BCS 100: Introduction to the Circumpolar North
University of the Arctic

MODULE 3: Northern Environments

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Overview

The landscapes of the Circumpolar North have been shaped by the interplay of physical, chemical and biological processes operating over many millennia or many millions of years. Many of the physical features and processes found in the Circumpolar North are unique to this part of the earth. The flora and fauna of the northern regions are unique because the environments they inhabit are extreme and finely balanced. The major factors involved in the development of northern landscapes and the evolution of the biology of circumpolar ecosystems are

- the large seasonal variations in solar energy throughout the year;
- the climate, including cold temperatures and low precipitation;
- the presence or absence of water in its various phases (gas, liquid or solid) and the dynamics and influence of water on northern landscapes and terrestrial and aquatic ecosystems; and
- the emergence of the region from the last Ice Age.

This module provides a brief introduction to the physical and biological features and processes of the Arctic and Subarctic regions and highlights the significant factors that influence those features and processes.

Learning Objectives

Upon completion of this module you should be able to:

1. Describe the spatial distribution of the dominant physical and biological features of the Circumpolar North.
2. Explain the importance of physical processes underlying the development of northern landscapes over geologic time; the importance of running water, snow and ice, permafrost, plate tectonics, volcanism and mountain building.

3. Summarize in general terms the unique environmental conditions that govern life in the Circumpolar North.

4. Articulate how plants and animals adapt to changing conditions in the North.

Required Readings

AMAP. 1997. "Polar Ecology", *In* Arctic Pollution Issues: A State of the Arctic Environment Report. Arctic Monitoring and Assessment Program (AMAP), Oslo, Norway. pp 35-49

Key Terms and Concepts

- Annual snow pack
- Bioaccumulate
- Carnivorous
- Cirques
- Continental climate
- Crustaceans
- Fauna
- Fennoscandia
- Fjords
- Flora
- Food chain
- Gelifluction
- Gelifluction lobes
- Glaciology
- Herbivorous
- Hydrologic cycle
- Igneous rocks
- Magma
- Maritime climate
- Metamorphic rocks
- Moraines
- Omnivorous
- Periglacial geomorphology
- Pingo
- Physiography
- Phytoplankton
- Plate tectonics
- Polynya
- Riparian
- Sedimentary rocks
- Surficial geology
- Thermokarst
- Trophic levels
- Troposphere
- Volcanism

Learning Material

3.1 Geography of the Circumpolar North

The eight countries that have territory within the circumpolar region surrounding the Arctic Ocean are, from the Prime Meridian eastward: Norway (including Jan Mayen Island and the Svalbard Archipelago), Sweden, Finland, Russia, United States (Alaska), Canada, Denmark (Greenland, Faeroe Islands {Føroyar}), and Iceland.

Along the coasts of each of these countries lie the seas of the Arctic Ocean and the northern seas of the Atlantic or Pacific oceans. Eastward from the Prime Meridian are the Norwegian Sea, the Barents Sea, the Kara Sea (Karskoye), the Laptev Sea (Laptevykh), the East Siberian Sea (Vostochnos-Siberskoye), the Chukchi Sea, the Sea of Okhotsk, the Bering Sea (a North

Pacific sea), the Gulf of Alaska (a North Pacific gulf), the Beaufort Sea, Hudson Bay, Baffin Bay, the Labrador Sea (a North Atlantic sea), and the Greenland Sea (Figure 1).

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Figure 1 Circumpolar North

Source: http://www.lib.utexas.edu/maps/islands_oceans_poles/arctic_ref802647_1999.jpg Public Domain. Courtesy of the University Libraries, The University of Texas at Austin.

There are a great many islands in the region. The largest, and the largest in the world, is Greenland, a province of Denmark. Iceland is the only northern island that is a sovereign nation. The other large ones belong to four of the Arctic Eight: the Svalbard island group belongs to Norway, Novaya Zemlya (New Land), Zemlya Frantsa-Iosifa (Franz Josef Land), Novosibirskiye Ostrova (New Siberian Islands), and Ostrov Vrangel (Wrangel Island) belong to Russia, St. Lawrence Island and Kodiak Island belong to Alaska (United States), Banks Island and parts of Victoria Island belong to the Northwest Territories (Canada), while Baffin, Devon, Ellesmere and Axel Heiberg islands belong to Nunavut (Canada) and support ice fields of various dimensions. Most of the other islands of the Canadian Arctic Archipelago belong to Nunavut.

Three oceanic ridges divide the Arctic Ocean basin into four separate basins. Moving from west to east, these ridges are known as the Alpha-Mendeleev Ridge, the Lomonosov Ridge and the Arctic Mid-oceanic Ridge, respectively. Similarly, the basins are known as the Canada Basin, the Makarov Basin, the Amundsen Basin and the Nansen Basin, respectively (Figure 2).

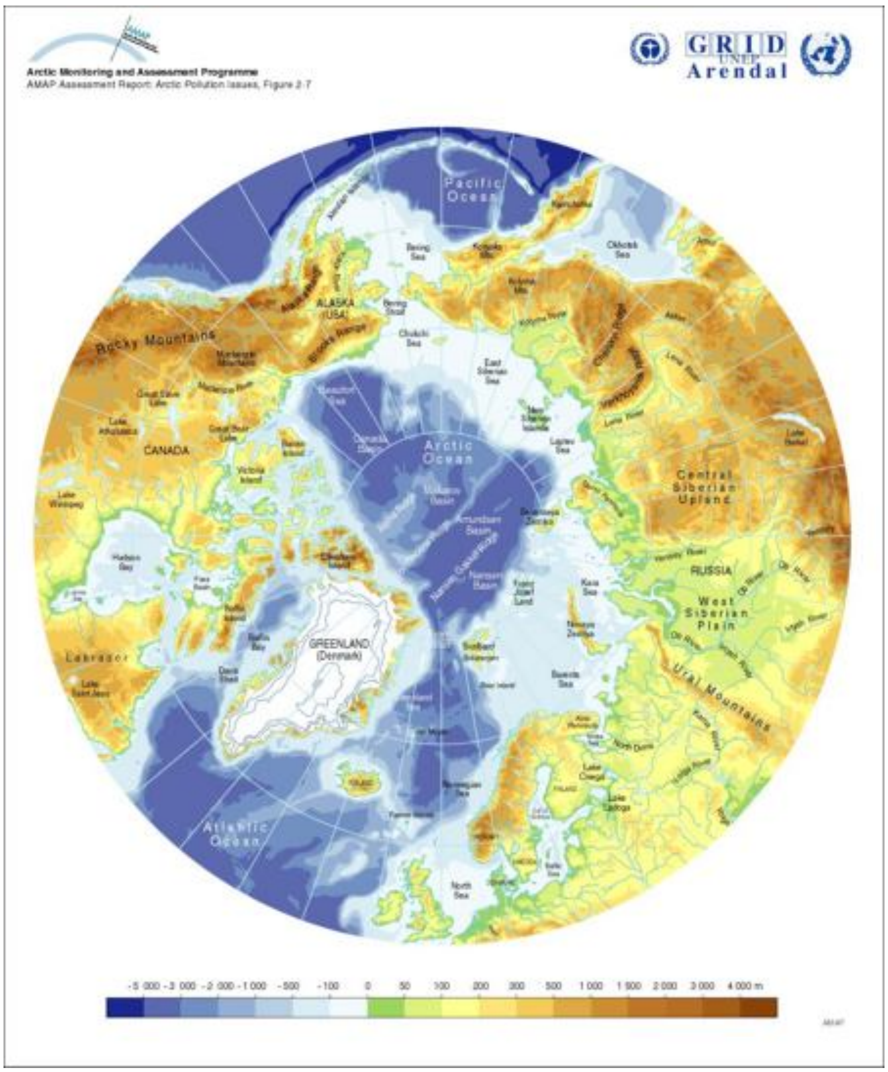

Figure 2: Circumpolar topography and bathymetry. Three oceanic ridges divide the Arctic Ocean into four separate basins.

Source: AMAP (1998). www.amap.no Posted with permission.

There are a number of large rivers that flow northward into the seas of the Arctic Ocean. Eastward from the Prime Meridian they are the Ob, Yenisey, Lena, and Kolyma in Russia, and the Mackenzie in Canada. The Yukon River is certainly a large northern river, but it empties into Norton Sound, part of the Bering Sea. There are, of course, a great many other rivers that flow northward; these are the largest ones. Each of these rivers has the capacity to discharge hundreds of cubic kilometres of freshwater per year (km^3/yr) into the Arctic Ocean and the adjacent northern seas (Figure 3).

