.1	9.1	2.6	–4.7	–15.9	–0.8
Prince George	15.5	14.8	10.1	4.6	–2.9	–7.8	4.0
Iqaluit	7.6	6.9	2.4	–5.0	–13.0	–21.8	–9.3
Resolute	4.3	1.5	–4.7	–14.9	–23.6	–29.2	–16.4

The range of seasonal temperatures across Canada's North defies latitude. For instance, Chibougamau in the Subarctic of Quebec at latitude has a much lower mean January temperature (–18.4°C) than the BC Subarctic city of Prince George, which has a mean January temperature of –9.6°C. Yet, Prince George lies further north (54°N) than Chibougamau (50°N). The explanation for the warmer winter temperatures at Prince George is attributed to its proximity to the Pacific Ocean and its relatively warm winter air masses. Chibougamau, on the other hand, remains in the grip of Arctic air masses for most of January.

Source: Environment Canada (2002).

Freezing temperatures can occur at any time. By late August, cool fall-like weather is common and there is an impending sense of winter. By November, the land, lakes, and rivers are frozen and winter, lasting until late April or May, has set in. During the winter, the warming influence of the Pacific keeps temperatures of the western Subarctic relatively high while the frozen Hudson Bay reinforces the cold continental effect on the winter temperatures of the eastern Subarctic. The average January temperatures for Prince George (–9.6°C) and Chibougamau (–18.4°C) demonstrate at the micro-level the impact of these differing climatic influences. As shown in Figure 2.12, Prince George is located at a more northerly location than Chibouogamau and yet Prince George has a milder climate (see Table 2.1).

Figure 2.12 Climatic Regions of Canada

Three climatic regions—the Cordillera, the Subarctic, and the Arctic—are found in the Canadian North. The north/south orientation of the Cordillera climate is related to its high elevations The cooling effect of the waters of Hudson Bay and the Labrador Current have extended the Arctic climate much further south in the eastern half of Canada's North. On the other hand, the continental effect has allowed the Subarctic climate to reach into high latitudes in the Northwest Territories.

Source: After Hare and Thomas (1979: 17).

Past, Present, and Future Climates

Since its existence, the Earth has experience many climates. Each climate represents an average of relatively long and stable weather conditions over a significant geological time frame. Over long periods of time, nature responds by creating ecosystems with similar natural vegetation and soils. At the macro-scale, climate creates global zonal patterns such as the Arctic. From our perspective, the prospect of a much warmer climate compared to the present and near past has only emerged recently and is connected to the prospect of significant warming of the Earth within a relatively short time by the addition of increasing amounts of greenhouse gases to the atmosphere. Ironically, the Arctic is most likely to see the greatest changes in temperature because, as the snow and ice melt, more and more of the Arctic will have a surface that absorbs rather than reflects solar radiation.

What exactly is 'climate'? Climate is an average of complex natural phenomena that make forecasting climate change or reconstructing past climatic changes very difficult. For instance, while the source of the Earth's heat is constant emission of solar radiation from the Sun, many variables affect the warming of the Earth. One is the capacity of the ground to absorb (or reflect) solar energy; another is the reduction of solar radiation reaching the Earth's surface because of dust in the atmosphere caused by volcanic activity or large meteorites striking the Earth's surface. In addition, radiation from the Sun may vary slightly and that variation can account for changes in the Earth's average temperature. For example, sunspots (flares of solar energy) might increase solar energy to the Earth, but this theory is unproven. Yet, the **Maunder Minimum**, a period of relatively few sunspots, occurred at the same time as the Little Ice Age, suggesting that a low level of sunspot activity on the Sun's surface could result in slightly less solar radiation reaching the Earth.

Reconstruction of past climates is a challenge. The recording of surface temperatures and precipitation began around 1850 in Europe and North America and somewhat later in other parts of the world, and these measurements provide the basis for our understanding of climates. As a result, reconstruction of ancient climates involves proxy methods such as interpreting the geological record and relating temperature change to variations in oxygen isotopes found in ice cores. As for predicting future climates, global climate models (gcms) focus on estimating temperature increases based on the amount of greenhouse gases in the atmosphere. Since long-term variations in climate are measured in decades, centuries, and even millennia, ice in the form of glaciers and polar ice caps are our best indicators of climate change because they 'average' out the short-term weather variations and reflect longer-term temperature trends. (See Chapter 8 for a more detailed account of the impact of global warming on the Arctic ice cap.)

From the geological record, a general interpretation of climatic change over the last two millions years (the **Pleistocene Epoch** and the current **Holocene Epoch**) is possible, but even more detailed geological evidence over the last 25,000 or so years allows for more precise estimates regarding the chilling of the Earth, which caused ice sheets to form over practically all of Canada and northern portions of the United States (Vignette 2.10 and Table 2.2). After this cold era, which began to end about 15,000 years ago, the Earth warmed again, causing the ice sheets to melt and thus allowing biological life to re-enter the ice-free terrain. Geologists refer

Vignette 2.10 The Pleistocene

Going back in time, the last major glacial period began about 2,000,000 BP and is commonly known as the Pleistocene Epoch. During the Pleistocene, large ice sheets covered much of North America for long periods of time, but short interglacial periods occurred when the ice sheets retreated because of milder temperatures. At least four distinct ice advances and retreats have affected the land that today is Canada. The last ice advance, known as the Late Wisconsin Ice Age, began about 25,000 BP and was followed, around 10,000 years later, by a glacial retreat. Geologists call this present period the Holocene Epoch, which they believe will be followed by another glacial period.

to this current warm period as the Holocene and within that very short geological period, minor climatic variations have taken place; the warmest period, known as the Climatic Optimum, occurred between 9,000 and 5,000 BP. During the Climatic Optimum global temperatures were considerably higher than those currently experienced. Kaufman and others (2004) reconstructed Climatic Optimum temperatures for Canada's western Arctic. Their findings support the notion that temperatures in higher latitudes rose during this period, largely due to the albedo effect. In more recent times, two minor variations in global temperatures took place—the Medieval Optimum (c. ad 800–1300) and the Little Ice Age (c. 1450–1850). The Little Ice Age did impact the Thule, who had previously hunted the bowhead whale in the open waters of the Arctic Ocean. Within this colder environment, more extensive ice cover took away their opportunity to harvest these huge sea mammals and the Thule (and later their descendants, the Inuit) had to hunt seal and caribou (Fossett, 2001).

