BCS 311: Land and Environments of the Circumpolar World I

Module 2: Northern Climates

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Overview

This northern climates module begins from the perspective of a person's experience with weather. We note the difference between between **weather** and **climate**, discuss common weather and climate terms, and study examples of climatic information for northern places. We review the main causes of climate, geographical and other factors that 'control' climate, emphasizing subarctic and arctic regions. We follow with exchange of energy at the surface based on the **radiation** and **energy budget** approach.

Water is an essential part of northern ecosystems and plays a key role in climate. **Atmospheric moisture, evaporation, transpiration, precipitation** and **runoff** are introduced in a simplified water budget. Snow and ice are seasonal and permanent features of northern lands and seas as is **permafrost**.

Climatic factors and the resulting range of **climatic elements** determine the climate of a region and provide the basis for describing and explaining a range of northern climates. Climate at the local level is more interesting and complex than the regional climatic type might suggest. We can understand climate at this level by linking local surface climates, defined by energy and moisture exchange, to the topography of the landscape. Examples are used from forests, tundra, wetlands and the land-fast ice zone. Recognizing that the arctic atmosphere is no longer pristine, we consider some of the main factors that affect air quality in the North such as local sources and long-range transport of **atmospheric pollutants**.

Learning Objectives

The main objective of this module is to introduce climates of the circumpolar region in terms of theire controlling factors and resulting characteristics.

Upon completion of this module, you should be able to:

1. Explain the difference between climate and weather.

2. Recognize climate is a system with positive and negative feedbacks.

3. Identify major factors that determine climate from the local to regional scale.

4. Explain the importance of ice and snow (cryosphere) in the circumpolar North and their influence on regional climate conditions.

5. Define the concept of climate zone using examples that illustrate the variety of climatic zones in the circumpolar North.

Required Readings

G. McBean, G. Alekseev, D. Chen, E. Førland, J. Fyfe, P.Y. Groisman, R. King, H. Melling, R. Vose and P.H. Whitfield. 2004. Arctic Climate: Past and Present. Chapter 2. In: *ACIA Scientific Report*, (22-34). Cambridge, U.K.: Cambridge University Press.

G. Weller. 2000. The Weather and Climate of the Arctic. Chapter 6. In: M. Nuttall and T.V. Callaghan (eds.). The *Arctic: Environment, People, Policy*. (143-160). Harwood Academic Publishers.

Key Terms and Concepts

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- Atmospheric Pollution
- Climatic Elements and Data
- Climate and Landscapes
- Energy and Water Budgets
- Factors that shape Climate
- Feedback Processes
- Regional Climates
- Weather and Climate

Learning Material

2.1 Weather and Climate

Everyone is aware of weather. This is especially true for northern people who spend much time on the land, sea ice or water. We are sensitive to heat and cold, wet and dry, and the effects of wind in making cold seem colder or bringing relief from biting flies in the summer. The ability to read clouds and wind for signs of changing weather is key to traditional ecological knowledge. Although such observations focus on local conditions, people in different parts of the North may have similar rules for interpreting weather (Campbell et al., 2008). There are many points of agreement between traditional knowledge and the science of weather and climate.

Conditions in the atmosphere at a particular time and place – **temperature, humidity, wind speed and direction, rainfall, snowfall, visibility** – are elements of **weather.** Most people are familiar with terms such as temperature or rainfall, but may have little understanding of elements such as **humidity or pressure**. Exact definitions of weather and climate terms can be found in standard textbooks or online (e.g., National Weather Service Glossary http://www.srh.weather.gov/srh/jetstream/append/glossary_a.htm). Every region has characteristic values and seasonal patterns of weather elements that in the long term define the **climate** of that region. Climate is often described in terms of average conditions, such as the average temperature of the coldest month. It is important to include in the description some indication of variability and extremes and occasional but significant phenomena, such as a mid-January thaw. Such descriptions consist of values for climatic elements, the most common being average maximum and minimum temperatures, and total rainfall and snowfall. Up-to-the minute weather and climatic data are available on the Internet from weather services of various countries or through the World Meteorological Organization (WMO) (www.worldweather.org).

Icelandic Climate – A Short Description for Tourists

Iceland enjoys a milder climate than its name and location adjacent to the Arctic Circle implies. The Gulf Stream flows along the southern and western coast greatly moderating the climate. The Gulf Stream brings mild Atlantic air in contact with colder arctic air resulting in a climate marked by frequent changes in weather and storminess. This leads to more rainfall in the southern and western part of the island than in the northern part.

The summer tourist season is from late May to early September. During the first half of the season, the sun remains above the horizon almost 24 hours a day and the interplay of light and shadows on mountains, lava fields and glaciers yields an ever changing landscape. During the middle of the summer, the sky is frequently cloudy or overcast and sunshine does not warm the air much so the daytimes are usually cool ("refreshing" is the local euphemism) and nights cold.
Source: http://en.vedur.is/climatology/climate_of_iceland/

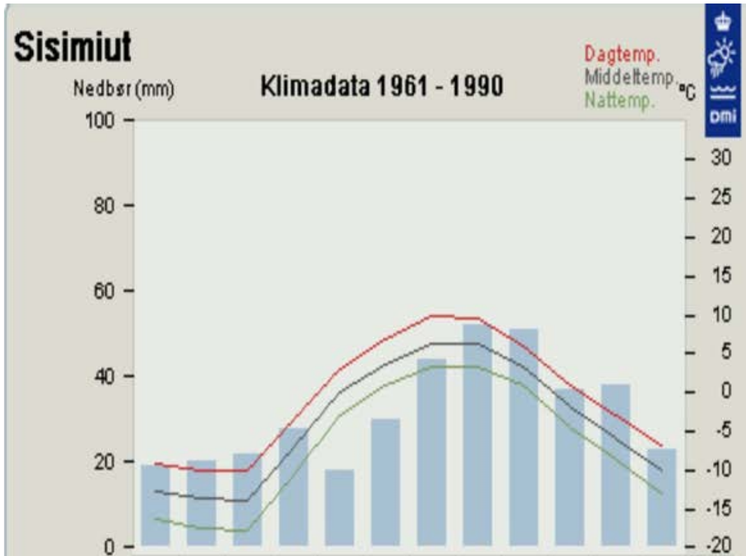
Standard climatological practice is to use the most recent 30-year averaging interval to construct **climatic normals**. Table 2.1 is a detailed climatic summary for Iqaluit, Nunavut Territory, Canada, that shows monthly averages for the period 1971-2000. Other averaging periods may be used for particular purposes like studies of climate change. It is often easier to view climatic data in graphical form as shown for Sisimiut and Nuuk, Greenland in Figure 2.1.

For most purposes a descriptive summary of the climate of a region is sufficient. If such a statement is clearly written and accurate, it contains information about the range of seasonal climatic conditions experienced and geographical factors that cause the climate to be as it is. Climatic data is often mapped to show spatial variations of the elements and their relationships to geographical features, e.g., University of the Arctic Atlas at http://map.uarctic.org/.

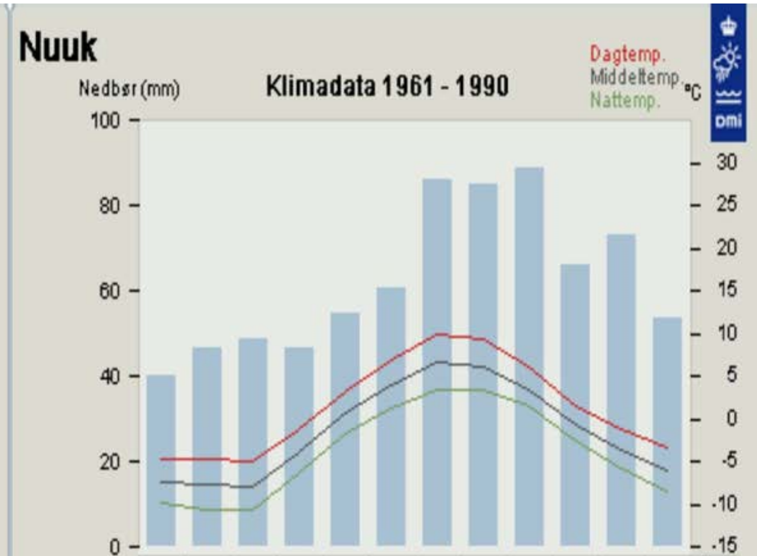
Table 2.1. Climatic Data for Iqaluit, Nunavut, Canada. Averages for Period 1971-2000.
(Abbreviated from: Environment Canada. http://www.climate.weatheroffice.ec.gc.ca/climate_normals/index_e.html)