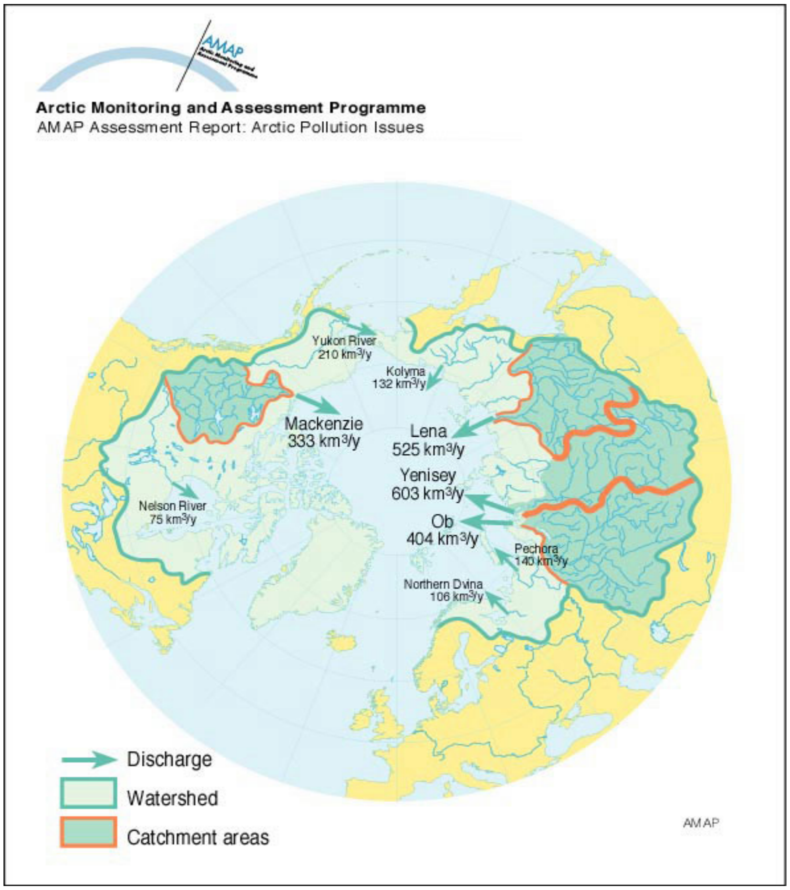

Figure 3: Mean annual discharge of the largest rivers draining into Arctic Ocean and its adjacent seas.

Source: AMAP (1998). www.amap.no Posted with permission.

Learning Activity 1: Using a Gazetteer

Locate the rivers named in the preceding paragraphs using an atlas. Identify several prominent communities nearest or along each river. Use a gazetteer to determine the latitudes and longitudes for these communities.

Most of the features that we think of as being typical of the northern physical environment are, directly or indirectly, the result of the northern climate. Everyone is aware of the arctic and subarctic regions as being cold places, but it is equally important to recognize that these are places where seasonality, the difference between summer and winter, is often considerable. Northern summers may be as warm as or warmer than those of many coastal regions in Western Europe. Winters in areas such as Siberia or northwestern Canada that lie deep within the interior of continents experience **continental climates** that are almost unbelievably cold, but winters in some northern regions near marine coasts may experience milder **maritime climates** with mean temperatures above freezing for even the coldest months. Continental climates exhibit a large annual range in air temperatures (Figure 4), reflecting the fact that in the absence of an insulating cover of snow and ice, land surfaces heat rapidly in summer and cool rapidly in winter. Cool summers and intensely cold winters are characteristic of continental climates in northern regions. Maritime climates, on the other hand, exhibit a much smaller annual range in air temperatures, reflecting the fact that large water bodies heat slowly in summer and cool slowly in winter. In many arctic environments the persistence of snow and ice on land and sea ice on the ocean diminishes the moderating influence of the maritime environment. The result is that coastal communities such as Churchill, Manitoba (58° 47'N, 94° 12'W) and Kuujuuarapik, Québec (55° 20'N, 77° 35'W) both situated along the shores of Hudson Bay, exhibit continental climates.

Learning Highlight 1

Visit the UArctic Atlas to see the Arctic as defined by temperature: *http://www.uarctic.org/AtlasMapLayer.aspx?m=642&amid=7246*

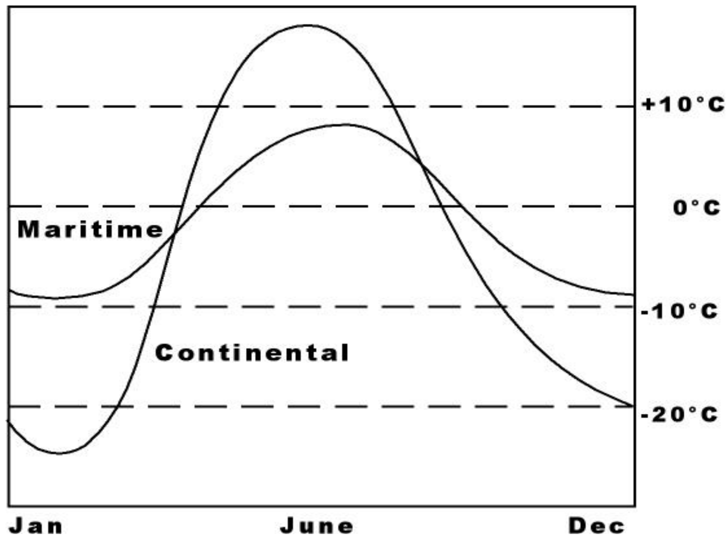

Figure 4: A comparison of annual temperature variations in a region experiencing a maritime climate and a region experiencing a continental climate (after Young 1989).

Source: Young, S.B. (1989). *To the Arctic: An Introduction to the Far Northern World.* New York: John Wiley & Sons, Inc. Posted with permission of the author, Steven B. Young.

The physical state of water, whether it is a solid or a liquid, is the dominant defining feature of northern environments. Biological activity is dependent upon the presence of liquid water. The liquid water present in lakes and rivers, and taliks within permafrost affects the well-being of plants and animals alike (see Basic Ecological Concepts below). The presence of water in its solid state; as glaciers, as sea and lake ice, as snow, or as ground ice associated with permafrost, creates many of the characteristic landforms of the Circumpolar North.

3.2 Snow

The source of snow is water vapour evaporated from the Earth's surface. In the **troposphere,** that part of the atmosphere that occurs from sea level to an altitude of 10 kilometres, the water vapour condenses to form clouds that might yield precipitation that ultimately returns to the Earth's surface, repeating the process indefinitely, as part of the **hydrologic cycle**. In temperate and tropical regions most of the precipitation falls as rain: however, during much of the year in the Circumpolar North, precipitation is in the form of snow. Throughout most of the Circumpolar North at the present time, the presence of the **annual snow pack** is the normal situation: however, the extent of snow cover in the Northern Hemisphere has decreased over the past several decades (Figure 5).

Learning Activity 2: Climate

Determine the mean annual precipitation and mean annual temperature in your community or region. Use an Internet search engine and type in "mean annual temperature" or "mean annual precipitation" and the name of your community or region. Governments usually gather and publish this information.

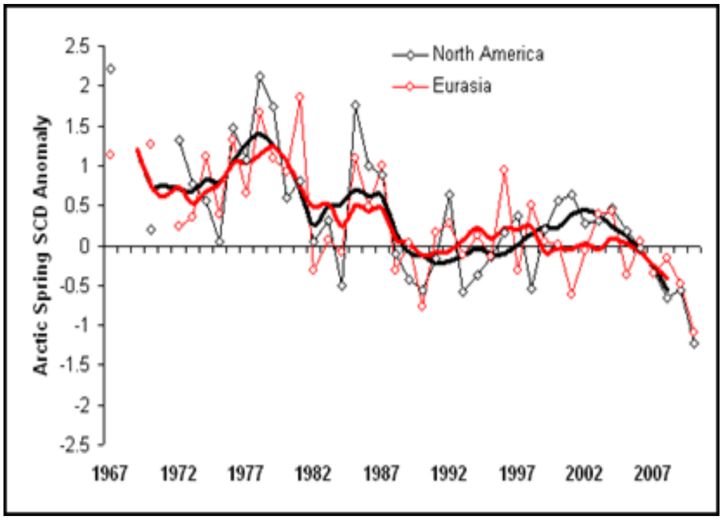

Figure 5. Arctic seasonal snow cover duration (SCD) anomaly time series (with respect to 1988-2007) from the National Oceanographic and Aeronautical Administration (NOAA) record for the spring snow season. Solid lines denote 5-yr moving average.

Source: Derksen, C., R. Brown and L. Wang, 2010: Terrestrial Snow [in *Arctic Report Card 2010*], http://www.arctic.noaa.gov/reportcard. Public Domain.

Snow is an important variable that influences the rate of soil warming and permafrost thawing. Dry snow effectively insulates the ground surface during the winter; hence an increase in the depth of the winter snow pack generally results in higher soil temperatures as summer heat is trapped below the snow cover. Small mammals such as lemmings and voles exploit this warm **subnivean** (i.e. beneath the snow) habitat. These animals are too small to store enough food within their bodies to survive a northern winter. They remain active burrowing beneath the snow to forage for dried grasses and sedges as well as seeds while protected from predators. The presence of a thin snow cover in the fall and early winter results in more rapid and deeper cooling of the soil. If the snow does not build up too deeply, and if the summers are warm enough, there are several snow-free months each year when the soil is warm enough and supplied with moisture so that living things can survive, grow, and reproduce.

3.3 Ice

Glaciation

If more snow falls on land surfaces than can melt each year, it begins to accumulate in deeper and deeper snow beds. This is particularly likely to happen in mountains, where the air is colder, where wind can blow the snow into deep drifts in hollows on the face of slopes, and where the sun may only shine for a short time each day if the slope faces northward. If, over the years, the snow becomes so deep that it is compressed into ice, it may begin to flow under its own weight to become a glacier. Glaciers can expand to enormous size, and even cover continents during the long cold periods called Ice Ages that last tens of thousands of years. The processes occurring on, within and beneath glaciers are complex: their study is called **glaciology**.

Glaciers are constantly in motion; immense masses of ice, flowing outwards from highlands toward the lowlands (Figure 6), and, ultimately, the sea. If the glacier ice reaches the sea before it melts, it disintegrates into the sea in large chunks of glacier ice called **icebergs** (Figure 7). The Greenland Ice Sheet is the greatest source of icebergs in the Northern Hemisphere. Outlet glaciers extend from the margin of this ice sheet into Baffin Bay and the Greenland Sea. Most of the icebergs in the North Atlantic Ocean drift across Baffin Bay and Davis Strait to the coast of Labrador moved by the West Greenland, Baffin and Labrador ocean currents, respectively. In this region of the ocean, the icebergs melt rapidly because of the sunshine and warm ocean water of the North Atlantic Drift. The greatest numbers of icebergs reach the North Atlantic Ocean in April, May, and June. That is why ships crossing the Atlantic follow a more southerly course during these months (http://www.nasa.gov/worldbook/iceberg_worldbook.html).