Table 2.2 Major and Minor Climatic Variations

Geological Period	Minor Variations in the Holocene Epoch	Time*	Temperature Change**
Late Wisconsin Ice Age		30,000–15,000 BP	−10°C
Holocene Epoch		12,000–present	
	Climatic Optimum	9,000–5,000 BP	+5°C
	Medieval Optimum	AD 800–1300	+1°C
	Little Ice Age	1450–1850	−1°C
	Present Warming Period	1850–present	+0.6°C
	Predicted Warming Period	2000–2100	+4°C

*Estimated data based on climate reconstruction research. For example, the start of the Little Ice Age is uncertain but is linked to extreme weather events in Europe. Such temperature 'measurements' provide only a rough approximation and hence the Little Ice Age may have begun as early as 1350. However, there is general agreement about its ending in the mid-nineteenth century.

**Estimated temperature changes relative to present climate are also derived from paleoclimatic reconstruction research based on surrogate measurements of regional temperatures such as ice cores.

Sources: IPCC (2007b); Houghton et al. (2001).

Climate Change

Since the mid-nineteenth century, the Earth began another warming cycle. Most climatologists believe that global temperatures are increasing because of anthropogenic actions, especially the burning of fossil fuels, which triggers the greenhouse effect (Vignette 2.1). Before the Industrial Revolution, natural forces alone affected climate change, including:

- known astronomical variations in the orbit and angle of the Earth vis-à-vis the Sun (the so-called Milankovitch theory) affect how much solar radiation reaches all parts of the Earth;
- changes in energy output from the Sun; and
- increases in volcanism that add huge amounts of fine volcanic particles into the stratosphere, thereby creating a dust veil that reduces the amount of sunlight reaching the Earth's surface and thus lowers temperatures.

World surface air temperatures have increased in the last century, but do these relatively minor increases fall within the range of 'normal' temperature fluctuations associated with our climate, or are they the forerunners of a climatic shift due to dramatic and permanent warming of the Earth? These warmer temperatures have caused glaciers to retreat or disappear and the summer melt of Arctic sea ice is increasing. The Intergovernmental Panel on Climate Change (IPCC) believes that human activities have been responsible for the rise in global temperatures in the twentieth century and that global temperatures will increase dramatically in the twenty-first century (Vignette 2.11). At the 2009 United Nations Climate Change Conference in Copenhagen, Stocker and Plattner predicted that the Arctic Ocean would be virtually ice-free by 2050. More specifically, the authors predicted that the geographic extent of Arctic ice would decrease from 9 million km^2 in 1950 to 1 million km^2 in 2050 (Stocker and Plattner, 2009: slide 9).

The fourth and most recent summary report of the IPCC (2007) stated that:

> Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level. Changes in atmospheric concentrations of greenhouse gases (GHGs) and aerosols, land-cover and solar radiation alter the energy balance of the climate system. Global GHG emissions due to human activities have grown since pre-industrial times, with an increase of 70 per cent between 1970 and 2004. Eleven of the last twelve years (1995–2006) rank among the twelve warmest years in the instrumental record of global surface temperature (since 1850). The 100-year linear trend (1906–2005) of 0.74°C [0.56 to 0.92] is larger than the corresponding trend of 0.6°C [0.4 to 0.8] (1901–2000) given in the Third Assessment Report . . . . The temperature increase is widespread over the globe, and is greater at higher northern latitudes.
>
> For the next two decades a warming of about 0.2°C per decade is projected for a range of SRES [The IPCC Special Report on Emission Scenarios (2000)]

Vignette 2.11 Intergovernmental Panel on Climate Change

The Intergovernmental Panel on Climate Change (IPCC) focuses its attention on potential global climate change. Formed in 1988 by the World Meteorological Organization and the United Nations Environment Programme, its role is twofold: (1) to assess the relevant scientific, technical, and socio-economic information dealing with human-induced climate change; and (2) to identify potential impacts and options for countering these impacts. The IPCC does not conduct research but bases its assessments on published scientific/technical literature, including global climate computer models that predict future climate conditions. Every six years, the IPCC issues its findings. The last report was published in November 2007.

Source: IPCC (2007a).

emission scenarios. Even if the concentrations of all GHGs and aerosols had been kept constant at year 2000 levels, a further warming of about 0.1°C per decade would be expected. Afterwards, temperature projections increasingly depend on specific emission scenarios. (IPCC, 2007b: 1, 4, 6)

Global Warming and Its Potential Impact on the North

Global warming could have a profound impact on the Arctic biome and, to a lesser degree, the Subarctic biome. If global temperatures increase substantially, why would the average annual temperatures in the high latitudes of the North increase more than temperatures in the lower latitudes found in southern Canada? The answer lies in the **albedo** effect (the proportion of solar radiation reflected from the Earth's surface). Under the global warming model, the annual extent and duration of snow cover will diminish. Under those two conditions, the North's surface would change from a highly reflective surface of snow and ice to a highly absorbing one of ground, i.e., a dark surface able to absorb more solar energy. In turn, the warmed Earth then re-radiates long-wave radiation to heat the lower portion of the atmosphere.