IQALUIT, NUNAVUT
Latitude: 63° 45.0' N Longitude: 68° 33.0' W Elevation: 33.5 m

TEMPERATURE	January	February	March	April	May	June	July	August	September	October	November	December	Year
Daily Average (°C)	-26.6	-28	-23.7	-14.8	-4.4	3.6	7.7	6.8	2.2	-4.9	-12.8	-22.7	-9.8
Daily Maximum (°C)	-22.5	-23.8	-18.8	-9.9	-0.9	6.8	11.6	10.3	4.7	-2.0	-8.9	-18.5	-6.0
Daily Minimum (°C)	-30.6	-32.2	-28.6	-19.6	-7.8	0.3	3.7	3.3	-0.4	-7.7	-16.7	-26.9	-13.6
PRECIPITATION													
Rainfall (mm)	0.1	0	0	0.2	2.8	24.7	59.2	64.8	41.5	4.5	0.5	0	198.3
Snowfall (cm)	22.8	16.8	25.3	32.4	25.1	9.8	0.1	0.8	13.7	34.9	32.4	21.7	235.8
Precipitation (mm)	21.1	15	21.8	28.2	26.9	35	59.4	65.7	55	36.7	29.1	18.2	412.1
Average Snow Depth (cm)	22	23	25	29	18	2	0	0	0	6	16	20	13
Median Snow Depth (cm)	21	23	25	28	16	1	0	0	0	6	15	19	13
Snow Depth at Month-end (cm)	23	25	29	27	10	0	0	0	1	10	21	21	14
WIND													
Speed (km/h)	15	14.8	14.1	15.8	17.3	15.3	12.4	13.9	15	17.6	17.6	15.4	15.4
Most Frequent Direction	NW	NW	NW	NW	NW	SE	SE	SE	SE	NW	NW	NW	NW
Maximum Gust Speed	146	114	156	153	103	93	117	109	126	137	126	141	156
Direction of Maximum Gust	NE	NW	NW	NW	NW	W	E	NW	SE	NW	NE	NW	NW



	JAN	FEB	MAR	APR	MAJ	JUN	JUL	AUG	SEP	OKT	NOV	DEC	ÅR
Nedbør (mm)	19	20	22	28	18	30	44	52	51	37	38	23	383
Nedbørdage	5	5	6	5	5	6	7	8	8	8	8	6	76
Dagtemp.	-9.4	-10.2	-10.1	-3.6	2.9	6.8	9.8	9.3	5.8	0.7	-3.2	-6.9	-0.7
Middeltemp.	-12.8	-13.9	-14.0	-7.1	-0.2	3.6	6.3	6.1	3.2	-1.9	-5.9	-10.1	-3.9
Nattemp.	-16.3	-17.7	-18.0	-10.9	-3.2	0.8	3.3	3.3	0.7	-4.4	-8.7	-13.3	-7.0
Solskinstimer	4	53	144	195	225	237	257	180	137	74	20	0	1550



	JAN	FEB	MAR	APR	MAJ	JUN	JUL	AUG	SEP	OKT	NOV	DEC	ÅR
Nedbør (mm)	40	47	49	47	55	61	86	85	89	66	73	54	752
Nedbørdage	9	9	10	9	9	8	10	9	12	10	11	10	114
Dagtemp.	-4.6	-4.7	-5.1	-1.2	3.1	7.0	9.9	9.3	6.0	1.4	-1.3	-3.5	1.4
Middeltemp.	-7.4	-7.8	-8.0	-3.8	0.6	3.9	6.5	6.1	3.5	-0.7	-3.7	-6.2	-1.4
Nattemp.	-10.0	-10.7	-10.7	-6.3	-1.7	1.1	3.5	3.5	1.4	-2.7	-5.9	-8.6	-3.9
Solskinstimer													

Figure 2.1 Climagraphs for Sisimiut (66° 56'N) and Nuuk (64° 10' N) Greenland. Numerical data are Nedbør = Precipitation (mm), Nedbørdage = Days with Precipitation, Dagtemp = Average Daily Maximum Temperature (°C), Meddletemp. = Average Daily Temperature, Nattemp. = Average Daily Minimum Temperature, and Solskinstimer = Total Bright Sunshine Hours.
(Source: Danish Meteorological Service: http://www.dmi.dk/dmi/index/gronland/klimanormaler-gl.htm)

Learning Activity 1

Access the cloud chart available at:

www.nws.noaa.gov/os/brochures/cloudchart.pdf

Observe the variations in cloud types and cloud cover in the sky above the place where you live for one week. Which types of clouds are associated with fair weather and foul weather?

2.2 Factors That Shape the Climate

Climate is a term that relates to the average state of the earth's atmosphere and incorporates statistics about temperature, humidity, atmospheric pressure and precipitation for a given region over long periods (i.e., 30 or more years).

The climate of a location is affected by its latitude, altitude, terrain conditions and proximity to large bodies of water and their currents. Climates can be classified according to average and typical ranges of different variables most commonly temperature and precipitation.

Learning Activity 2

Review the climatic summary for Iceland (Table 2.2). Identify the main factors ("controls") of the climate. Does the description give a good idea of what to expect for someone who has not been there before? What information would you add to make it more complete? Choose a northern place or region of interest and write a short climatic summary for it.

System Feedback

Earth's climate is driven by energy received from the sun. This energy input, in the form of **shortwave radiation**, is balanced in the long-term by **longwave radiation** emitted back into space from earth and its atmosphere. This balance between energy inputs and outputs results in a long-term average temperature for the planet. Earth's atmosphere is a mixture of different gases. The dominant gases are nitrogen (78 percent) and oxygen (21 percent) with the remaining one percent made up of trace gases. The trace gases include relatively small amounts of carbon dioxide and other gases, which absorb longwave radiation and raise the air temperature resulting in what is called the **greenhouse effect** (Figure 2.2).

Scientists view the global climate as a **system** consisting of many physical and biological components and their interactions (Figure 2.3). These interactions include positive and negative **feedbacks**, which magnify (positive feedbacks) or reduce (negative feedbacks) the effect of particular actions. The climate system is complex and not constant. Climate undergoes variation and change over time.

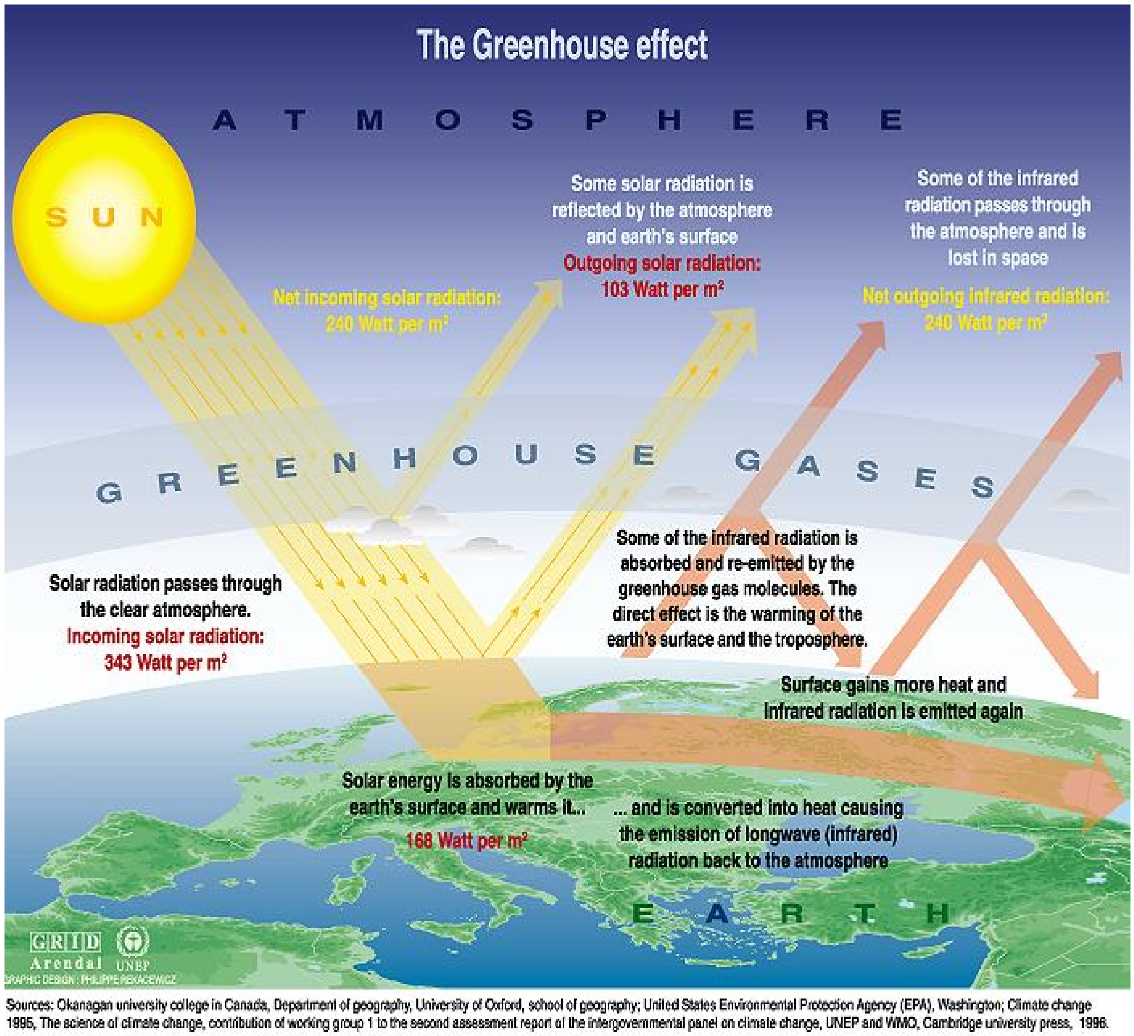


Figure 2.2. The Greenhouse Effect. (Source**:** United Nations Environment Programme. GRID-Arendal. Vital Climate Graphics and The National Atlas of Canada. http://atlas.nrcan.gc.ca/site/english/maps/climatechange/figure_4.jpg/image_view)