Figure 6: An alpine valley glacier.

Source: Glaciers Online www.swisseduc.ch Photograph by Jürg Alean. Posted with permission.

Figure 7: Icebergs off the Greenland coast of the North Water polynya.

Source: http://en.wikipedia.org/wiki/File:Glaciers_and_Icebergs_at_Cape_York.jpg Creative Commons. Photograph by Mila Zinkova.

Just like rivers, glaciers are continually sculpting the landscape. Much of the work of glaciers happens deep beneath the ice, and the results can only be seen during warmer periods of the earth's history, such as the comparatively warm period we are living in now when the glaciers melt and recede. Vast areas in the Circumpolar North owe their nature to the now-vanished glaciers that have molded the landscape into a wide array of easily identifiable features, including **cirques**, **moraines** and **fjords** (Figures 8, 9 and 10). The study of glaciated landscapes is called **glacial geology**. It involves not only the study of the erosion of the landscape by moving ice, but also of the enormous quantities of material that are carried down from the highlands and deposited as the ice melts.

Figure 8: Cirque with a perennial snow bed, Torngat Mountains, Labrador, Canada.

Source: http://gsc.nrcan.gc.ca/landscapes/ Reproduced with the permission of Natural Resources Canada 2011, courtesy of the Geological Survey of Canada (GSC Photo No. 2002-407 by Hazen Russell).

Figure 9: End moraine of a glacier, Bylot Island, Nunavut, Canada.

Source: http://gsc.nrcan.gc.ca/landscapes/ Reproduced with the permission of Natural Resources Canada 2011, courtesy of the Geological Survey of Canada (GSC Photo No. 2002-218 by Ron DiLabio).

Figure 10: Inner Inugsuin Fiord, a flooded glacial trough in eastern Baffin Island, Nunavut, Canada.

Source: http://gsc.nrcan.gc.ca/landscapes/ Reproduced with the permission of Natural Resources Canada 2011, courtesy of the Geological Survey of Canada (GSC Photo No. 2002-241 by Douglas Hodgson).

Learning Activity 3: Glaciations

Determine whether your area was glaciated during the last Ice Age. If so, how did the ice affect the landscape? If not, how is your area different than areas that were glaciated? How do earth scientists determine whether particular regions were glaciated?

Sea Ice

Ice that forms on the surface of the ocean is different from glacier ice: the former is derived from salt water while the latter is derived from snow. Because sea ice mainly forms by freezing from the surface of the ocean downwards, there is a limit to how thick it may become. What is particularly important here is the fact that when water freezes into ice, it actually expands and becomes less dense, so that ice always floats on the surface of water. Ice forms over much of the northern seas each winter. In the past few years, it has been easy to study the changes in the extent of sea ice from month to month, and from year to year, using satellite imagery. Studies of this sort can be useful in learning about changes in the earth's climate. Ocean currents, wind, and tides affect sea ice (Figure 11). As it moves under these forces, it becomes rugged and broken, and is then called pack ice**.** Much of the Arctic Ocean pack ice is carried in a slow clockwise circle, because of the motion of cold ocean currents beneath it (Figure 12: the Beaufort Gyre, Transpolar Drift, and East Greenland Current), and moves out of the Arctic Ocean off the east coast of Greenland into the western North Atlantic Ocean, where it may extend southward to the Gulf of Maine transported by the Labrador Current. In the eastern North Atlantic, by contrast, pack ice seldom reaches even the northernmost shores of Scandinavia, and ships can travel to the Russian Arctic port of Murmansk (68^{o} 57'N, 33^{o} 10'E) throughout the year. Here, the warming influence of ocean currents known as the North Atlantic Current and North Cape Current inhibit the development of pack ice. Pack ice also forms south of the Bering Strait in the Bering Sea, and in the Sea of Okhotsk between Kamchatka Peninsula and the coast of the Russian Far East.

Figure 11: Sea ice in Foxe Basin off Melville Peninsula, Nunavut, Canada. Landfast ice develops at and is attached to the shoreline while mobile pack ice develops further offshore.

Source: http://gsc.nrcan.gc.ca/landscapes/ Reproduced with the permission of Natural Resources Canada 2011, courtesy of the Geological Survey of Canada (GSC Photo No. 2002-522 by Lynda Dredge).

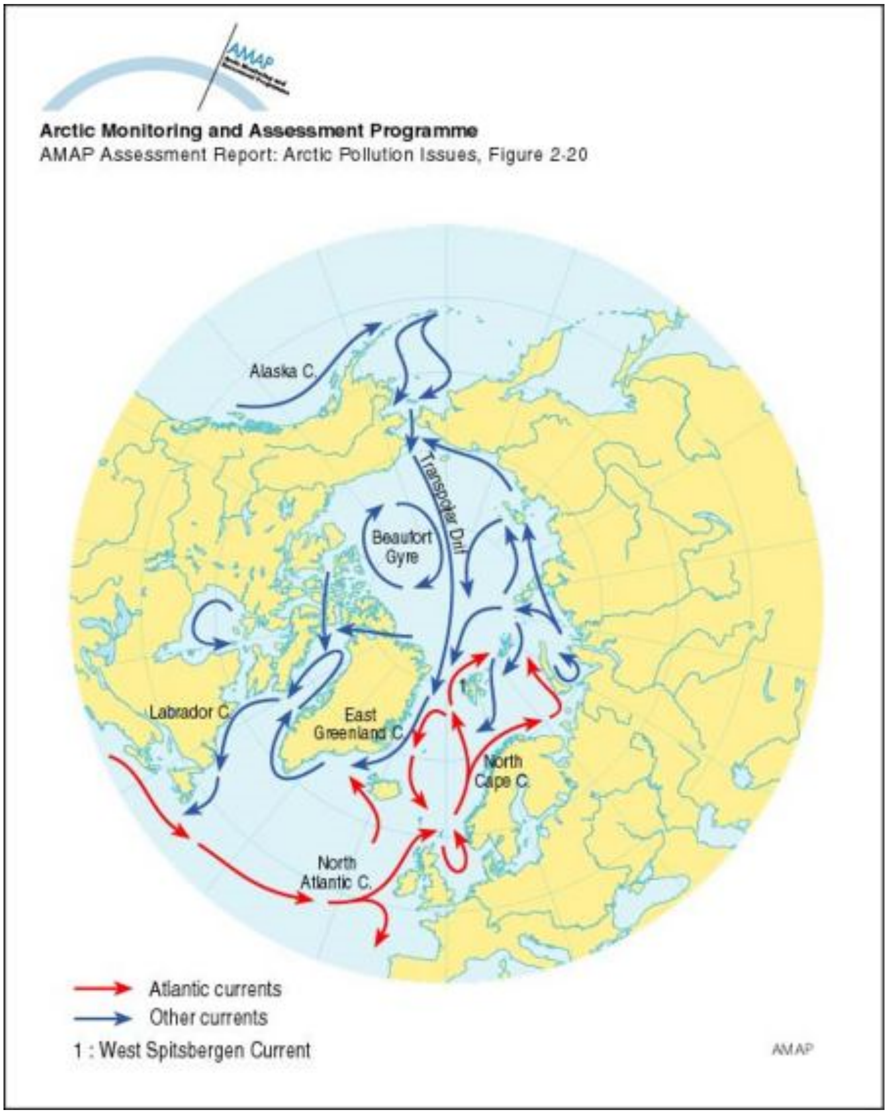

Figure 12: Ocean surface currents in the Arctic region. The warm North Atlantic Current, North Cape Current and West Spitsbergen Current are shown in red; the cold currents of the Beaufort Gyre, the Transpolar Drift, the East Greenland Current and Labrador Current are shown in blue.

Source: AMAP (1998). www.amap.no Posted with permission.

Learning Highlight 2

Visit the UArctic Atlas for a view and explanation of sea ice.
http://www.uarctic.org/AtlasMapLayer.aspx?m=643&amid=5992

Lake and River Ice

Lakes and rivers in the North are often frozen for many months of each year. Only the largest lakes, however, develop anything approaching true pack ice. During winter, most northern rivers have a flat, smooth, ice cover. But when spring breakup arrives, currents carry huge masses of ice downstream, where they often pile up as massive ice dams, flood enormous areas and erode riverbanks (Figure 13). This is particularly true in the many large rivers that flow northward into the Arctic Ocean, where melting may occur weeks earlier in their upstream (southern) portions than at their mouths. In winter, the flow of even fairly large rivers may be reduced significantly, since the headwater streams are often frozen solid. Large masses of river ice may be stranded on the riverbanks and last throughout the summer.

Figure 13: Ice scouring of the riverbank of the Mackenzie River, Northwest Territories. This photograph depicts a bank of the Mackenzie River that has been scoured by river ice during the spring break-up; this example was observed near the confluence with the Keele River. Spring break-up is an important process in shaping the morphology of the Mackenzie River. Major ice jams can form in the channel and the shearing of the jammed ice along the riverbanks shapes the riverbank profile, damages and destroys bank vegetation, and is a serious threat to any structure built too close to the river's edge.

Source: http://gsc.nrcan.gc.ca/landscapes/ Reproduced with the permission of Natural Resources Canada 2011, courtesy of the Geological Survey of Canada (GSC Photo No. 2002-707 by Greg Brooks).