The potential impact on the Canadian North falls into three categories. First, the IPCC predicts that the polar ice pack will diminish in size and could possibly disappear. Under this scenario, natural conditions in the Arctic could return to those during the Medieval Climatic Optimum. During that time, bowhead whales frequented the Arctic Ocean because of the open water. In turn, the Thule based their harvesting economy on the bowhead whales. In modern times, an ice-free Northwest Passage would provide a much shorter shipping route between Asia and Europe. Second, the IPCC sees the boreal forest extending close to the shores of the Arctic Ocean (see also Bouchard, 2001). Such an advance would see the Arctic biome greatly reduced in geographic extent. The loss of tundra vegetation would affect the caribou calving grounds and their migration routes. Reduction of the duration and extent of sea ice would affect the polar bear population, which depends on seals as the main food source. Third, the IPCC believes that warmer temperatures will reduce the time that rivers and lakes are frozen and will result in the thawing of permafrost. One consequence for remote mining companies and communities that rely on winter ice roads for supplies would be to force them to turn to air transportation, which is much more expensive. Then, too, a warmer climate and the loss of tundra vegetation and river/sea ice would affect Inuit snowmobile travel. Already the Inuit recognize that travel by snowmobile on snow and ice has become less predictable and more dangerous. Such conditions could make access to country food more challenging and expensive and thus increase food shortages in Inuit communities, forcing them to purchase more store foods (Nickels et al., 2005). As well, warmer temperatures could cause the permanently frozen ground to thaw. Besides releasing water from the frozen ground, this would affect various buildings and other structures. Construction in permafrost areas has taken advantage of the frozen ground by placing piles within the frozen ground. These piles form the foundation for the various structures, whether they are government buildings, schools, or dwellings. If the permafrost melts, those structures would be at risk.

Geomorphic Regions

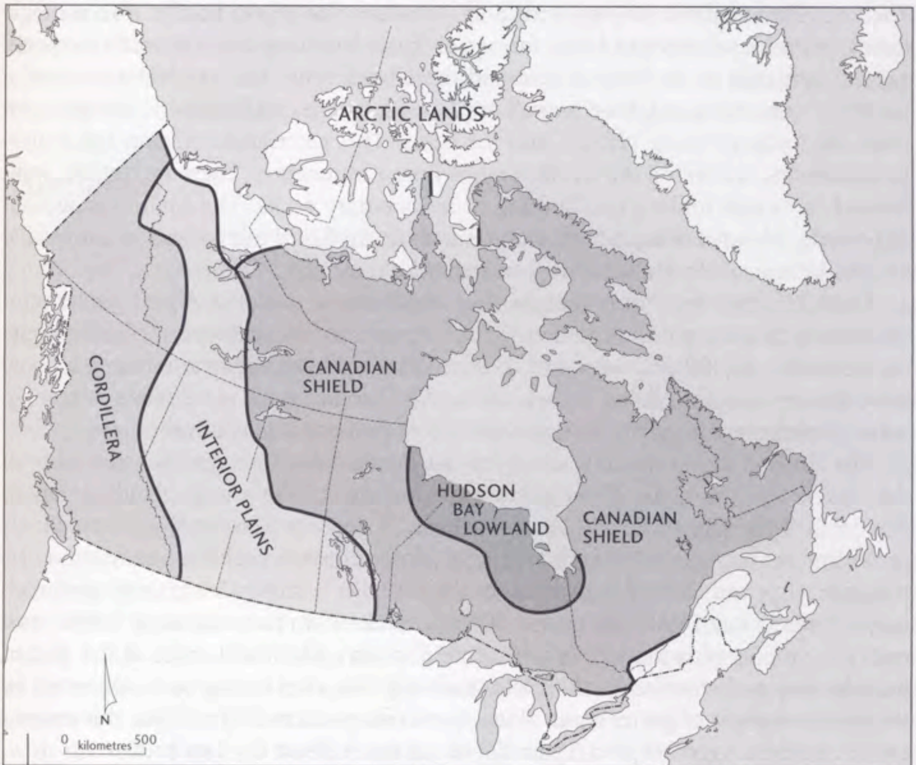
The North's physical geography is far from homogeneous. At a macro-scale, five geomorphic regions provide one insight to the North's heterogeneous nature.

Across the Canadian North, the surficial geology or landscape reflects the major geomorphic regions.[1] These regions have three major characteristics—they cover a large, contiguous area with similar relief features; they have experienced similar geomorphic processes that shaped the terrain; and they have had a similar geological history and therefore possess a common geological structure. These geomorphic regions extend over hundreds of km^2, making them easily identified from a high-flying aircraft or from satellite photographs.

The five geomorphic regions found in the North are the Canadian Shield, the Interior Plains, the Cordillera, the Hudson Bay Lowland, and the Arctic Lands (Figure 2.13). The Laurentide Ice Sheet of the Late Wisconsin period modified the surface of these geomorphic regions either directly, by glacial erosion or deposition, or indirectly, by the formation of glacial lakes and the invasion of depressed land by seawater. **Erratics**—huge boulders moved great distances and then deposited on the ground—are one example of the power of glacial erosion; **nunataks** are mountain peaks that rose above the alpine glaciers. The Canadian Shield, stretching from Labrador to the Northwest Territories, is the largest geomorphic region in the Canadian North. It is the geological core of the northern landscape. Its Precambrian rocks are more than 2.5 billion years old and are found under most of the more recently formed strata, such as the Interior Plains and the Hudson Bay Lowland.

Over most of the northern areas of Manitoba, Ontario, Quebec, Labrador, the northern half of Saskatchewan, the northeast corner of Alberta, and about half of the Northwest Territories, the Canadian Shield is exposed at the Earth's surface. Shaped like a saucer, its highest elevations are found around its outer limits while the central area lies beneath the waters of Hudson Bay. Much of the exposed Canadian Shield consists of a rough, rolling upland. Along the east coast from Labrador to Baffin Island, the Shield has been strongly uplifted. Glaciers moving downslope to the sea deeply scoured valleys and created fjords, giving the coast spectacular scenery.

Figure 2.13 Geomorphic Regions of Canada



Five of Canada's seven geomorphic regions are found in the Canadian North. The other two are the Great Lakes–St Lawrence Lowland, located in southern Ontario and Quebec, and the Appalachian Upland in Atlantic Canada.

Source: After Bird (1972) and Slaymaker (1988).

The Interior Plains, a flat to gently rolling landscape, lie between the Cordillera and the Canadian Shield. The sedimentary rocks of the Interior Plains were formed after the end of the Precambrian era (some half-billion years ago) and include Cretaceous-age rocks formed some 100 million years ago. Within these Cretaceous-age rocks, vast oil and gas deposits exist. At the end of the last glacial advance, a mantle of glacially deposited debris or glacial till covered these sedimentary rocks. In other places, glacial lakes drained, forming flat lowlands consisting of **glaciolacustrine** material, while outwash plains resulted from meltwater streams that deposited **glaciofluvial** materials. At the same time, fast-flowing rivers fed by the melting ice sheet carved deep valleys known as glacial spillways. These and other glacial features on the landscape are indications of the last ice age. The Mackenzie River and its tributaries created a river valley system that extends to the Arctic Ocean. Two huge deltaic landforms exist. One is at the western end of Lake Athabasca, where the Peace and Athabasca rivers deposit their silt. The other is the Mackenzie Delta, located at the mouth of the Mackenzie River.