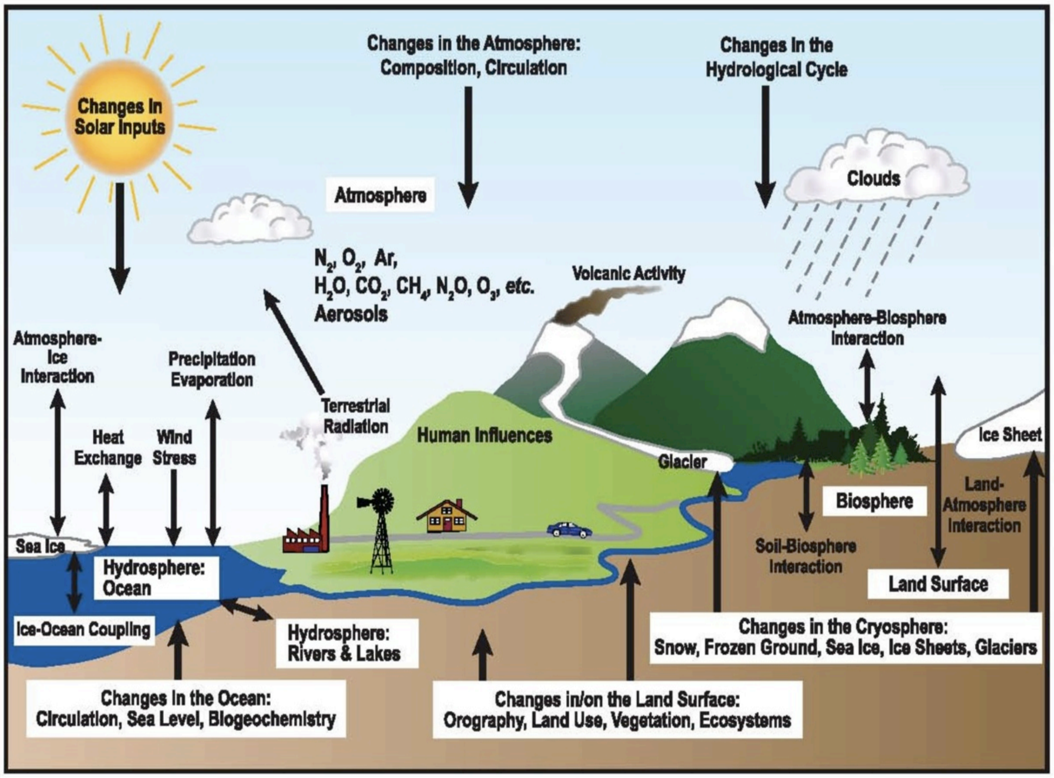


Figure 2.3. Schematic view of the components of the global climate system, their processes and interactions that cause the climate to change. (From: Le Treut et al. (IPCC, 2007))

Climate is determined by its location. Geographical factors or **controls** work together to shape particular seasonal and long-term climates. Climatic controls include:

- **Latitude** (seasonally affects solar radiation and length of day);
- **Continentality** (relative position with respect to coasts and continental interior);
- **Elevation** above sea level (related to atmospheric lapse rate);
- **Prevailing and seasonal large-scale atmospheric circulation features** (determine the transport of heat and moisture, severe weather and other phenomena);
- **Regional factors** (such as warm or cold ocean currents or presence of mountain ranges);
- **Local and landscape-scale features that affect the surface energy and water budgets** (forests, wetlands, lakes, glaciers or ice fields).

The first four climatic controls are described in detail.

Latitude, Solar Altitude and Length of Day

The earth's rotational axis is tilted with respect to the plane of its orbit around the sun by approximately 23.5^o (Figure 2.4). The sun appears to be overhead at different latitudes each day, moving seasonally between the Tropic of Cancer (23.5^{o}N) and the Tropic of Capricorn (23.5^{o}S). The sun never appears directly overhead north of 23.5^{o}N or south of 23.5^{o}S.

The angle that the sun-earth line makes with respect to the equator is called the **declination** of the sun, which ranges from + 23.5^o to -23.5^o between the northern hemisphere summer solstice (around June 21) and winter solstice (around December 22). The sun appears directly overhead at the equator and its declination is zero degrees at the equinoxes (21 March and 22 September).

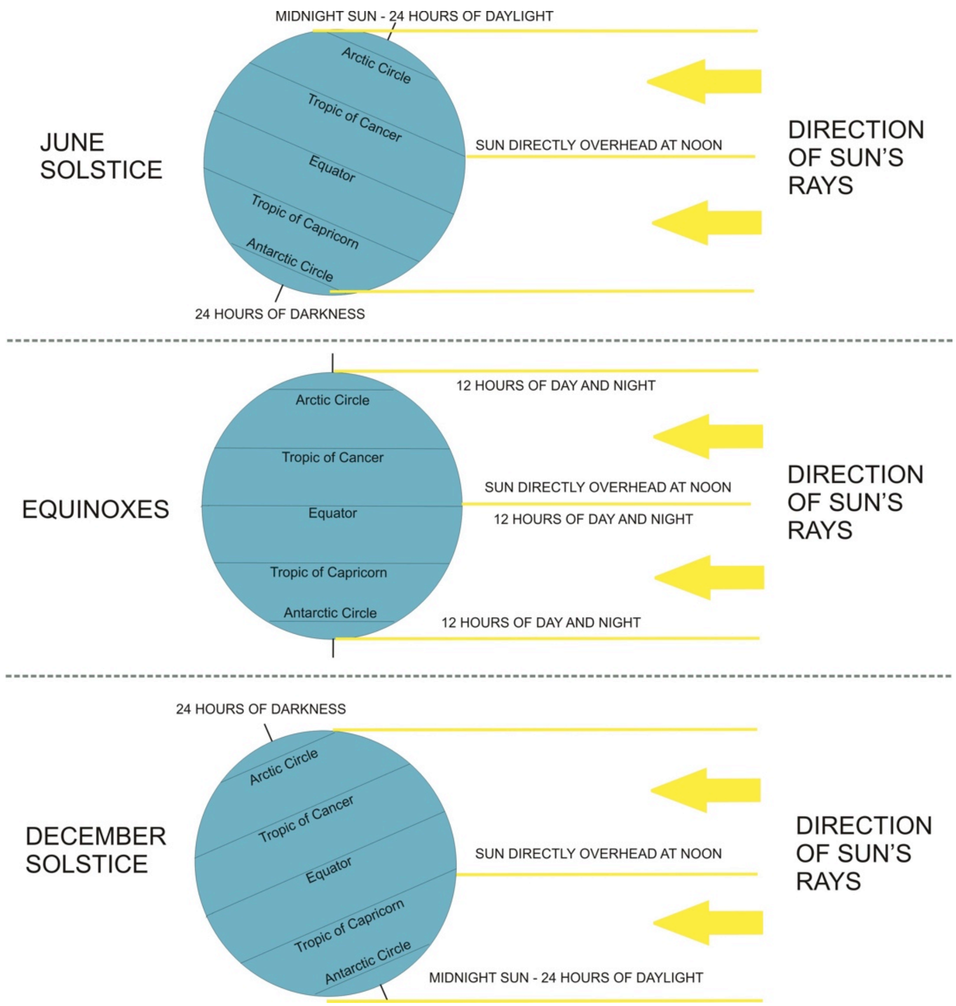


Figure 2.4. Earth showing angle of sun's rays at solstices and equinoxes. (Source: J. Jacobs)

At any location at local noon on a given day, the sun's **altitude** or angle above the horizon in degrees is given by the expression:

$$\text{Altitude} = 90^o - (\text{Latitude} - \text{Declination})$$

The declination of the sun on June 21 is +23.5 degrees so at noon at latitude 60^o N, the sun will be 53.5 degrees above the horizon. As seen from Figure 2.5 where the sun's altitude is low, the radiant energy per unit area (irradiance) at the surface is less concentrated than when the sun is higher in the sky. For example, at 20 degrees, the irradiance is only 1/3 as great as it would be if the sun were overhead. **Absorption** of the radiation by the atmosphere further reduces incoming energy.