3.4 Permafrost

Characteristics

When the mean annual air temperature of an area is below freezing, the ground that freezes during the winter may not entirely thaw

> Learning **Activity 4: Permafrost**
>
> *Determine whether your area is located over permafrost and, if so, whether it is continuous, discontinuous, or sporadic. What effects has permafrost had on construction in your community?*

during the succeeding summer. This perennially frozen ground is called **permafrost**. Permafrost is defined as soil or rock or peat that exhibits temperatures at or below 0°C for more than two consecutive years. It is important in terms of ecosystem structure and function and affects many landscape processes at a variety of scales: permafrost limits the access of plants to liquid water and soil nutrients, restricts the depth of the rooting zone for plants, and disrupts soil structure. Frozen ground is a critical consideration in any discussion related to the development of northern landscapes; the study of landscapes underlain by permafrost is called **periglacial geomorphology**.

Learning Highlight 3

Visit the UArctic Atlas to see a permafrost map. Note the differences among continuous, discontinuous, sporadic and isolated. http://www.uarctic.org/AtlasMapLayer.aspx?m=643&amid=7149

Permafrost is particularly deep in parts of northeastern Asia and northern Alaska. Here, winters are extremely cold, and a covering of glaciers never insulated the ground during the Ice Ages. The frozen ground may extend to depths of many hundreds to thousands of meters. Various processes may allow for the buildup of great amounts of nearly pure ice beneath the ground surface. If this ground ice should melt, as a result of changing climate or rising sea level, for example, vast land areas can be affected (Figure 14).

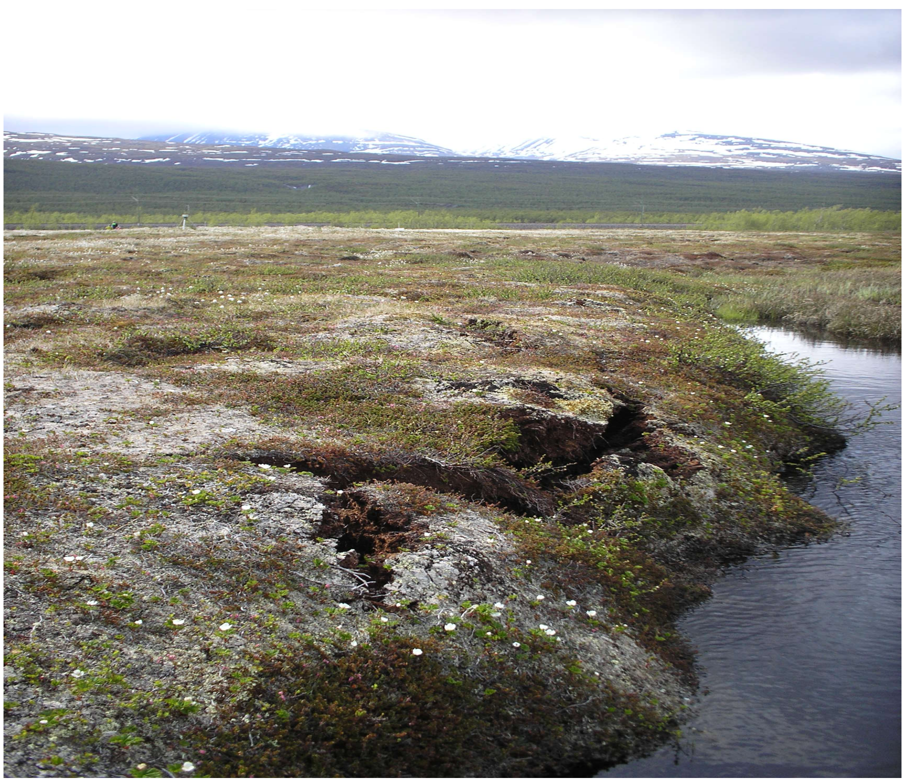

Figure 14: Permafrost peatbog border, Storflaket, Abisko, Sweden.

Source: http://en.wikipedia.org/wiki/File:Storflaket.JPG Public Domain.
Photo attribution: Dentren at en.wikipedia (http://en.wikipedia.org)

Extent

Permafrost underlies the surface of most Arctic regions, the exceptions being coastal areas, such as in Iceland and Norway, where warm ocean currents such as the North Atlantic Drift produce relatively mild winters. Permafrost has enormous effects on the northern environment. It keeps water from draining away through the soil, and this is largely responsible for the fact that much of the tundra is actually wetland. The creation and destruction of permafrost is often a highly dynamic situation; it can easily become destabilized by human activity and cause great destruction to buildings, pipelines, and roads built upon it (Figure 15). The melting out of ice-rich ground can also occur naturally causing the ground surface to subside; in either case, the result is known as **thermokarst**.

Figure 15: Ground subsidence due to thawing permafrost beneath railway tracks at Gillam, Manitoba, Canada.

Source: http://gsc.nrcan.gc.ca/landscapes/ Reproduced with the permission of Natural Resources Canada 2011, courtesy of the Geological Survey of Canada (GSC Photo No. 2001-175 by Lynda Dredge).

Geomorphological Features

Many of the processes that build up ice beneath the ground surface contribute to the development of various kinds of **patterned ground.** Among the most common landforms are ice-wedge polygons, which are found almost everywhere in the tundra areas of Alaska, northern Canada, and Siberia underlain by continuous permafrost. Persistent and intense freezing of the ground surface causes cracks to develop as the mineral soil or peat contracts. These cracks are filled with water derived from melting snow in early summer that subsequently freezes to produce ice wedges in the soil. The ice wedges become wider and deeper with each freeze-thaw cycle. As the ice wedges enlarge, the mineral soil adjacent to the frost cracks continues to be thrust upward to form distinct ridges forming low-center polygons (Figures 16a and c). Gradual accumulation of plant debris also serves to raise the ground surface within the central depression above the surrounding terrain. Progressive widening of the ice wedges accompanied by deformation of the mineral soil produces a dome-shaped landform referred to as high-center polygon (Figures 16b).

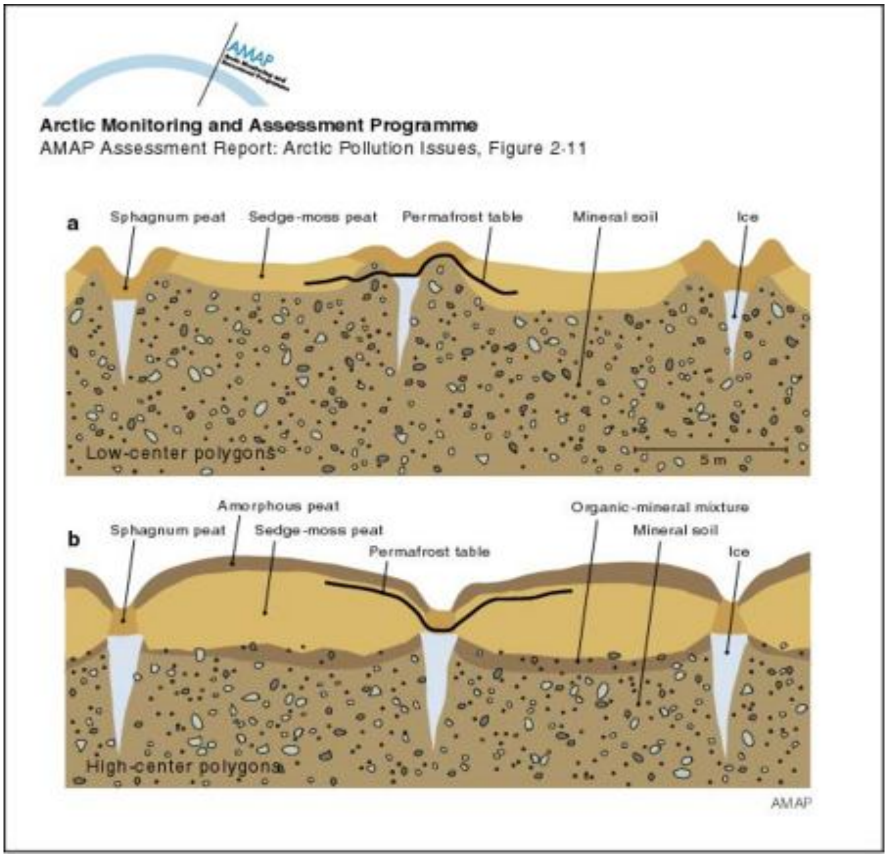

Figure 16a-b: Low-centre and high-center ice wedge polygon development.

Source: AMAP (1998). www.amap.no Posted with permission.

Figure 16c. A melting pingo and low-centred ice wedge polygons near Tuktoyaktuk, Northwest Territories, Canada.

Source: http://en.wikipedia.org/wiki/File:Melting_pingo_wedge_ice.jpg Public Domain. Photo by Emma Pike.

Other kinds of patterned ground are associated with intense freeze-thaw cycles, where the variation in air temperatures is more important than the actual annual mean air temperature. Heaving of soil and rock associated with the repeated freezing and thawing of water contributes to the sorting of these materials into coarser and finer fractions, creating landforms such as sorted stone circles (Figure 17).

Figure 17: Stone rings formed in coarse rock debris, Svalbard, Norway.

Source: http://en.wikipedia/wiki/File:Permafrost_stone_rings_hg.jpg Public Domain. Photo by Hannes Grobe.

Deformation of permafrost aided by the force of gravity can be the mechanism for moving large quantities of soil and frost-shattered rock down slopes. The general name for this process is **gelifluction** (movement of frozen material). Gelifluction is responsible for the surface features known as **gelifluction lobes** (Figure 18). Frost heaving in conjunction with gelifluction produces a variety of patterned ground known as stone stripes consisting of soil, stones and frost-shattered rock debris on alpine slopes (Figure 19).