The Cordillera, a complex mountainous region, occupies much of British Columbia, Yukon, and a small portion of southern Alberta and the Northwest Territories west of the Mackenzie River. The Canadian Cordillera begins at the forty-ninth parallel. The Cordillera is about 800 km wide and extends to the Alaska border. Two geologic forces, known as faults and folds, formed its basic landform features while erosional agents, primarily ice and water, reshaped these landforms. The Cordillera contains a variety of mountainous terrain as well as plateaus, valleys, and plains. It also includes what are today remnant glaciers and ice fields. This geomorphic region has majestic mountains, including the world-famous Rocky Mountains. These mountains were formed by severe folding and faulting of sedimentary rocks. The highest mountain in Canada, Mount Logan, has an elevation of nearly 6,000 metres and is part of the St Elias Mountains in the southwest corner of Yukon.

During the Late Wisconsin Ice Age, the Cordillera was glaciated. Alpine glaciers created arêtes, cirques, and U-shaped valleys. Over most of the Cordillera, the land became ice-free some 10,000 years ago and in this post-glacial period, river terraces, alluvial fans, flood plains, and deltas were formed. While today many glaciers are retreating, some glaciers are still active, though their rate of movement is relatively slow.

The Hudson Bay Lowland is a low, flat coastal plain that has recently emerged from the Tyrrell Sea, the name of the prehistoric and considerably larger Hudson Bay of some 8,000 years ago. The surface of this lowland consists of recently deposited marine sediments combined with reworked glacial till. These deposits accumulated in the post-glacial period when the lowland was beneath the Atlantic Ocean (part of a much larger Hudson Bay). With the retreat of the ice sheet from this area some 8,000 years ago, the process of isostatic rebound came into play. More and more of the seabed became land as the surface of the Earth gradually rose after having been depressed by the massive weight of the ice sheet. With the receding waters of Tyrrell Sea, this process created a distinct geomorphic region known as the Hudson Bay Lowland.

The Precambrian bedrock underlying the Hudson Bay Lowland is masked entirely by glacial and marine sediments. The inland boundary of this region is marked by elevations of around 180 metres, which indicate that, with the removal of the weight of the ice sheet, the Earth's crust began to regain its former shape. This phenomenon is called **isostatic uplift** or isostatic rebound. Assuming that the rate of isostatic uplift remains around 70 to 130 cm/100 years, Professor Barr speculated that the Hudson Bay Lowland will continue to increase in size and Hudson Bay will recede further. Within 12,000 years, Hudson Bay could become a fraction of its present size (Barr, 1972). However, this hypothesis, presented in 1972, does not account for the possibility of rising sea levels caused by global warming.

The Arctic Lands are a complex geomorphic area centred on the Arctic Archipelago. Here, geological events and geomorphic processes have created lowlands, hilly terrain, and mountains. The cold, dry climate results in many periglacial features, such as tundra polygons, that provide a distinctive appearance to the land. Scattered bedrock and patterned ground are widespread in the lowlands, while alpine glaciers occur in the more mountainous landscapes. Rolling to hilly terrain underlain by permafrost is affected by slumping, caused by **solifluction** or **gelifluction**: 'soil flow' down a sloping frozen surface (Trenhaile, 1998: 84–5). A variety of landforms are found in the Queen Elizabeth Islands (those islands lying poleward of the Northwest Passage, including Prince Patrick Island in the west and Devon Island in the east). Most of Canada's glaciers are found in the mountainous terrain of the eastern section of the Queen Elizabeth

Islands, especially Ellesmere Island. These glaciers are retreating, signalling the start of a major shift in their geographic extent. If the warming trend continues, glaciers could disappear in time. A similar retreat is taking place with sea ice and permafrost, though changes in the latter are more difficult to measure. As well, ice in the ground is less exposed to sunlight and is insulated from surface heat by vegetation cover.

Glaciation

Glaciation is one of the principal erosional agents that have fine-tuned a variety of landscapes in Canada's North. Glaciation involves the formation, advance, and retreat of glaciers. The most recent phase of continental glaciation began some 25,000 years ago. Glacial formation took place as the climate cooled, causing snow to accumulate and eventually forming glaciers. Glacial retreat commenced when the climate began to warm, causing the front of the continental glaciers to melt. As the glaciers melt and recede, material contained in the ice is deposited on the ground. In the Canadian North, unglaciated terrain is limited to a small area of Yukon where there was not enough precipitation to nourish the expansion of glaciers.

During the last glacial advance of the Pleistocene Epoch, two huge ice sheets, the Laurentide and the Cordillera, covered most of Canada. These ice sheets reached a maximum thickness of 4,000 and 2,000 metres, respectively. In comparison, today the largest Canadian glaciers are found on Ellesmere Island and have a thickness of nearly 1,000 metres. Some time around 15,000 BP, the climate warmed, causing these huge ice sheets to melt, i.e., retreat. By 14,000 BP, an ice-free corridor appeared along the eastern edge of the Cordillera ice sheet, connecting the unglaciated areas in Yukon with the rest of ice-free North America. By about 10,000 BP, most of these two ice sheets had melted.

During this process of advance and retreat, two geomorphic processes took place. First, the advancing ice sheet caused glacial erosion; later, the retreating ice sheet deposited debris on the land. Glacial erosion took various forms, such as scraping off the unconsolidated material and plucking out huge chunks of bedrock. Where the bedrock was highly resistant, the rock was scraped and scoured. In the mountains, alpine glaciers moved quickly downslope, which had the effect of 'sharpening' mountain features, as shown in Figure 2.14. Alpine glaciers create mountain peaks formed by cirques (basins carved by the glaciers) and arêtes (razor-like ridges). Other evidence of the erosional power of alpine glaciers is found in U-shaped valleys in the Cordillera and the coastal fjords of Labrador and Baffin Island.