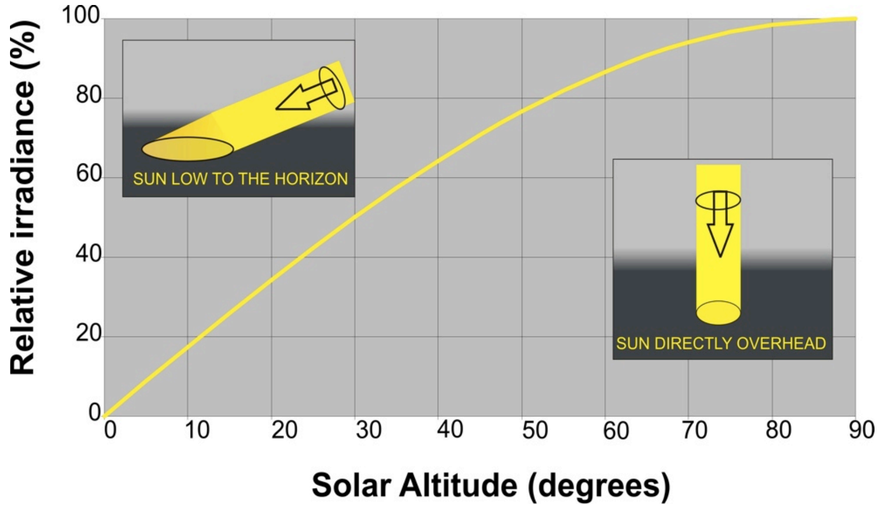


Figure 2.5. The higher the sun is above the horizon (altitude), the more concentrated the solar irradiance is on a horizontal surface. (Source: J. Jacobs).

Variation in day length, including polar day and night, is directly related to the sun's changing declination throughout the year. Only at the equator is the length of day and night the same, 12 hours, throughout the year. Figure 2.6 shows variation in day and night length with latitude and season. The amount of solar radiant energy received at the top of the earth's atmosphere follows the seasonal change in solar declination and is generally greatest at the equator (Figure 2.7). For a period of several weeks around the June solstice, arctic and polar regions receive a greater quantity of solar radiation than is received in equatorial regions. This situation arises from an increase in solar declination and day length.

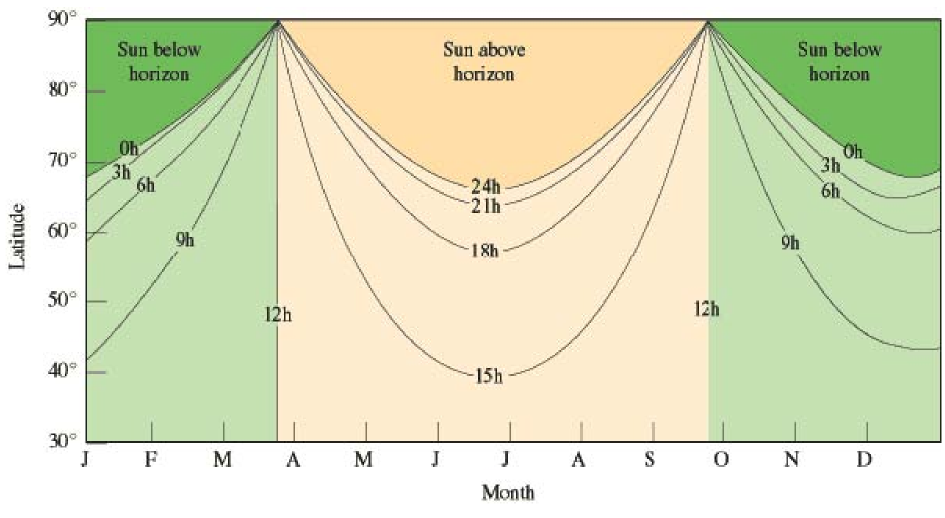


Figure 2.6. Seasonal variation in day length, measured in hours, at various latitudes in the northern hemisphere in relation to solar declination. (F.K. Hare and M.K. Thomas. 1974. Climate Canada. Toronto: Wiley Publishers.)

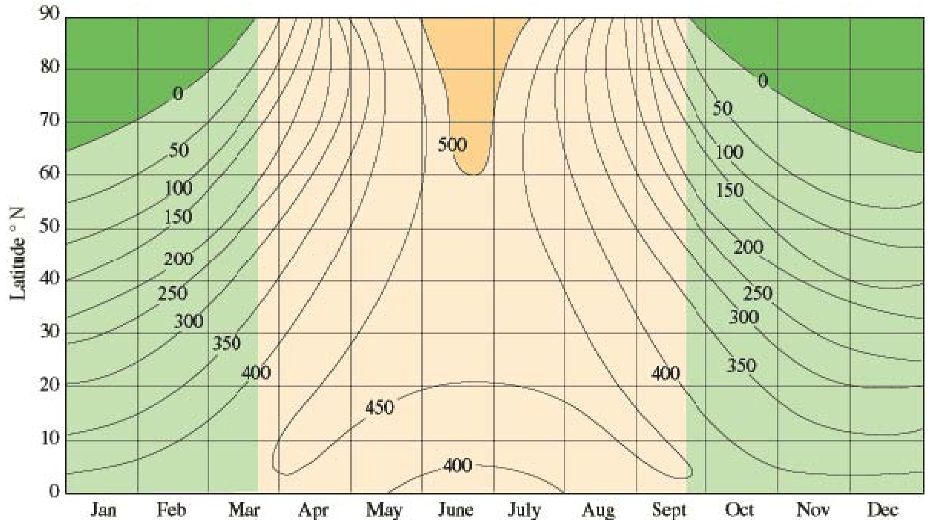


Figure 2.7. Seasonal variation in the receipt of solar radiation, measured in watts per square metre (W/m^2), at various latitudes in the northern hemisphere in relation to the solar declination. (R.W. Christopherson, M.L. Byrne, A. Aitken. 2006. Geosystems: an introduction to physical geography. Toronto: Pearson Prentice Hall.)

Continentality

Water has a greater **heat capacity** than soil or rock, therefore, land surfaces tend to warm and cool faster than large bodies of water, especially oceans. This means inland areas generally have higher summer (and daytime) temperatures and lower winter (and night-time) temperatures than coastal or island locations at the same latitude, although average yearly temperatures in both locations may be the same. This effect is known as **continentality.**

Elevation

As one moves upward in the free atmosphere and away from the earth's surface, the temperature usually decreases. On average this decrease, known as the **lapse rate**, is approximately 6.5^o C per kilometer. Accordingly, one would expect high elevations to have lower temperatures than lower elevations, all else being equal. Generally, this is a correct assumption. However, in northern regions there are large regional and seasonal variations in lapse rates. In large areas of the north, the lapse rate is much less than the global average. In winter, the temperature lapse over large areas is reversed so the air above the surface to a height of several kilometers is warmer than it is near the ground. This phenomenon, known as a **temperature inversion**, is mainly due to strong radiative cooling (i.e., Longwave radiation emitted from the earth's surface into the atmosphere) at the ground when the sun is low or below the horizon. The relationship of temperature to altitude is more complicated in high terrain than in the free atmosphere. In mountainous regions no simple rule applies.

Prevailing Winds and Atmospheric Circulation Patterns

Energy received from the sun is most concentrated in the lower latitudes (Figure 2.7). In contrast, longwave energy emitted by the earth into space is more evenly distributed with latitude. This means more energy enters the atmosphere at low latitudes than is lost (a net energy gain), while at high latitudes more is lost than is gained from the sun (net energy loss). This latitudinal radiant energy imbalance results in excessive atmospheric heating in low latitudes, which sets up horizontal **pressure** gradients that drive the movement of air (and heat) toward polar regions with corresponding movement of cold air toward the equator. The resulting flow is modified by the earth's rotation, internal atmospheric dynamics and interactions with topography to produce seasonal and long-term wind and pressure patterns that characterize earth's **planetary-scale circulation**.

The Arctic and Antarctic act as **heat sinks** where more energy is lost from the surface and atmosphere to space than is gained from the sun. To balance this loss, heat is imported to high latitudes by the atmosphere through the exchange of air. Picture an imaginary wall around the Arctic Circle extending to the top of the atmosphere. The atmospheric circulation flowing through it would consist of equal exchanges of poleward and equatorward flowing air. This results in a net import of heat to the polar region as cold air flows south and warm air flows north. This exchange varies seasonally, is strongest in winter and is focused on specific pathways or trajectories.

Figure 2.8 is a simplified view of planetary circulation. Poleward heat transport is broken into three cells which represent average north-south air and energy exchanges. Between the **Hadley Cell** and the **Ferrel Cell,** centered at approximately 30^{o}N, is the **subtropical high pressure zone**. Air in the lower atmosphere flows from this zone equatorward (the **northeasterly Trade Winds**) and poleward (the ***Westerlies***). In this model, winds in the north polar region are shown as mainly from the northeast, converging with the westerlies in a subpolar zone of low pressure, the **Polar Front**.