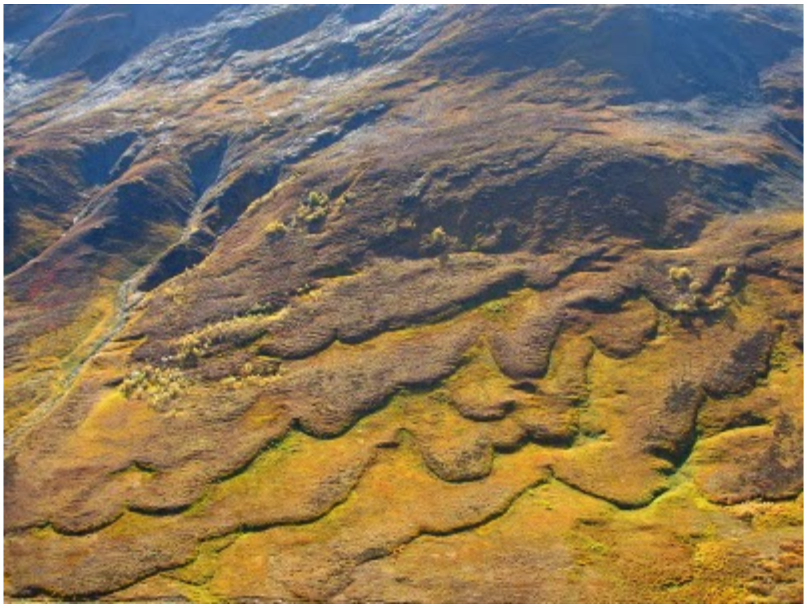

Figure 18. Gelifluction lobes developed on an alpine slope in Alaska.

Source: ©edplumb.blogspot.com Posted with permission.

Figure 19. Stone stripes

Source: http://scaa.usask.ca/gallery Northern Research Portal,
University of Saskatchewan, Saskatoon, Canada.

Among the most spectacular of permafrost features are steep-sided, ice-cored hills rising above otherwise flat tundra (Figure 20). These landforms are called **pingos**, and they have an interesting origin (see "Pingo Origin," Supplementary Reading). The term originated as the Inuvialuktun word for a small hill.

Figure 20. Pingo near Tuktoyaktuk, Northwest Territories, Canada.

Source: http://en.wikipedia.org/wiki/File:Pingos_near_Tuk.jpg
Public Domain. Photo by Emma Pike.

3.5 Subsurface Geology

Bedrock

Although the climate and **surficial geology** of the Circumpolar North have many distinctive features, the underlying bedrock is usually similar to that of temperate and tropical regions of the Earth. Much of this similarity is related to the processes of **plate tectonics**: the slow movement of various parts of the Earth's crust over hundreds of millions of years. The Earth's crust consists largely of igneous rocks with smaller proportions of sedimentary and metamorphic rocks.

Igneous rocks are derived from molten rock or **magma** that originates deep within the Earth. **Sedimentary** rocks are derived from the weathering and erosion of pre-existing rocks or are formed by chemical processes in lakes and oceans. **Metamorphic** rocks are derived from igneous and sedimentary rocks that have been changed physically and chemically by the application of heat and pressure deep within the Earth's crust during periods of mountain building. Fossils of dinosaurs and tropical forest plants (Figure 21) preserved in sedimentary rocks on Greenland, and Axel Heiberg and Ellesmere islands in the Canadian Arctic Archipelago indicate that many Arctic lands were once located in more temperate regions that experienced warmer climates than at present.

Figure 21. Fossilized tree stumps, Axel Heiberg Island, Canada.

Source: http://scaa.usask.ca/gallery Northern Research Portal, University of Saskatchewan, Saskatoon, Canada.

Physiography of the Circumpolar Region

Variations in the topographic relief of the Circumpolar North reflect the constant interaction between geologic processes that create topographic relief such as **volcanism** and the folding and faulting of rock associated with plate tectonics, and the processes of weathering and erosion that reduce topographic relief. Three large-scale landforms can be observed on the map of the circumpolar region illustrated in Figure 22: continental shields composed largely of ancient igneous and metamorphic rocks; plains and plateaux composed of sedimentary rocks (e.g. Interior Plains of Canada, East European Plain); and mountain ranges composed of a mix of igneous, folded sedimentary rocks, and metamorphic rocks (e.g. North American Cordillera, East Siberian Highlands, Ural Mountains, Arctic Lands). The Circumpolar North contains three ancient continental shields; the largest is the Canadian Shield, which makes up much of the eastern Canada and Greenland. The others are the Baltic Shield and the Angara Shield in north-central Siberia (i.e. Central Siberian Plateau in Figure 22).

The presence of continental shields is important, since they are often rich in various important mineral ores (e.g. copper, iron, nickel, zinc), gold and diamonds. Much of the pressure to exploit northern resources will continue to come from a desire to mine these ore bodies. Mountain ranges within the circumpolar region include the North American Cordillera, portions of the Arctic Islands (i.e. Devon Island, Ellesmere Island, and Axel Heiberg Island), the Ural Mountains, and the East Siberian Highlands. Sedimentary rocks in the North (i.e. Interior Plain, East European Plain, and the West Siberian Lowland) have proven to be rich in petroleum resources, and the production of oil and natural gas has driven much of the recent development of the North. Coal is mined actively from sedimentary rocks on Svalbard by the nations of Norway and Russia.

Figure 22. Geologic and physiographic regions of the Arctic.

Source: AMAP (1998). www.amap.no Posted with permission.

3.6 Basic Ecological Concepts

To begin to understand the living Arctic and Subarctic, we need to consider a few basic concepts:

1. All living things are part of a system and cannot exist except as part of this system;
2. Most living systems depend on energy that originates in the sun;
3. Living things can thrive only in the presence of liquid water; and
4. Many arctic and subarctic environments are comparatively new having emerged from beneath the continental ice sheets that once inundated vast areas of the northern hemisphere during their retreat over the past 20,000 years.

Since living things are part of an ecosystem, we cannot study them without being aware of their relations with other organisms and with the non-living parts of the ecosystem, such as solar energy and inorganic nutrients. If we want to study wolves, we cannot go very far unless we also study their prey that provide their source of energy. Similarly, we cannot study their prey, such as caribou, hare, and lemmings, without studying the plants that they eat.

At the same time, individual animals, or kinds (species) of animals and plants have certain characteristics and requirements that are unique to them. For example, the tree species that form the Arctic treeline include spruce, pine, larch (tamarack), balsam poplar, and birch. Black spruce, white spruce and larch are all shallow-rooted coniferous trees that are not adversely affected by the presence of permafrost beneath them. Black spruce and larch, however, grow well in heavy clay soils and wet peat bogs, saturated with acidic groundwater, whereas white spruce requires better-drained soils. In contrast, broad- leaved trees such as balsam poplar and birch have deep taproots that require unfrozen soils to thrive such as in **riparian** environments adjacent to stream channels.

Energy

To be alive requires energy, and for many organisms all of this energy is ultimately derived from the sun (Figure 23). Green plants are capable of photosynthesis, that is, they are able to change solar energy and other non-organic compounds directly into chemical energy (organic compounds), which they then store in their tissues (roots, stems, leaves, or flowers). This makes them primary producers for the whole system. These green plants can live on land or in water. Many organisms depend on solar energy that has been stored by plants for their energy, either directly or indirectly. When **herbivorous** animals such as caribou, eat plants or lichens, they are directly consuming plant-stored energy so they can live and grow. When **carnivorous** animals such as wolves eat caribou they are indirectly consuming the plant-stored energy. Plant energy has been converted to flesh by the prey species. **Omnivorous** animals like bears can derive energy from both plants and animals, because they are capable of digesting and benefiting from both.

Learning Activity 5:

Energy

You have a bacon, lettuce, and tomato sandwich for lunch. Trace the energy in the various components of your lunch (bread, butter, bacon, lettuce, and tomato) back to the sun. Which part went through the greatest number of trophic levels?

Each time there is a transfer of energy to a "higher" level in the system, much of the energy is lost through inefficiency because not all of the living matter in the lower levels gets eaten, not everything that is eaten is digested, and energy is always being lost as heat. About 10% of the energy available in one trophic level will be passed on to the next. Wolves are at a higher trophic level than caribou, since they eat caribou. In the system, there must always be many fewer wolves than caribou. In terrestrial (land) ecosystems, the **food chain** or number of **trophic levels** is usually short: for example plants, caribou, and wolves.