As the Earth warmed, both alpine and continental glaciers deposited vast amounts of debris. Glacial features of deposition consist of water-sorted deposits and unsorted deposits. As the ice sheets melted, some of the material contained in the ice was discharged into running meltwater and glacial lakes. The debris held in the ice sheets was deposited on the land; in some cases, glacial meltwaters sorted the debris or till into eskers and outwash plains. **Eskers**—long, narrow ridges of sorted sands and gravel—were deposited from melt streams within or beneath the decaying ice sheet (Figure 2.15). Some eskers are over 100 kilometres in length. The most common glacial deposit is **glacial till**, which consists of unsorted material deposited by a melting ice sheet or glacier. Glacial till extends over vast areas while **drumlins**, formed by

Figure 2.14 Alpine Glaciers

The St Elias Mountains, located in southern Yukon, contain many alpine glaciers with an erosional force that sharpens the features of mountains. The three shown in this photograph are descending in three parallel valleys from a much larger glacier located in the bowl-shaped basin (called a cirque) at the top of the mountain, Between the valleys are sharp-edged ridges or arêtes.

Source: Reproduced with the permission of Natural Resources Canada 2011, courtesy of the Geological Survey of Canada (Photo 2002-678 by Bélanger, Robert).

massive subglacial flooding, appear as clusters of low, elongated, whale-backed hills, shaped by the flow of the ice. Most drumlins are believed to have been formed a short distance behind the ice margin just prior to deglaciation and therefore record the final direction of ice movements. As the massive ice sheets melted, enormous quantities of water were released. These meltwaters either overtaxed the existing southern-flowing drainage system or formed glacial lakes. Often, these glacial lakes were created when the northward-flowing rivers were still blocked from reaching the sea by the remaining ice sheet. The largest glacial lake, Lake Agassiz, occupied much of Manitoba.

Glaciation has created different landforms in each of the five geomorphic regions. In the Cordillera, mountain features have been sharpened into arêtes and peaks; in the Interior Plains, deposits of glacial debris are everywhere; the Canadian Shield has been subjected to ice plucking, scraping, and scouring; the Hudson Bay Lowland was depressed by the weight of the ice sheet; and, in the higher elevations and latitudes of the Arctic Lands, disintegrating glaciers, including the remnants of the Ellesmere Ice Shelf, stand out.

Periglacial Features

Periglacial landforms, i.e., areas on the perimeter of glaciated or permanently frozen regions, are widespread in the Arctic Lands. The most distinctive periglacial landforms

Figure 2.15 Esker in Arctic Quebec

This esker is located near the Inuit settlement of Salluit, on Hudson Strait at the top of northern Quebec. In general, eskers range from small, sinuous ridges a few tens of metres long, to linear features up to 15 km long and even longer. They consist of post-glacial gravel and other sediments that were deposited by subglacial or englacial streams.

Source: Natural Resources of Canada, 'Esker', *Interpretation Guide of Natural Geographic Features*, 2008 Centre collégial de développement de matériel didactique, photo no 6432, at: <www.cits.rncan.gc.ca/site/eng/resoress/guide/esker/pg07.html>.

are ice-cored hills known as **pingos**. These hills are associated with permafrost and a cold, dry Arctic climate where frost action (the freezing-and-thawing cycle) is the dominant geomorphic process. They occur in lowlands where continuous permafrost exists, and are formed when an ice lens in permanently frozen ground is nourished by extraneous water. Over time, the ice lens grows and pushes itself upward, forming a mound and eventually a hill. However, the most common periglacial feature is **patterned ground**—symmetrical forms, usually polygons, caused by intense frost action over a long period of time (Figure 2.16). Patterned ground includes frost-sorted circles of polygon patterns of stones and pebbles. The general process of frost heave causes coarse stones to move to the surface and outward.

During the **Late Wisconsin glacial period**, these conditions were associated with the southern edge of the Laurentide and Cordillera ice sheets. As these ice sheets retreated, more periglacial features were formed. Hugh French (1996: 5) has described this process:

> During the cold periods of the Pleistocene, large areas of the now-temperate middle latitudes experienced intense frost action and reduced temperatures because of their proximity to the ice sheets. Permafrost may have formed, only to have been degraded during a later climatic amelioration.

Figure 2.16 Tundra Polygons

Tundra polygons rearrange the surface of the ground into polygon-like shapes. They are formed because of the freeze–thaw cycle, which is the principal erosional agent in areas of continuous permafrost. The freeze–thaw cycle causes the ground to contract and expand, thus rearranging the surface material into polygon-like forms. Relic tundra polygons still exist in areas in which continuous permafrost conditions once existed.

Source: Reproduced with the permission of Natural Resources Canada 2011, courtesy of the Geological Survey of Canada (Photo KGS-791 by Harrison, J.M.).

French estimates that periglacial features are found over one-fifth of the Earth's surface. Today, relic periglacial features exist great distances from Canada's cold, dry Arctic climate, but the formation of new patterned ground and other periglacial features continues to take place in the Arctic Lands.. Tundra polygons are a common periglacial feature found in the Arctic Lands.