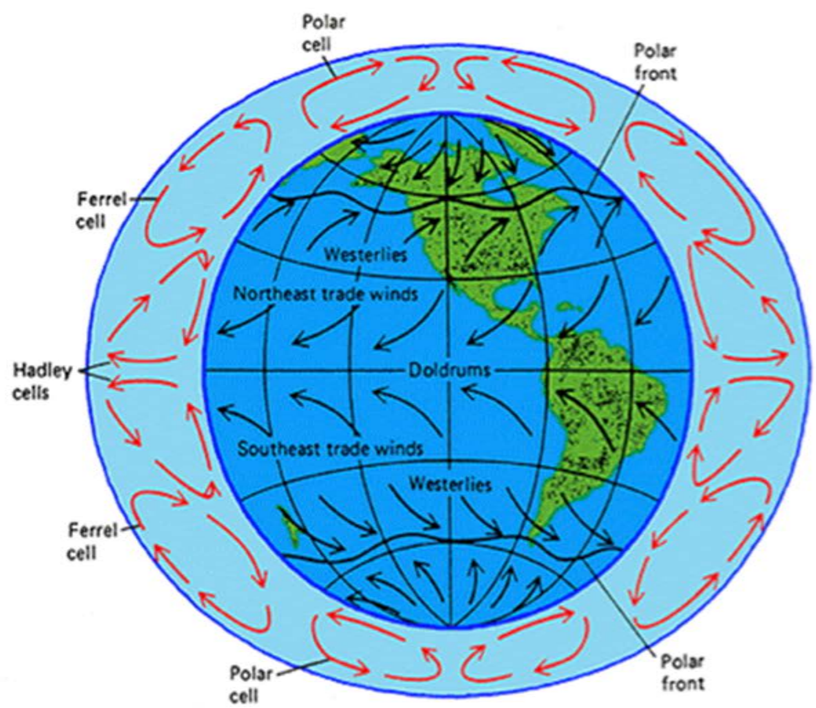


Figure 2.8. Schematic representation of the general circulation of the atmosphere. (Berner, E.K. and R.A. Berner. 1987. Global Water Cycle. New Jersey: Prentice-Hall, Inc. p.28.

2.3 Seasonal Variations of Energy Exchange at the Surface

The global climate system is driven by radiant energy received from the sun. Energy arrives at the top of the atmosphere as **shortwave radiation**, which is mainly visible light. Shortwave radiation is absorbed within the atmosphere or reflected by clouds and some is reflected at the surface. On average about 49 percent of energy that reaches the surface is absorbed at the surface (Table 2.2). About 30 percent is reflected back to space by the surface and atmosphere, which is referred to as the earth's **planetary albedo**. The absorbed energy heats the surface – rocks, soil and waters – and heat energy is returned to the atmosphere as **longwave radiation.** Unlike shortwave radiation, which passes easily through the atmosphere, nearly all longwave radiation is absorbed in the atmosphere producing the **greenhouse effect**. Over time there is a balance between the total shortwave energy received by the earth (atmosphere and surface) and the amount of longwave and reflected shortwave radiation returning to space.

Table 2.2. Albedo (K↑/ K↓) for various surfaces (Sellers, 1965; Serreze and Barry, 2005).

Fresh snow	0.70 – 0.90
Melting snow	0.50 – 0.60
Water	0.06 – 0.10 (higher for low sun angle)
Dry tundra	0.23 – 0.26
Wet tundra	0.10 – 0.20
Deciduous forest	0.50 in winter, 0.15 in summer
Coniferous forest	0.67 in winter, 0.16 in summer
Thick first year sea ice	0.30 – 0.60
Multiyear sea ice	0.55 – 0.75
Melt ponds on sea ice	0.15 – 0.40

This balance follows a fundamental principle of physics called the **conservation of energy**. In practical terms this means heat energy going into an object is balanced by an equal amount of heat radiating from that object when the object is at a constant temperature. If the energy input increases, the temperature rises resulting in an increase of energy radiating outwards to restore the balance.

Exchanges of energy in different parts of the global climate system can be viewed in terms of an **energy budget.** Figure 2.9 shows the short- and longwave radiation terms in the surface radiation budget.

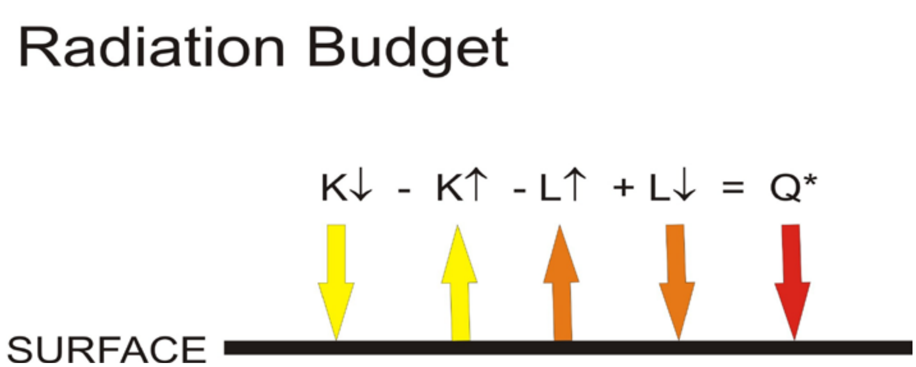


Figure 2.9. The surface radiation budget (Source: J. Jacobs)

K↓ and **K↑** are incoming and reflected shortwave radiation terms. **L↑** is longwave radiation from the surface and **L↓** is the proportion of atmospheric longwave radiation directed to the surface. The surface **albedo** is equal to **K↑** divided by **K↓**. The lower the albedo the greater the amount of solar radiation available to heat the surface. The diagram expresses the radiation budget as an equation with **net radiation Q*** being the algebraic sum of the four radiation terms. When net radiation is equal to 0, there is a balance among various short- and longwave terms. If **Q*** is positive, the surface is heating. If **Q*** is negative, the surface is cooling.

Radiation is not the only way energy is exchanged at the surface. Three other heat transfer processes work to offset net radiation (Table 2.3), which are:

- $\mathbf{Q_S}$ is heat conducted down into or up from the ground;
- $\mathbf{Q_H}$ is **sensible heat** associated with the upward movement or **convection** of air that warms and rises after contact with the ground; and
- $\mathbf{Q_E}$ is **latent heat** flow associated with evaporation of water at the surface, melting or sublimation of snow, and thawing of permafrost (negative when water is condensing or ground is freezing).

Table 2.3. Selected examples of surface energy budgets for northern sites in Canada. (Source: Rouse, 1993 and sources cited therein).

Reference	*Site characteristics*	*PF*	*Season*	Q^*	Q_s	Q_E	Q_H	B_r
High Arctic								
Ohmura (1982)	Upland tundra	Y	Pre-melt	18	2	6	10	1.67
	(Axel Heiberg I., NWT)		Melt	83	28	28	27	0.96
			Snow-free	90	13	46	31	0.67
Low Arctic								
Rouse (1984c)	Upland tundra	Y	Melt	27	10	9	8	0.89
	(Churchill, Man.)		Snow-free	120	20	51	49	0.90
Rouse and Bello	Wet sedge tundra	Y	Melt	108	24	45	39	0.87
(1985)	(Churchill, Man.)		Snow-free	143	21	63	59	0.94
	Upland lichen heath	Y	Melt	122	38	45	39	0.87
	(Marantz Lake, Man.)		Snow-free	138	15	63	60	0.95
Subarctic								
Rouse, Mills, and Stewart	Lichen woodland	N	Midsummer	132	6	83	43	0.52
(1977)	Burned lichen woodland	N	Midsummer	117	4	62	51	0.82
	Shallow tundra lake	N	Midsummer	148	0	109	39	0.39
	(Thor Lake, NWT)							
Lafleur and	Upland sedge	N	Snow-free	112	5	55	46	0.84
Rouse (1988)	Sedge marsh	N	Snow-free	116	11	62	43	0.70
	Woodland swamp	N	Snow-free	124	12	71	41	0.58
	(southern James Bay)							

Note: Q^*, Q_s, Q_E, and Q_H are net radiation, ground heat storage, and sensible and latent heat fluxes, respectively (W/m^2); Br_r is the Bowen ratio; *PF* refers to the presence (*Y*) or absence (*N*) of permafrost.

Q_E is the product of **latent heat of vaporization (L_V)** and **E,** the mass of water vapor being evaporated. Together with **Q*** these terms make up the **surface energy budget** (Table 2.3) used to analyze the effects of different surface characteristics on local climate. A simple example is the difference between a wet surface where energy is used to evaporate the water (Q_E), and a dry surface where energy heats the air (Q_H) and ground (Q_S). If net radiation is assumed to be positive and equal for both surfaces, air above the dry surface will be warmer than air above the moist surface.