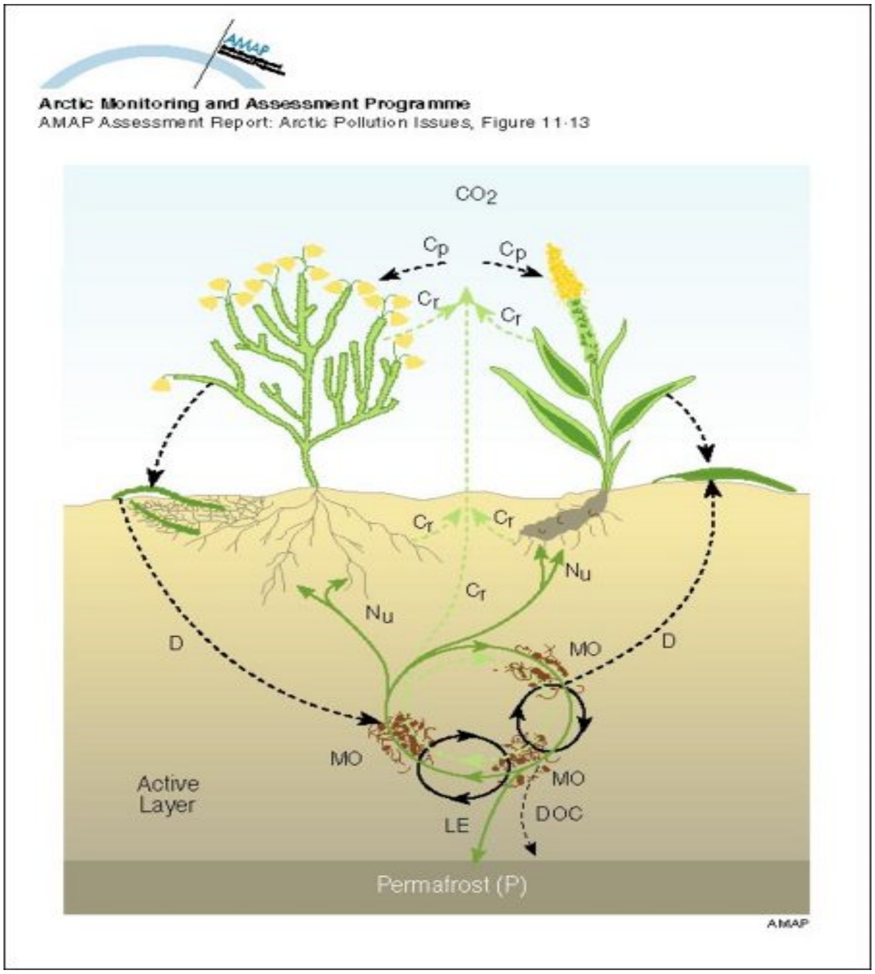

Figure 23. Diagram showing the movement of carbon and plant nutrients through a tundra ecosystem. Abbreviations in this figure: Cp – photosynthesis; Cr – respiration; D- detritus; MO – microbes; DOC – dissolved organic carbon; LE – leaching; N – plant nutrients. Plants use the sun's energy to produce simple sugars from carbon dioxide and water: this process is known as photosynthesis. The sugars are stored in plant tissues and eventually consumed to support plant growth: this process is known as respiration. As plants die their tissues accumulate in the soil as detritus; these organic materials are consumed by soil microbes, releasing mineral nutrients and dissolved organic carbon into the soil. These nutrients are either absorbed by the plant roots or are lost from the soil via leaching (after Callaghan and Jonasson, 1996).

Source: AMAP (1998). www.amap.no Posted with permission.

In aquatic ecosystems (rivers, lakes, and oceans) the plants consist largely of microscopic **phytoplankton** and are eaten by small **crustaceans** (zooplankton) that, in turn, are eaten by progressively larger animals. Aquatic food chains can have many trophic levels: phytoplankton, zooplankton, fish, seals and polar bears, for example.

Much of the transfer of energy through the systems occurs when organisms, or parts of organisms, such as the aboveground leaves of perennial plants, die naturally. Other living things such as fungi and bacteria break down their bodies. These organisms, called decomposers, use much of the energy to maintain their own lives, but they return important inorganic and organic materials to the soil and water, and these materials, including inorganic plant nutrients such as nitrogen, phosphorous, and potassium, are essential for other plants to grow in abundance.

Water

It is not only lack of energy that limits life in the northern winter. Biological activity in terrestrial environments is influenced directly by air temperatures and the availability of liquid water. Living cells can only function if temperatures are warm enough for liquid water to exist. Many plants and some animals have the ability to survive freezing. Some have cells that are able to go into a dormant state, in which most activities are nearly or totally shut down, if they are able to cool down slowly. Other cells are destroyed by the formation of ice crystals inside them. Whether they can survive freezing or not, cells cannot grow, reproduce, or fulfill most of the functions of truly living organisms until temperatures return to those that allow their contents to be liquid.

Survival Strategies

In the circumpolar region, the energy supply is seasonal. North of the Arctic Circle, there is actually a period each year when there is no direct solar energy available. Even when the sun does shine, temperatures are often so low that plants are not able to utilize solar energy. Living things need to be able to use energy that was stored by plants during the warm summer season. Plants and animals utilize various survival strategies to survive the periods when resources are hard to find and energy available in the environment is low.

Poikilothermic (cold-blooded) organisms, such as insects and plants, can be prevented from completing their life cycles or storing enough energy to survive by lack of available energy during the growing season. Hairiness and melanism (dark body pigmentation) allow insect bodies to absorb and retain heat in cold environments. Reduced body size allows insects to efficiently exploit limited food resources during the relatively short period of summer warmth. Limited food resources may result in extended multi-year life cycles. For example, the life cycle of the moth *Gynaephora groenlandica* varies from seven to fourteen years. Finally, freezing tolerance among insects includes the selection of microhabitats such as clumps of ground-hugging plants that offer protection from winter cold.

Many northern plants are characterized by small stature with their leaves growing close to the ground surface. Heating of the ground surface in the spring warms these plants and allows cells to renew their activity after a prolonged period of winter dormancy. Hairiness and the presence of evergreen leaves allow some northern plants to absorb and retain heat and resist the effects of drying winds in cold environments. Strong and deep taproots allow some plants to establish and thrive in nutrient-poor frost-heaved soils.

Homeothermic (warm-blooded) animals deal with the problem of winter cold in a different way; they keep their bodies always at a temperature well above freezing. In the North, this is an energy demanding strategy, since it requires the animal to spend the greatest quantity of energy to keep warm during the time of year when the least energy is available. There is little margin for error; freezing is generally lethal although some animal species (e.g. the wood frog (*Rana sylvatica*)) have adaptations to freezing.

Warm-blooded animals have three main ways of dealing with cold: adaptation, hibernation and migration.

(a) Adaptation involves slow genetic changes to **floral** or **faunal** physiology that improve the species' and the individual's chances of surviving particularly harsh conditions. Some Arctic animals, such as Peary caribou and muskoxen have short legs and tails (Figure 24) to minimize heat loss. In most northern species, ears are small, too. Many species develop thick layers of fat. Others have specially adapted hair: caribou hair is hollow, to trap air, and polar bear fur is transparent with a hollow core. A polar bear's hairs trap heat, sending it to the skin (which is black). Subarctic lynx, ptarmigan, and moose have adaptations that allow them to move in snow. Lynx and ptarmigan feet are furred and feathered to act as snowshoes and spread the animal's weight over a wider area. Moose legs are jointed in a way that allows the animal to lift its feet high and thus walk through deep snow.

(b) Hibernation is a survival strategy of some smaller Arctic and Subarctic homeothermic animals. As noted, animals need energy to maintain their biological systems. They acquire that energy from the environment by consuming plants or other small animals. In winter, there are few plants to eat and the cold means that the animals need a great deal of energy to produce body heat. Hibernating animals are able to reduce their body temperatures by as much as 30°C or lower their metabolisms by 95 per cent. Their heat and breathing rates can be reduced. Hibernating Arctic ground squirrels have body temperatures that vary cyclically: body temperatures as low as -3°C have been recorded, though most are around 5°C. Bears become dormant in winter, which is not quite the same as the hibernation of Arctic ground squirrels. Bear body temperatures only decrease slightly, by about 3 to 5°C. They are able to move around and even nurse their young, which deep hibernators cannot do.

(c) Migration is a survival strategy employed by a large variety of animals, from oceanic zooplankton, to fish, seals and whales, birds, and terrestrial mammals such as caribou. Moving around allows the migrants to use the best environments for breeding and survival. For example, the barren ground caribou (*Rangifer tarandus*) is among the most abundant terrestrial mammals in northern Canada with a population of about 1.2 million animals. Some populations of these caribou undertake long seasonal migrations (i.e. several thousand kilometres per year) between winter habitats within the sparse coniferous forests known as taiga and summer habitats on the Arctic tundra bordering the Beaufort Sea. Caribou graze almost exclusively on ground and tree lichens during the winter. As spring arrives the caribou move out of the taiga and onto the tundra where their diet shifts to shrubs, forbs (flowering, non-woody plants), grasses, sedges and mushrooms. Pregnant cows deliver their calves on the tundra in late May and early June and they are joined later by bulls and cows not bearing calves. Cows, bulls and calves spend the summer fattening up on tundra vegetation in preparation for their return to their taiga habitat in late September (Figure 24).

Figure 24. Aerial view of a migrating caribou herd.

Source: http:www.flickr.com/photos/sami/73/ Public Domain. Photo by Sami Keinanen.

Population Cycles

Short growing seasons with low temperatures keep many species of plants and animals from being able to colonize the Arctic at all. Most Arctic and Subarctic ecosystems contain relatively few species, although with large numbers of individuals, as compared to temperate or tropical forests. In theory, this makes the ecosystem less complex, and scientists used to point to the Arctic as a 'laboratory' to learn about ecosystems, and then apply the lessons learned there to other areas with more species. We now know that northern ecosystems compensate for the comparatively few species by all the complexities associated with changing seasons and other phenomena. This includes large variations in populations of various interrelated organisms from year to year, as in the famous lynx-hare cycles (Figure 25). Abundant prey produces well-fed predators that have the resources to produce offspring, often many more than in leaner years. The predator population expands and places greater pressure on the prey species. Prey numbers decline and predators pay the consequences by starving or succumbing to diseases in their weakened states. The weaker predators produce fewer offspring, the prey species is able to expand once again, and the cycle continues.

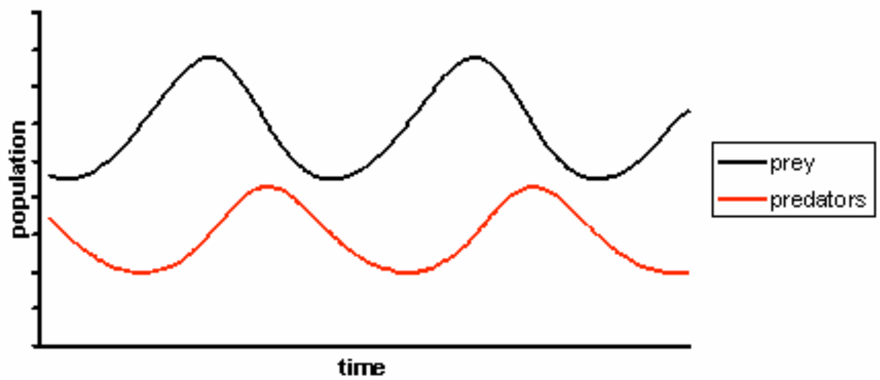

Figure 25. Schematic diagram showing the relationship between prey abundance and predator abundance. Note that the maxima and minima of predator abundance lag behind the maxima and minima of prey abundance, respectively.