Permafrost

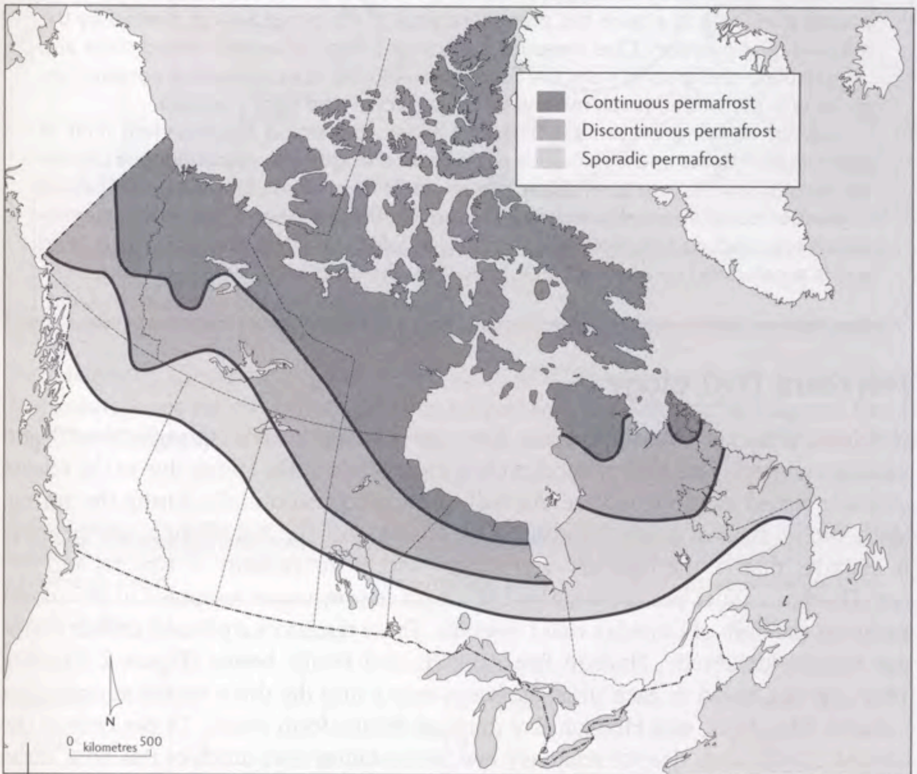
Permafrost, or perennially frozen ground, is found in almost all of the Canadian North. It is defined as ground remaining at or below the freezing point for at least two years. Permafrost reaches its maximum depth in high latitudes where its frozen state extends to several hundred metres or more into the ground; at more southerly sites its depth may be less than 10 metres. The greatest recorded thicknesses in Canada, on Baffin and Ellesmere islands, are over 1,000 metres.

Permafrost has existed for thousands of years in the Canadian North. The upper layer of permafrost (called the active layer) thaws each summer. The thickness of the active layer varies from a few centimetres in the Arctic to several metres in the Subarctic. The southern extent of permafrost is associated with the mean annual air temperature isotherm of 0°C (Williams, 1986: 3).

Since permafrost varies in depth and geographic extent, it is divided into four types—continuous, discontinuous, sporadic, and alpine (Figure 2.17). An area is classified as having continuous permafrost when over 80 per cent of the ground is permanently frozen; for discontinuous permafrost, 30–80 per cent must be frozen; and for sporadic permafrost, less than 30 per cent of the ground in an area is permanently frozen. The sporadic permafrost zone represents a transition area between permanently frozen and unfrozen ground. Alpine permafrost is not defined by the percentage of permanently frozen ground but by its presence in a mountainous setting. Such permafrost is found in British Columbia and Alberta. In terms of geographic distribution, continuous permafrost is found where the mean annual temperature is around –7°C while discontinuous permafrost lies between –5°C and –7°C (see Figure 1.3). Sporadic permafrost is often found between 0°C and –5°C.

Permafrost affects the land surface by slowing the growth of vegetation, impeding surface drainage, and creating periglacial landforms such as pingos and thermokarst features. While permafrost and periglacial landforms are often found in the same geographic area, permafrost refers to permanently frozen ground while periglacial features are created by the action of freezing and thawing. The melting of permafrost has only become a problem since efforts have been made to develop the North by building

Figure 2.17 Permafrost Zones in the Canadian North



The three permafrost zones extend across the Canadian North. In addition, occurrences of permafrost are found at higher elevations in the Cordillera.

Source: After *The Atlas of Canada*, at: <atlas.gc.ca>.

roads, pipelines, and towns, and, more recently, by warmer summer temperatures (Vignette 2.12). The design of these human-made features must take into account the presence of permafrost. Exposure of ice-rich ground during construction can result in retrogressive thaw slumps (Burn and Lewkowicz, 1990), and such slumps can prove costly to the project and to the environment. Permafrost has made northern construction 'a matter of geotechnical science and engineering' (Williams, 1986: 27).

Vignette 2.12 Melting of Permafrost

Disturbance or removal of vegetation cover by construction projects can result in the melting of permafrost and the resultant subsidence or sinking of the ground. How does this melting come about? The natural vegetation cover provides insulation from the Sun's radiation. When removed, the darker ice-rich ground then becomes warmed by the Sun and the higher soil temperatures melt the ice contained in the ground. The result is a shift from stable terrain to unstable terrain. One effect is subsidence, with the ground settling to a lower level. Another is gelifluction in hilly areas where slumping takes place on the steep slopes. Finally, subsidence results in thermokarst topography where the melting of ice embedded in the ground forms an irregular or hummocky landscape. For many decades, construction firms have taken special measures to ensure the thermal regime of the ground is not altered by the removal of vegetation. One measure is to cover steep slopes with wood chips and thus insulate the ground from the Sun's rays. Another is to undertake construction projects in the winter, which minimizes the impact on the frozen ground.