Table 2.3 indicates surface energy budgets observed at northern locations under different surface conditions. Examine the changes in the energy flux terms at the High Arctic upland tundra site as the snow cover first warms then melts. The table introduces the Bowen Ratio, which is simply the ratio Q_H/Q_E and indicates what proportion of available energy heats the air relative to that used to evaporate water from the surface.

Factors that contribute to seasonal variation in net radiation and various energy balance components are described below.

Winter

The sun is below the horizon for most of the winter season. During periods when the sun is above the horizon, the combination of low sun angle, short day length and high surface albedo ensure net radiation is low. The small quantity of available energy is used to melt or sublimate snow and ice and/or evaporate water from open water surfaces. Little or no energy is available to warm the ground surface; therefore, cold air temperatures characterize winter.

Spring

Sun angle and day length increase during the spring season. This serves to increase net all-wave radiation. Much of the available energy is used initially to melt and sublimate snow and ice on the surface. Once the snow and ice cover is removed, surface albedo is reduced by the presence of dark-coloured surfaces. Increased absorption of radiation provides energy to heat the ground surface, raise air temperature, evaporate water and begin to thaw permafrost. Air temperature gradually increases throughout the spring.

Summer

The sun is above the horizon for most of the summer season. The combination of high sun angle, long day length and low surface albedo ensure net radiation is high. A small portion of available energy is used to remove remaining snow and ice on the ground surface. The remainder of available energy heats the ground surface, evaporates water, raises air temperature and continues thawing permafrost, which leads to the development of the permafrost **active layer**.

Fall

Sun angle and day length decrease during the fall season. This decreases net all-wave radiation reducing energy available to heat the ground surface, raise air temperature, evaporate water and sustain thawing of permafrost. Longwave radiative surface cooling begins leading to progressive cooling of air temperature and refreezing of the active layer of permafrost.

2.4 Preciptation and the Water Budget

The global **water cycle** describes how water on earth moves from various "compartments" (ocean, atmosphere, snow and ice, lakes and streams, soil moisture and ground water) and the physical processes involved (Figure 2.10). No significant amount of water appears in or is lost to the system. Water is a finite but renewable resource.

Less than 0.001 percent of the earth's water is in the atmosphere. If it all rained out at one time, it would cover the entire earth to approximately a 2.5 cm depth. Since the earth's average yearly precipitation is approximately 100 cm, water must cycle many times per year. Water falls as **precipitation** (rain and snowfall). It is temporarily held in the soil or seasonal snow covering the land, glaciers or sea ice. Water then moves as **runoff** into streams, perhaps to groundwater, and eventually to the ocean. Energy from the sun drives the return flow from the land and ocean to the atmosphere through the processes of **evaporation** and **transpiration**.

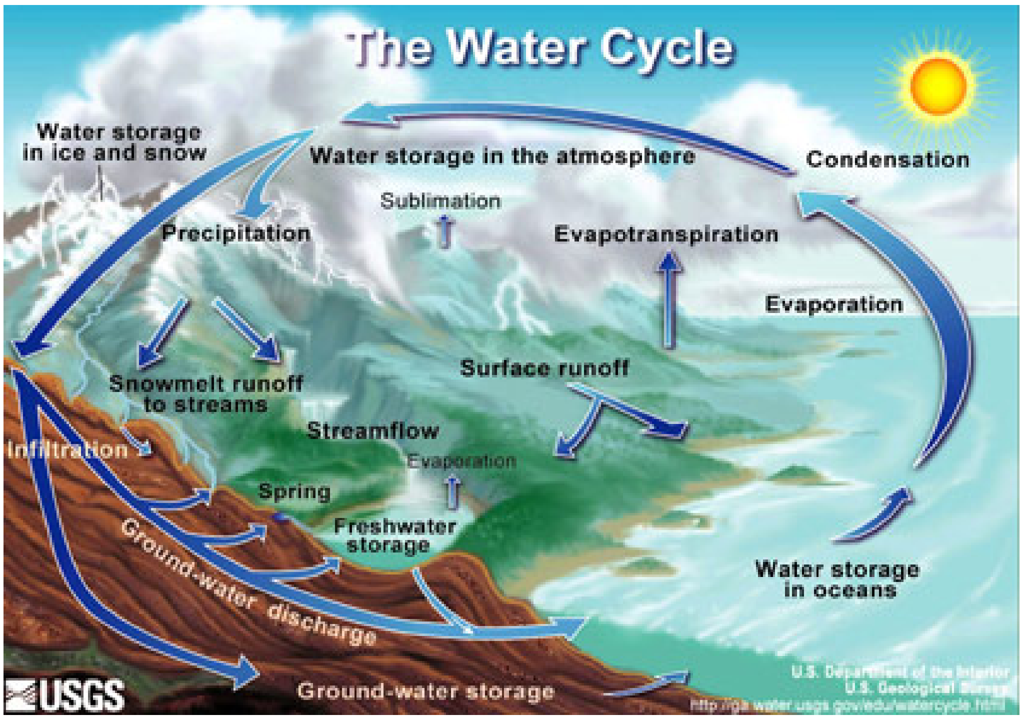


Figure 2.10. The Water Cycle or *Hydrologic* Cycle showing various storage and flow terms and processes involved in those flows.
(Source: US Geological Survey http://ga.water.usgs.gov/edu/watercycle.html).

Streams occur on all scales, but principles learned from the study of the global water cycle (Figure 2.10) can be applied to understanding stream behavior. A stream system is defined by a **drainage basin** (also called a **watershed**)*,* which is a land area where precipitation runs off into streams, rivers, lakes and reservoirs and eventually the ocean. Water may fall as snow and be held until it melts in the spring or be held for decades or centuries as ice in a glacier. A drainage basin can be delineated on a map by tracing a line along the highest elevations that enclose a stream and its tributaries (i.e., a drainage divide).

The Arctic Ocean receives water from many northward flowing rivers. The main rivers and their drainage basins are shown in the University of the Arctic Online Atlas http://map.uarctic.org/. The largest rivers basins, the Lena River in Russia and the Mackenzie River in Canada, contain thousands of smaller drainage basins.

It is possible to discuss water movement in budget terms because of the **conservation of mass** principle. **Outflows** from part of the system must equal **inflows** plus or minus any change in the amount of water **storage** in a compartment. For example, the mass of water discharged from the mouth of a river (**R**) is equal to the precipitation that falls on it (**P**) less the mass of water evaporated or transpired (**E**) plus or minus any change in water stored in various parts of the drainage basin (**ΔS**).

$$\mathbf{P - E \pm \Delta S = R}$$

On a yearly basis, averaged over many years, the change of storage term can be assumed to be zero so the relationship becomes:

$$\mathbf{P - E = R}$$

It is relatively easy to measure precipitation and runoff for small stream basins, but evaporation and transpiration are more difficult to measure. For large basins, all measurements are approximate. Table 2.4 shows estimates of annual water budget terms for four major arctic rivers. **P** was measured using networks of climate stations, **R** was measured using stream gauges at river mouths, and **E** was estimated from the difference. Several methods were used to estimate **E**, showing that uncertainties or errors in these estimates could be as large as 20 percent. Evaporation and transpiration are clearly important processes in northern areas. The runoff ratio **R/P** indicates the proportion of precipitation that runs off directly to streams rather than infiltrating into the soil to be transpired by vegetation. In the Arctic, a high runoff ratio is associated with large areas of impenetrable **permafrost** within the basin. In the table, the data suggests that the Ob River basin has the smallest area of permafrost compared to the other three basins.

Table 2.4. Mean annual water budget components in four major drainage basins (Data Source: ACIA, 2004; Serreze et al., 2003). Data period 1960 – 1989.

Name of Basin	P (mm)	E (mm)	R (mm)	R/P
Ob	534	396	138	0.26
Yenisey	495	256	239	0.48
Lena	403	182	221	0.55
Mackenzie	411	241	171	0.41

Learning Activity 3

Look at a map of river systems of the circumpolar North (http://map.uarctic.org). Confirm that most major rivers flow into the Arctic Ocean. If you have maps showing annual precipitation and evaporation over a region, describe how to estimate the amount of water flowing annually to the ocean from a river. What happens to the water from a river after it flows into the sea (see Module 7)?

2.5 Snow and Ice in the Climate System

Most Arctic and subarctic regions are covered by snow and ice for at least six months of the year. Ponds and smaller lakes begin to freeze in October and retain ice cover until early summer. Except for areas influenced by warm currents (southwest Greenland waters and the Norwegian Sea), northern oceans freeze in the winter. Seasonal changes in surface cover over the North are a response to seasonal changes in energy budgets and involve a number of feedbacks between the surface and atmosphere.

Snow

Snow falls at any time in the North, but begins to accumulate on land only when the air temperature falls below freezing. Table 2.1 indicates that on average there is snow cover at Iqaluit, Nunavut for eight months of the year. This cover changes the surface energy budget, insulates the ground and stores water until spring. Arctic plants and animals have adapted to the changes that seasonal snow cover brings.