Source: http://en.wikipedia.org/wiki/File:Volterra_lotka_dynamics.PNG Public Domain.

Aquatic Environments

Plants and animals in aquatic environments do not need to deal with the large seasonal changes in air temperatures that characterized terrestrial environments. Many marine ecosystems maintain a nearly constant temperature summer and winter, with the water always just above the freezing point. But marine organisms need to deal with long periods of low light conditions, especially if there is a thick covering of ice. Air-breathing marine mammals, such as whales, seals, and walruses, must make some provision for getting to the surface of the ice to breathe. Other aquatic organisms must deal with the often-low levels of oxygen in the winter when plants cannot photosynthesize in the darkness, and so produce little or no oxygen. Some animals migrate to more productive areas. Others remain in the North and concentrate in areas where the water remains relatively free of sea ice year-round because of tides, currents or other local factors (Figure 26). These areas are called **polynyas**.

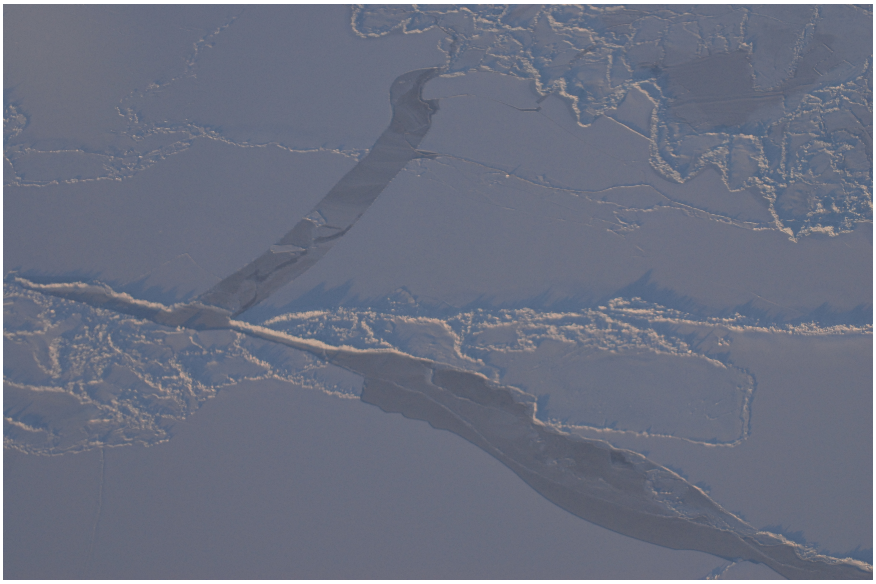

Figure 26. Polynya in the Beaufort Sea, Western Canadian Arctic.

Source: Photo by William Williams, Institute of Ocean Sciences, Fisheries and Oceans Canada.

3.7 Changing Environments

The present Arctic and Subarctic ecosystems have existed for only a brief period of geological time extending back to approximately 20,000 years ago when continental glaciers covered much of North America, Greenland, Iceland, and **Fennoscandia**. The build up of ice sheets on the continents resulted in the lowering of global sea level by more than 120 metres, exposing the continental shelves bordering the Arctic Ocean, and creating a land bridge between Alaska and Siberia across the floor of the Bering Sea. Ice-free areas north of the continental ice sheets extended from the present-day Yukon Territory and northern Alaska, across the Bering Land Bridge (Beringia) to eastern Siberia. These refugia provided habitats for tundra plants and animals to survive until the melting and retreat of the ice sheets allowed them to recolonize the northern landscape.

It must be emphasized that the tundra ecosystem has not been static in the past and is not now. The positions of the current glaciers and the margins of plant life are constantly but slowly changing. In cooler periods, when uplands and higher latitudes were dominated by ice, the plants could survive at lower elevations. In warmer, interglacial periods, the plants could survive at higher altitudes and latitudes. In between full glacial periods, when populations were isolated for long periods in unconnected mountain ranges, genetic differentiation took place and gave rise to new species. Some of the earliest members of the tundra ecosystem, including the woolly mammoth (*Mammathus primigenius*) and woolly rhinoceros (*Coelodonta antiquatis*), have become extinct while others such as caribou (*Rangifer tarandus*) and muskox (*Ovibos moschatus*) continue to inhabit northern landscapes. It is possible that the tundra ecosystem is still recovering from the loss of many of its species, and new colonists might, even now, be coming in from the temperate regions.

Polar Bears as Indicators of Ecosystem Health

The movement of processed energy up through the food chain, or across a food web, is of particular interest to scientists studying organic pollutants in plants and animals of the North. The Arctic Monitoring and Assessment Program (AMAP) reading "Polar Ecology" includes a discussion of the way that pollutants are transported to the North from more heavily industrialized areas. It also explains how these pollutants are concentrated in the bodies of animals that feed on contaminated plants and other contaminated animals.

For many people interested in the Circumpolar North, polar bear populations have become an indicator of the overall health of the northern environment. Because polar bears are at the top of a complex food chain, environmental pollutants tend to **bioaccumulate** in their systems, making them particularly susceptible to fairly low levels of background chemical toxins. The problem of concentrated pollutants occurs in aquatic ecosystems in the same way as it occurs in terrestrial ecosystems.

Because polar bears are intimately connected to the seasons and population cycles of their prey species, shifts in bear populations, or aberrant behaviour within populations are sometimes taken as signs of changes further down the food chain (Figure 27). While polar bear populations may be a good measure of environmental health, it is dangerous to rely too heavily on just one indicator. For example, declining polar bear populations in the southern Beaufort Sea and western Hudson Bay have been linked to the recent reductions in the annual sea ice cover in these regions which limits production of the bear’s primary prey, ringed seals. Polar bears are extremely adaptable to changing conditions, and that ability may mask problems within the overall system.

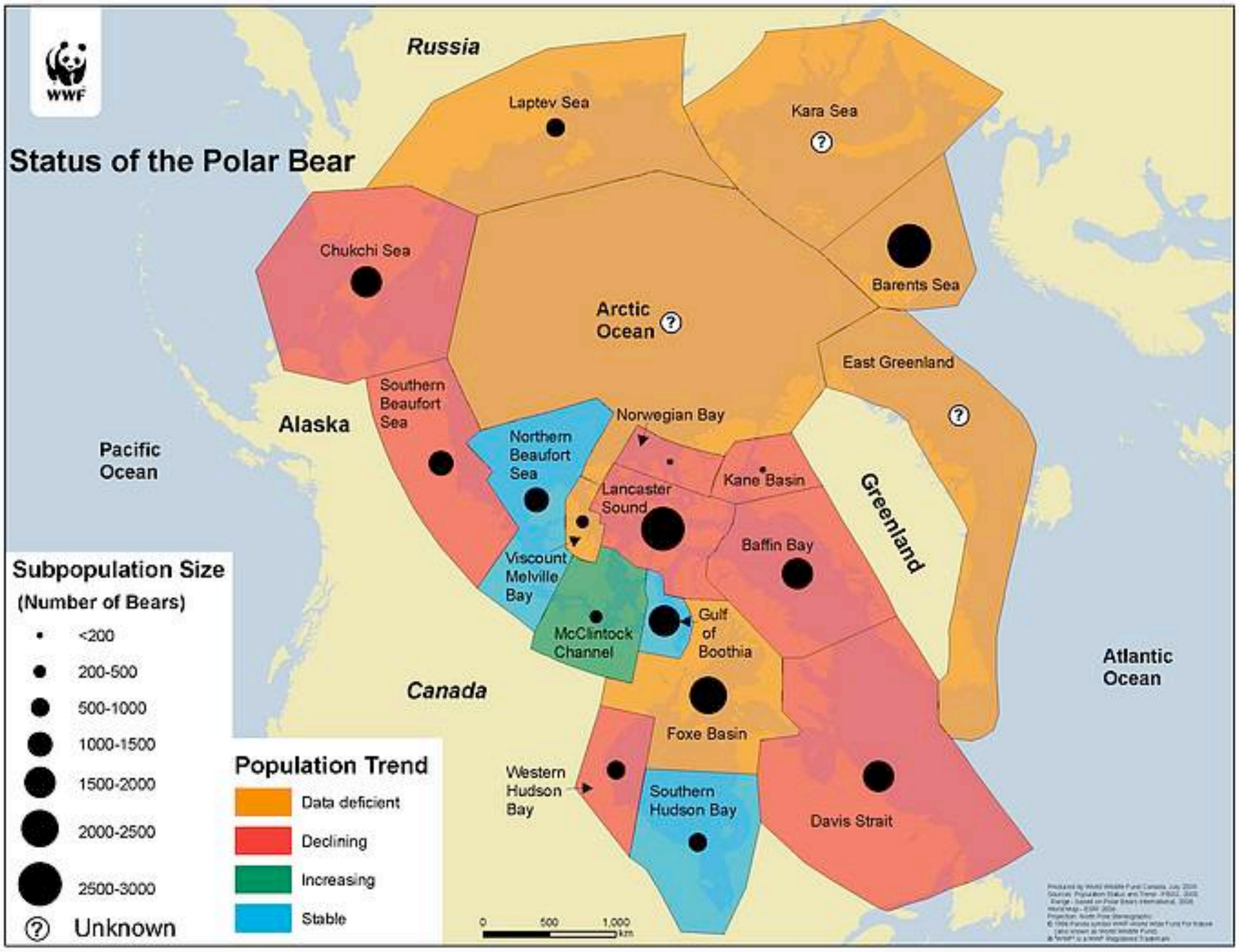

Figure 27: Population trends for polar bear populations around the Arctic as of July, 2009.