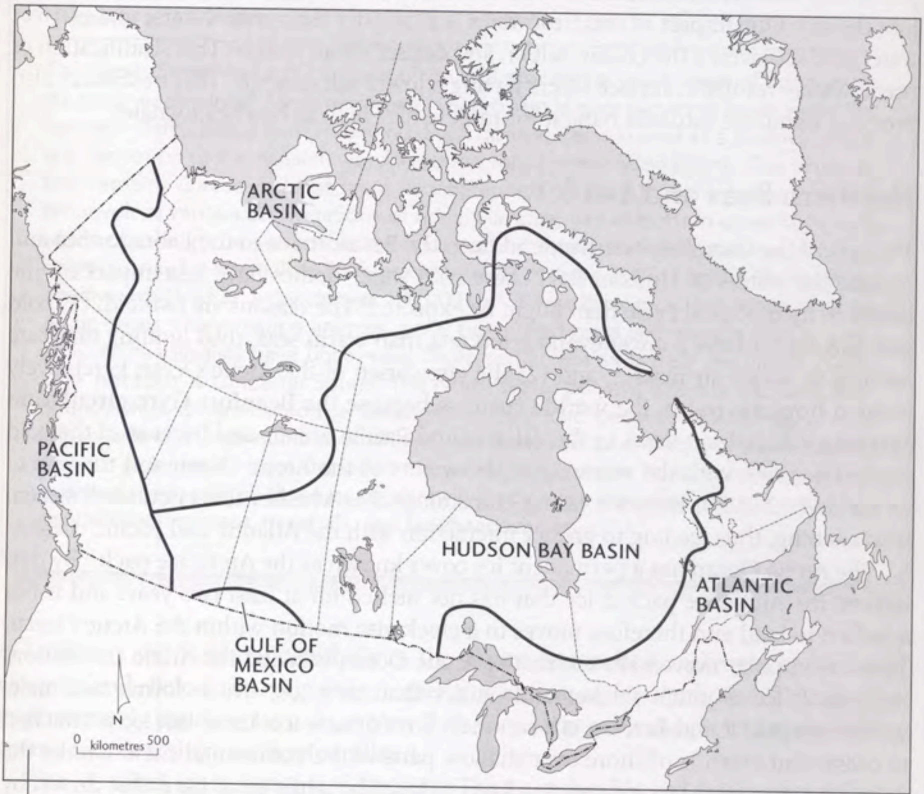
Global warming presents a new and wider concern as the southern limit of permafrost retreats and continuous permafrost changes into discontinuous permafrost and discontinuous permafrost into sporadic permafrost. However, with natural vegetation cover intact, this retreat is slowed. On the other hand, when ice in permafrost is exposed, such as along the shoreline at Tuktoyaktuk, its disintegration is rapid and is accelerated by wave action.

Northern Hydrology

Northern Canada's rivers and lakes have two phases—active (spring/summer) and inactive (winter). This hydrological cycle is most active in the spring due to the release of water stored as snow and ice. As well, most precipitation falls during the spring. With such a rush of water, flooding often occurs. For the rest of the year, the cycle is inactive, that is, the flow of water is well within the capacity of streams and rivers. Though annual precipitation in the North is low, water resources in the North make up the bulk of Canada's water reserves. These resources are found in four drainage basins—the Arctic, Hudson Bay, Atlantic, and Pacific basins (Figure 2.18). The river systems found in each drainage basin empty into the three oceans surrounding Canada. The Arctic and Hudson Bay drainage basins form nearly 75 per cent of the area of Canada and, despite relatively low precipitation over much of this area, these two basins account for almost 50 per cent of the stream flow (Table 2.3).

In terms of runoff volume, the Mackenzie River is the most important river in the North. Since most of its headwaters are located in British Columbia, Alberta, and

Figure 2.18 Drainage Basins of Canada



Canada has four major river basins and one minor basin, the waters of which flow to the Gulf of Mexico. A more detail account of river basins is shown in *The Atlas of Canada*.

Source: After *The Atlas of Canada*, at: <atlas.gc.ca>.

Saskatchewan, spring melting first occurs south of 60°N while the lower reaches of the Mackenzie River are still frozen. Ice jams frequently occur, causing widespread flooding. The Mackenzie River discharges vast quantities of freshwater into the Beaufort

Table 2.3 Drainage Basins of Canada and Their Streamflows

Drainage Basin	Area (million km²)	Streamflow (m³)
Hudson Bay	3.8	30,594
Arctic	3.6	20,491
Atlantic	1.6	21,890
Pacific	1.0	24,951
Total	10.0	97,926*

*The drainage basin of the Gulf of Mexico extends into a small portion of southern Alberta and Saskatchewan, and accounts for an area of 21,600 km² or 0.003 per cent of Canada's territory. Accordingly, the Canadian section of the Gulf of Mexico drainage basin contributes a similarly small amount of streamflow: 209 m³.

Sea. Other northern rivers, such as La Grande and Churchill, also empty freshwater into the sea. One impact of this freshwater is to stratify the ocean waters, that is, river water tends to overlie the colder, saltier, and denser ocean waters. This stratification of ocean waters results in surface layers having a lower salt content. This freshwater also provides a suitable estuarial habitat for marine life, such as bowhead whales.

Northern Seas and Sea Ice

The seas of the Canadian North extend from the Beaufort Sea to the Labrador Sea and include the waters of Hudson Bay. These cold water bodies have less impact on the northern hydrological cycle than might be expected. The reasons are twofold: (1) cold seas and sea ice have a lower evaporation rate than warm seas, thus limiting moisture forming in Arctic air masses; and (2) the circulation of the Arctic Ocean is relatively isolated from the rest of the world's currents because the **Beaufort Gyre circulation system** tends to limit flows to the Atlantic and Pacific oceans and because of the cold water. However, with the warming of the waters of the Arctic Ocean and the loss of its ice cover, a major question facing climatologists is whether this circulation system is weakening, thus leading to greater interaction with the Atlantic and Pacific oceans.

The Arctic Ocean has a permanent ice cover known as the Arctic ice pack.[2] By definition, the Arctic ice pack is ice that has not melted for at least two years and is not attached to land and therefore moves in a clockwise motion within the Arctic Ocean. This circumpolar movement within the Arctic Ocean is called the Arctic Oscillation. Polar pack ice is much thicker and harder than new ice, which forms and melts within one year. **Land-fast ice** is a common form of new ice. Land-fast ice is attached to coasts and extends offshore over shallow parts of the continental shelf. Unlike the polar pack ice, land-fast ice remains fixed in location while pack ice drifts, driven by currents and winds.

Arctic ice and waters in relatively small amounts flow into the Atlantic Ocean around Baffin Bay, where it mixes with the warmer Atlantic waters, forming Subarctic water. Baffin Bay is connected to the Arctic Ocean through Nares Strait and Jones and Lancaster sounds, and to the Labrador Sea through Davis Strait. Most icebergs are formed from the Greenland Ice Sheet. The Labrador Current carries them to the waters off Newfoundland, where they represent a hazard to both ocean shipping and offshore drilling rigs. During winter, when there is extensive ice cover, a **polynya** or open-water area (called 'North Water') exists in the northern part of Baffin Bay. The explanation for the natural factors that create open water in a frigid environment still eludes physical scientists (Vignette 2.13).