Sea Ice

In winter the open ocean takes on a cover of drifting **pack ice**, while protected coasts and bays have **landfast ice** (Figure 2.11) of varying extent, which grows several metres thick by spring. The area of ice-covered ocean reaches its maximum of approximately 15 million km^2 in March when seasonal warming slows and reverses ice growth. The ice melts and contracts to about half the area by late September. In the central Arctic Ocean and part of the Canadian Arctic Archipelago, ice persists into the following winter and is known as **multiyear ice.** In recent years, the amount of sea ice remaining in the Arctic at the end of summer has significantly decreased, raising the possibility of a seasonal ice-free Arctic Ocean in the future.

Figure 2.11. Midnight sun over melting landfast ice, Baffin Bay, July 1975. (Photo: J. Jacobs)

Feedbacks

Links between snow cover, ice and climate provide several examples of **feedback** mechanisms. Table 2.2 indicates water, tundra and forest have relatively low albedos compared with snow, particularly fresh snow. In autumn, as air cools and snow begins to accumulate, the amount of solar radiation absorbed by land decreases further cooling air near the surface. This is an example of a positive feedback. In the spring, as land warms and snow melts the exposed ground and vegetation absorb more radiation and speed up the melting and warming process, a positive feedback.

Another type of feedback occurs as water bodies freeze in the fall. Once formed, ice cover reduces convective loss of heat to the atmosphere from the water, allowing air to cool further and ice to grow downward. However, as ice thickens heat loss to the atmosphere decreases as does the rate of ice growth. Thickening ice works against ice growth, a **negative** feedback, which sets an upper limit on how thick multiyear ice becomes.

2.6 Climate and Landscapes

Field scientists and traditional hunter-gatherers share a similar perspective with respect to northern lands. The perspective is the spatial scale of the **landscape,** what we view from a particular place, but it also can include an extension beyond the horizon of what we comprehend from the scene before us. Landscapes have more complexity than most of us recognize, not only in terms of more obvious elements such as landforms, vegetation and animals, but in the context and relationships that come from our experience and understanding. The biologist might recognize habitats and ecosystems in what others view as a stand of trees or a pond. Likewise, the climatologist will infer different microclimates from the terrain characteristics and knowledge of the regional climate.

Learning Activity 4

Contemplate a familiar landscape; an environment that you interact with on a regular basis. Use your personal knowledge of this landscape to address the following questions:

Where does the vegetation cover shade the ground surface, resulting in slow snow melt?

Where are the open spaces brightly lit by sunshine where the snow melts early to produce ponds at the ground surface?

Compare and contrast the energy balance at the ground surface in these two settings during the spring snow melt season.

Figure 2.12 is an example of a summer landscape in Arctic Canada. The inexperienced eye can pick out elements such as the pond, wetlands, late-lying snowbeds and a variety of geomorphic features that contribute to the complexity of this landscape. It is interactions through the exchange of energy and moisture between the atmosphere and terrain elements that shape the local climate.

Figure 2.12. Arctic mountain landscape - International Polar Year field camp and climate station, Torngat Mountains, Labrador, July 2007 (Photo: J. Jacobs).

Evidence of climatic influence on the landscape can be seen in the vegetation. Growing season heat and moisture set limits for the extent of different vegetation forms from forest to shrub land to low tundra and finally **polar desert** (see Module 6). The northern **treeline** (see http://map.uarctic.org/) and its altitudinal counterpart in the mountains (Figure 2.13) are larger-scale extensions of a temperature limit on the growth of trees in the North. This limit corresponds approximately to the end of the zone above which July temperatures average less than 10^{o}C.

Figure 2.13. Well-defined altitudinal treeline in Red Wine Mountains, Labrador (Photo: T. Bell).

Landscapes include natural features and cultural elements. Cultural elements may be as simple as an ancient hearth site or as complex as a modern town site. Where the cultural elements dominate the landscape, e.g., a large area flooded behind a hydroelectric dam or large areas of forest are burned or clear-cut, the local climate is modified.

2.7 Characteristics of High Latitude Northern Climates

The combined land and sea area of the circumpolar North between latitude 60^{o}N and the North Pole represent less than 10 percent of the earth's area and approximately half of this area is ocean. The configuration and topography of this region are strong determinants of its climate. It is centered on and mostly draining toward the Arctic Ocean with topographic barriers that constrain the flow of air and direction of ocean currents. Within the region, a diversity of surface conditions, energy and moisture budgets, and associated temperature and moisture regimes yield a range of distinctly different subregional climates. Such climatic detail is missed in the usual regional climatic classification schemes that place most of the North into four or five categories (Figure 2.14). Nevertheless, such maps allow us to see the interplay of the main climatic controls, e.g., following 60^{o}N latitude around the circumpolar North.

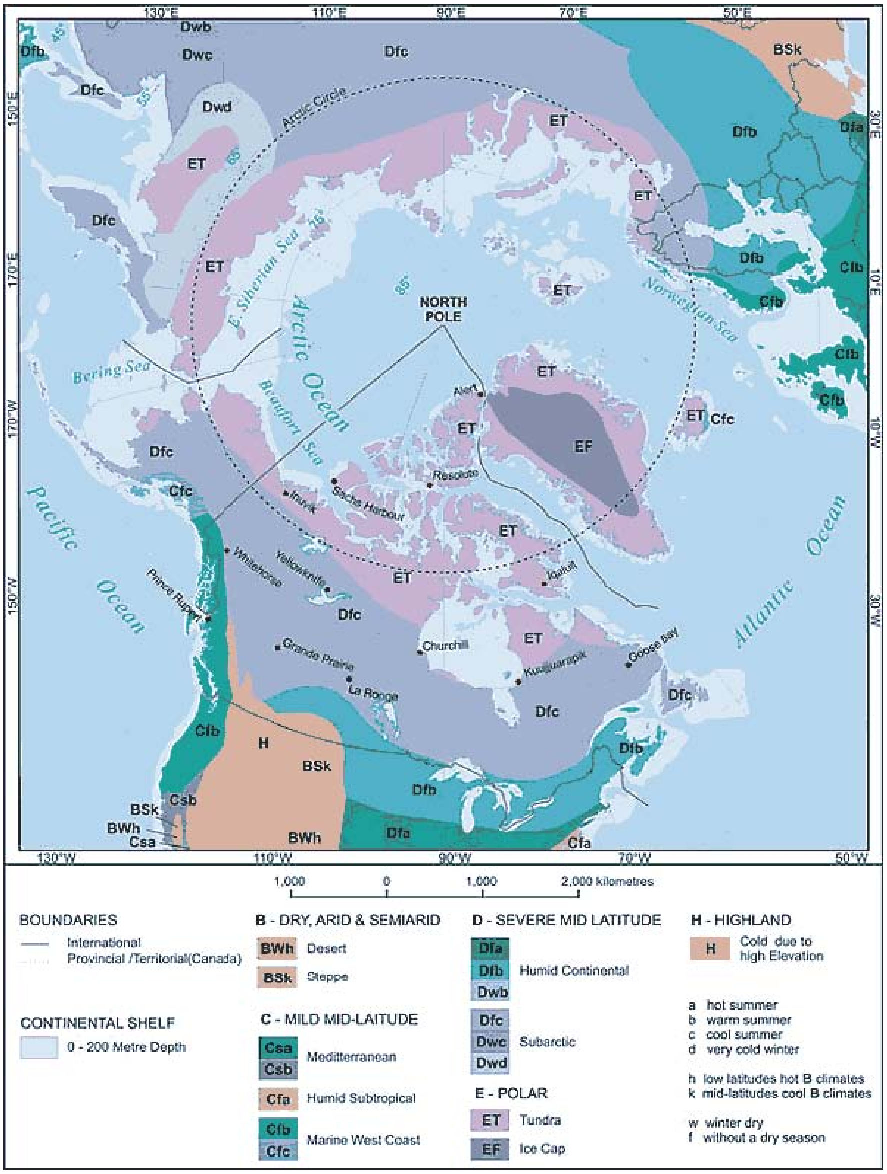


Figure 2.14. Circumpolar mapping of regional climatic types according to the Koeppen–Geiger system. Source: Elise Pietroniro, GIServices, University of Saskatchewan.

Storm Tracks

Research over past decades has shown atmospheric circulation over the Arctic to be complex. There are several frontal zones marking the boundary between air of Arctic origin and air from the south. Large masses of air containing heat, moisture and pollutants move from middle to higher latitudes in **cyclonic depressions** that follow favored tracks, especially in the North Atlantic sector between Greenland and Scandinavia (Figure 2.19). Although cyclonic storms are mainly a mid-latitude phenomenon many move northward bringing heat and moisture to affect the subpolar and polar regions.