Source: WWF (World Wildlife Fund) ©WWF-www.panda.org Creative Commons.

3.8 Conclusions

The Circumpolar North encompasses the territories of eight nations: the United States of America (Alaska), Canada, Denmark (Greenland, Faroe Islands), Iceland, Norway (including Svalbard), Sweden, Finland and Russia. The bedrock geology of these various landmasses provides a vast storehouse of mineral resources. The landscapes of the Circumpolar North are largely the product of glacial erosion and deposition during the last Ice Age, frost action, and the mass movement of surficial materials above permanently frozen ground (permafrost).

The flora and fauna of the Circumpolar North have been shaped by the interplay of physical, chemical and biological processes operating over millennia, even millions of years. Access to solar energy, either directly or indirectly, liquid water, and mineral nutrients are limiting factors for living organisms inhabiting terrestrial and aquatic environments in the Circumpolar North. Adaptations in plants and animals have emerged to allow organisms to exploit periods of resource abundance and to survive periods of resource scarcity.

Study Questions

1. Describe the natural forces that combine to give the Circumpolar North its present geography and physical features.

2. Explain the importance of ice, its formation, persistence, and melting in the physical processes of the North.

3. Articulate the importance of water, as both liquid and ice, in the physical and biological processes of northern landscapes.

4. Describe, in general terms, the unique environmental conditions that govern life in the Circumpolar North.

5. Illustrate examples of environmental change taking place in the Circumpolar North.

Glossary

Annual snow pack: Snow that accumulates over the winter and melts or evaporates during the next summer (as opposed to snow that accumulates over many seasons and eventually forms glaciers).

Bioaccumulation: The build up of organic compounds in the fatty tissues of organisms. Bioaccumulation of toxins and other organic pollutants in food animals dramatically increases in concentration as one moves up the food chain.

Carnivorous: Species that are flesh-eating or predatory.

Cirque: A steep bowl-shaped hollow occurring at the upper end of a mountain valley, especially one forming the head of a glacier or stream.

Continental Climates: The climate of regions that lack the temperature-moderating effects of the ocean and that exhibit a greater range of minimum and maximum temperatures, both daily and annually.

Crustacean: Predominantly aquatic arthropods, including lobsters, crabs, shrimps, and barnacles, characteristically having a segmented body, a chitinous exoskeleton, and paired, jointed limbs.

Fauna: English word from the Latin—referring to all animal life. This word can be modified by various prefixes, such as megafauna (very large animals), microfauna (very small animals), etc.

Fennoscandia: The region in northern Europe, including Scandinavia, Finland, and Northwest Russia west of the White Sea.

Flora: A general term meaning plant or bacterial life.

Fjord: A glaciated valley flooded by the sea to form a long, narrow, steep-walled inlet. Fjords are common in Norway.

Food Chain: A straight-line sequence of steps by which energy passes to the next highest trophic level, that is, a hierarchy of organisms in which each feeds on those below and is the source of food for those above.

Gelifluction: a form of mass movement in which thawed upper soil layers move over permafrost

Gelifluction lobes: Rounded projection of frozen soil

Glaciology: The study of glaciers.

Glaciers: Glaciers are large, moving masses of ice formed over land through the accumulation, compaction, and recrystallization of snow.

Herbivorous: Refer to species that eat vegetable matter.

Hydrologic Cycle: This is the process by which water is recycled through the environment.

Igneous rocks: rocks resulting from solidification from a molten state.

Magma: Molten rock.

Maritime Climates: The climate of regions that are strongly influenced by the temperature-moderating effects of the ocean and that exhibit a smaller range in minimum and maximum temperatures than continental climates, both daily and annually.

Metamorphic rock: rock altered by pressure and heat.

Moraine: The accumulation of earth and stones deposited by a glacier

Omnivorous: Refer to species that eat both plants and animals as their primary food source.

Pingo: A dome-shaped mound found in permafrost areas, consisting of a layer of soil covering a large core of ice.

Periglacial geomorphology: Is the scientific study of landforms and the ground ice and freeze/thaw processes that shape them.

Physiography: The study of the natural features of the earth's surface

Phytoplankton: plankton that obtain energy by photosynthesis.

Plate Tectonics: A theory that proposes to account for the physical qualities of the Earth's surface. The fundamental premises of plate tectonics are that the Earth's surface is covered by a series of crustal plates; the ocean floors are continually, moving, spreading from the centre, sinking at the edges, and being regenerated; convection currents beneath the plates move the crustal plates in different directions.

Polynya: Year-round ice-free areas in polar ice pack.

Riparian: Relating to, or located on, the banks of a river or stream

Sedimentary rock: A rock formed from the consolidation of sediment that has accumulated in layers.

Surficial geology: Geological study relating to surface layers such as soil or glacial deposits.

Thermokarst: Topography in which melted permafrost has produced hollows, hummocks, and other features.

Trophic: Concerned with nutrition.

Trophic Level: An organism's trophic level refers to its position in the food chain. Organisms that convert sun energy and inorganic compounds into organic compounds are autotrophs and are located at the base of the chain. Organisms that eat autotrophs are called herbivores or primary consumers. Organisms that eat herbivores are carnivores. A carnivore that eats a carnivore that eats an herbivore is a tertiary consumer, and so on.

Troposphere: The lowest portion of Earth's atmosphere; from the surface to between 9-16 KM depending on latitude.

Volcanism: The natural phenomena and processes associated with the action of volcanoes, geysers and fumaroles.

References

Bliss, L.C., O.W. Heal and J.J. Moore (eds.). 1980. Tundra Ecosystems: A Comparative Analysis. Cambridge: Cambridge University Press.

Bone, R.M. 2008. The Canadian North: Issues and Challenges. Oxford: Oxford University Press.

Callaghan, T.V. and S. Jonasson. 1996. Arctic terrestrial ecosystems and environmental change. *In* P. Wadhams, J.A. Dowdeswell and A.N. Schofield. (eds.) The Arctic and Environmental Change, Gordon and Breach Publishers, UK, pp. 59-76.

Chapin, F.S. III and C. Körner (eds.) 1995. Arctic and Alpine Biodiversity: Patterns, Causes and Ecosystem Consequences. New York: Springer-Verlag.

Crampton, C.B. 1977. "A Study of the Dynamics of Hummocky Microrelief in the Canadian North." *Canadian Journal of Earth Sciences* 14, pp. 639–649.

French, H. M. and O. Slaymaker (eds.) 1993. *Canada's Cold Environment*s. Montreal: McGill Queen's University Press.

Harris, S.A. et al. 1988. *Glossary of Permafrost and Related Ground-ice Terms*. Technical Memorandum No. 142. Ottawa: National Research Council of Canada.

Kious, W. Jacquelyne and Robert I. Tilling. 1996. *This Dynamic Earth: The Story of Plate Tectonics*. Washington, DC: US Department of the Interior, US Geological Survey. Available online at http://pubs.usgs.gov/publications/text/dynamic.html

Nuttall, M. And T.V. Callaghan (eds.) 2000. T*he Arctic: Environment, People, Policy*. Amsterdam: Harwood Academic Publishers.

Pielou, E.C. 1994. A Naturalist's Guide to the Arctic. Chicago: The University of Chicago Press.

Pingo Origin. n.d. *Simply Science*. Web document. Inuvik, NT: Aurora Research Institute. Available online at http://collections.ic.gc.ca/simply_science/scirep1k.htm

Romanovskii, N.N., et al. 1996. "Periglacial Processes as Geoindicators in the Cryolithozone." In A.R. Berger and W.J. Iams (eds.) *Geoindicators: Assessing Rapid Environmental Changes in Earth Systems*. Rotterdam: A.A. Balkema. pp. 47-68.

Sage, B. (ed.) 1986. The Arctic and its Wildlife. New York: Facts on File. pp. 118-154.

Sater, John E., A. G. Ronhovde, and L. C. Van Allen. 1971. *Arctic Environment and Resources*. Washington, DC: Arctic Institute of North America.

Sharp, R.P. 1988. *Living Ice: Understanding Glaciers and Glaciation*. Cambridge: Cambridge University Press.

Williams, P. J. and M. W. Smith. 1989. *The Frozen Earth: Fundamentals of Geocryology*. Cambridge: Cambridge University Press.

Woo, M.K. 2000. "Permafrost and hydrology." In M. Nuttall and T.V. Callaghan (eds.) *The Arctic: Environment, People, Policy*. Amsterdam: Harwood Academic Publishers. pp. 57-96.

Young, S.B. 1989. To the Arctic: An Introduction to the Far Northern World. John Wiley and Sons, Inc. pp. 29-36.

Supplementary Resources

Arctic Monitoring and Assessment Programme. 2005. Transport of contaminants to the Arctic and their fate. Accessed at http://www.amap.no/fs-trnasport.pdf.

Gazetteer

Local language name	***English name***
Føroyar	Faeroe Islands
Zemlya Frantsa-Iosifa	Franz Josef Land (island group)
Novosibirskiye Ostrova	New Siberian Islands (island group)
Ostrov Vrangel	Wrangel Island
Karskoye More	Kara Sea
Laptevykh More	Laptev Sea
Severnaya Zemlya	Northern Land (island group)
Vostochnos-Siberskoye More	East Siberian Sea