Sea ice is one of the unique features of northern oceans. Another is icebergs. In late winter, sea ice extends from the Arctic Ocean to the North Atlantic waters offshore from Labrador and the island of Newfoundland. Icebergs are floating masses of freshwater ice that broke away from glaciers. Most icebergs in the North Atlantic have calved (broken away) from glaciers as the glaciers enter the sea. Each year, 10,000 to 15,000 icebergs enter the North Atlantic, with most originating from glaciers along the west coast of Greenland. A few come from glaciers in the eastern Canadian Arctic islands. Icebergs float in the Labrador Current beyond the edge of the land-fast sea ice. This zone, known as 'Iceberg Alley', extends from Baffin Bay to the waters off the coast

Vignette 2.13 Polynyas

The Arctic Ocean has a thick cover of ice, but a dozen or more areas of open water do occur each winter. Many recur each winter. The largest recurring open water lies between Baffin Island and Greenland. Such open water is known as a polynya, which is a derivation of the Russian word for open water surrounded by ice. The explanation remains unresolved but most hydrographers believe that the basic mechanism involves various combinations of tides, currents, ocean-bottom upwellings, and winds that keep the surface waters moving and thus prevent them from freezing. Polynyas may be as small as 50 metres across or as large as the famous North Water polynya, which often extends over 130,000 km^2. These biological 'hot spots' serve as Arctic oases where marine animals, polar bears, and birds congregate. Not surprisingly, archaeologists have uncovered Thule settlement sites near the North Water. One 'hot spot' is Lancaster Sound. The North Water polynya extends into Lancaster Sound, which is considered the 'Serengeti of the Arctic' because most of the world's narwhals and a large number of whales, walruses, and seals frequent these waters. As well, polar bears roam the perimeter of the open water, hunting for ringed and bearded seals, though these bears also will feed on the carcasses of beluga whales, grey whales, walruses, narwhals, and bowhead whales

of Labrador and Newfoundland. Once the sea ice has melted, icebergs can be found close to land. Before disintegrating, icebergs may float as far south as 40°N, which is approximately the same latitude as New York City. Iceberg viewing is an important late spring tourist activity in Newfoundland.

Sea ice varies in thickness and duration. The most durable and thickest ice is found in the **Arctic ice pack**. In the summer, sea ice disappears first in the Great Lakes and offshore of Atlantic Canada and last in the Arctic Ocean. Accordingly, the length of time for open water in the Arctic Ocean is very short—perhaps only weeks—while in mid-latitude waters open water exists for most of the year.

Sea ice has a dynamic element that affects climate. A NASA ice expert, Josefino Comiso (NASA, 2010), expresses this relationship:

> The oceans are crucial to Earth's climate system, since they store huge amounts of heat. Changes in sea ice cover can lead to circulation changes not just in the Arctic Ocean, but also in the Atlantic and Pacific oceans. If you change ocean circulation, you change the world's climate.

More specifically, the increasing summer reduction in ice cover in the Arctic Ocean has altered its currents and thus the amount of ice/water/energy flowing into the North Atlantic Ocean through Baffin Bay.

The trend over the last three decades is clear. The Arctic Ocean is warming. Satellite imagery and on-site measurements reveal that the ice cover has diminished in both extent and average thickness. The significance of the Arctic ice cover having a greater proportion of new ice is that this thinner ice melts more quickly in the summer, thus creating a longer period of open water. In September 2007, for instance, satellite imagery indicated that the extent of open water in the Arctic Ocean was more extensive than in the previous decades, with the extent of sea ice diminished to 4.3 million km^2 (National Snow and Ice Data Center, 2007b). The most recent data, from 29 September 2010, revealed that Arctic sea ice reached its third lowest minimum extent at 4.6 million (the 2008 minimum was 4.7 million km^2, and the 2009 figure of 5.4 million km^2 reversed the trend for one season (NASA, 2010). For more on this subject, see the section 'Changing Geography of the Arctic Ocean' in Chapter 8.

Grand Themes

From this discussion of the North's physical geography, we can see that the complex but changing nature of this cold environment provides many challenges and calls for continued research to monitor its changing nature, especially that of the Arctic Ocean and its potential impact on the global climate, as well as on the people and communities for whom the North is their homeland. Reflecting back to the impact of climate warming on the Ward Hunt Ice Shelf mentioned at the beginning of this chapter, this impact symbolized the enormous change taking place in all aspects of Arctic geography as a result of a warmer climate. At this juncture, the reader is alerted to four of the grand themes in geography, and these themes will reverberate in the following chapters:

1) Is our physical world changing and, if so, how will it impact the North's biomes?
2) Can human activities, but especially those related to resource development, reduce their stamp on the physical environment?
3) Climate change as a global political and environmental issue is a new phenomenon, and its impact on the North, especially as recorded by retreating sea ice, glaciers, and permafrost, is remarkable. But why is climatic warming taking place more robustly in the North than in other areas of the world?
4) Are the Inuit benefiting from Arctic warming or is their way of life threatened?

The answers to these questions will determine to a large extent not only what happens in and to Canada's North but also, quite possibly, the future course of humankind.

Challenge Questions

1. What is the basis of the relationship between climate and natural vegetation?
2. What natural feature provides a visible mark on the landscape suitable for determining zonal boundaries?
3. Why is the North considered a fragile environment?
4. Temperature increases are predicted to be much greater in the Arctic than in southern Canada. What role does the albedo effect play in these temperature increases?
5. Based on the information in Table 2.2, which past climatic variation in the Holocene best describes our current climate?

6. Why are most periglacial features found in the region known as Arctic Lands?
7. Why did the glaciers create different landforms in the Cordillera than in the Interior Plains?
8. How would the loss of Arctic Ocean ice stand out as a pivotal change that would affect the global heat balance?
9. Why has the amount of greenhouse gases in the atmosphere increased over the last century?
10. Why is ice, in the form of glaciers, ice shelves, and Arctic pack ice, more likely to melt than ice contained in permafrost?

Notes

1. Sauderson, Smith, and Woo (2000) summarize recent developments in Canadian geomorphology. Much of their discussion deals with research advances in geomorphology occurring in northern Canada.
2. The Arctic ice pack is sometimes referred to as the polar ice pack. However, since there are ice packs in both the Arctic and Antarctic oceans, the term 'Arctic ice pack' is preferred.

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