Not all Arctic storms come from the south. **Polar lows** are intense, short-lived storm systems that form over ocean areas along the boundary between cold and warmer waters, as in the Labrador Sea and Norwegian Barents Seas. Polar lows bring strong winds, rapid temperature change and heavy precipitation that usually falls as snow (Figure 2.15) (See: http://www.weatheronline.co.uk/reports/wxfacts/The-Polar-low-the-*arctic*-hurricane.htm).

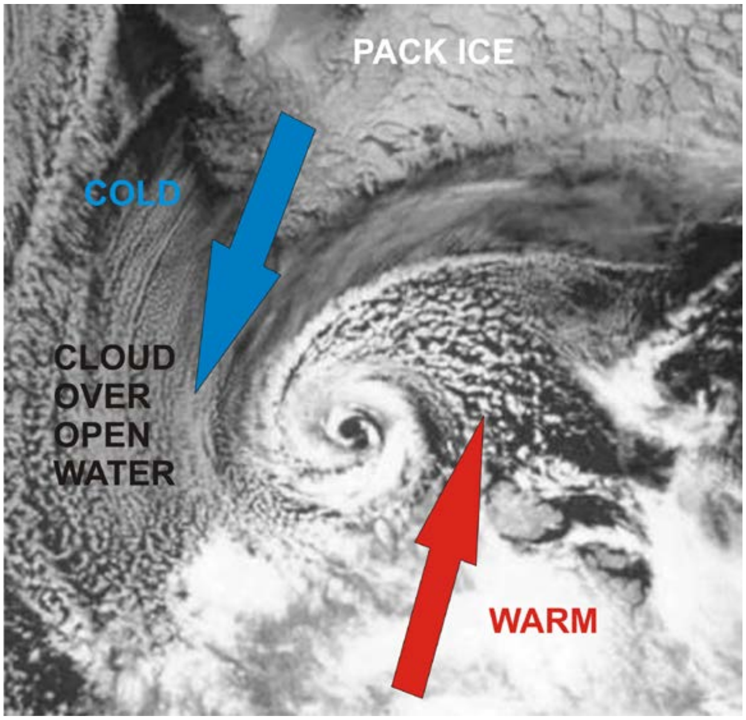


Figure 2.15. Satellite image of Polar Low over Barents Sea 27 February 1987 (Source: NOAA and www.islandnet.com/.../arc2006/alm06jan.htm with notation added by author)

Temperature and Precipitation Patterns

Figure 2.16 shows summer and winter temperature patterns for the Arctic, averaged over a number of years. Winter temperatures are coldest in the continental interiors (Siberia) and warmest in areas influenced most strongly by relatively warm ocean currents and storm tracks associated with the North Atlantic Ocean (Norwegian and Barents Seas). Summer temperatures are highest in the continental interiors, remaining most depressed over the Greenland Ice Cap and the Arctic Ocean.

Precipitation is relatively low across much of the North, compared with the global average of approximately 1,050 mm per year (Pidwirny, 2006). Major river basins shown in Table 2.4 average approximately 400 to 500 mm of precipitation annually. Winter and summer precipitation amounts over the Arctic are indicated in Figure 2.17. Polar desert regions of the High Arctic experience less than 30 mm in July (200 mm annually), while coastal areas adjacent along principal storm tracks receive more than 1,000 mm annually with the greatest amounts in the fall and winter.

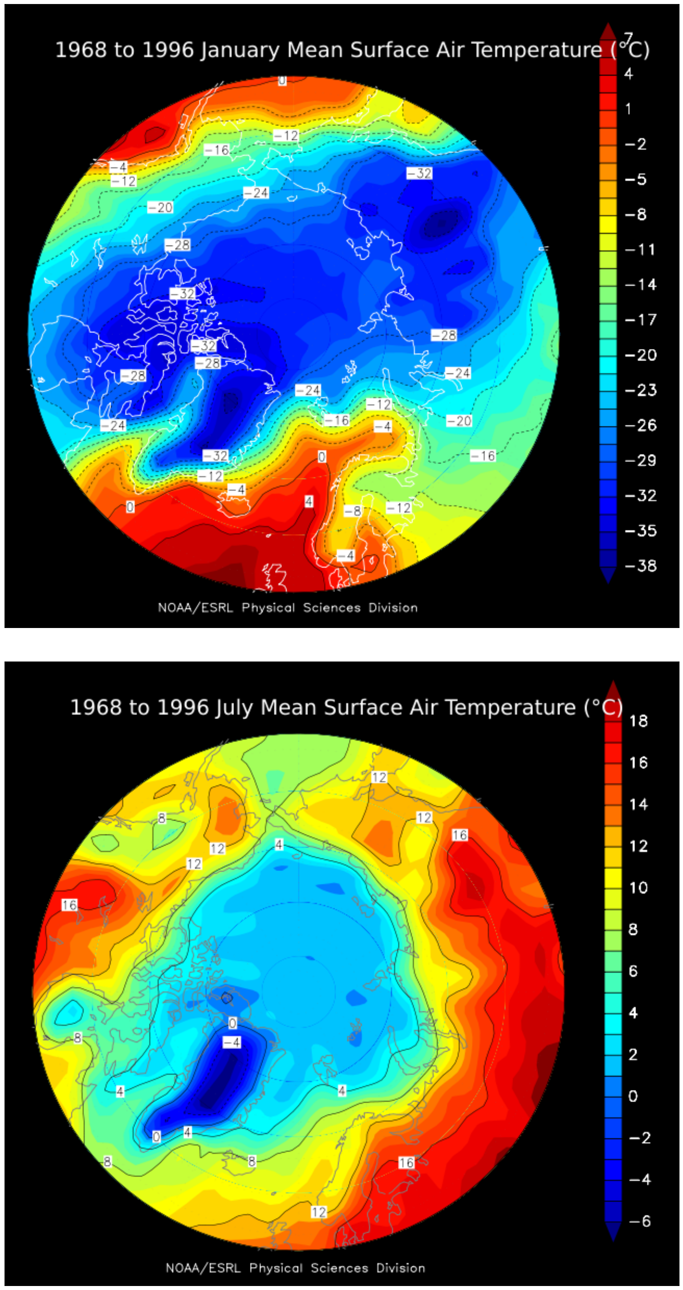


Figure. 2.16. These maps show the mean surface air temperature (2 meters above the surface) over the Arctic in January and July, from NCEP/NCAR Reanalysis data from 1968 to 1996. http://www.cdc.noaa.gov/cgi-bin/DataMenus.pl?dataset=NCEP.

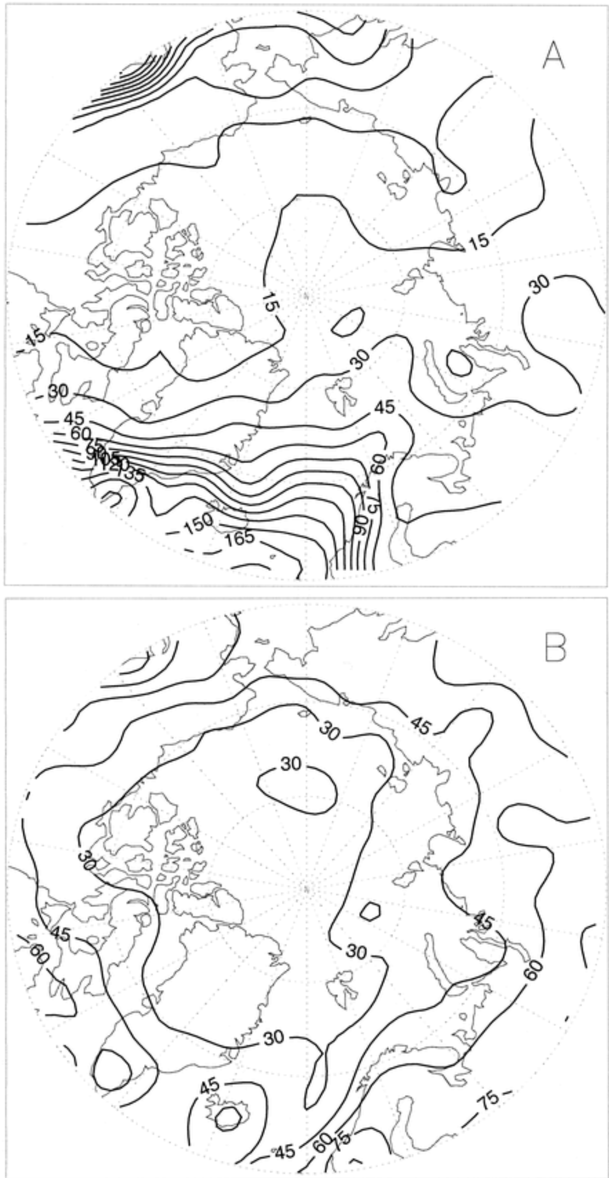


Figure 2.17. Mean Arctic precipitation (mm) for (a) January and (b) July. (Source: Serreze and Hurst, 2000).

2.8 Air Pollution in the North

In the past, people living in the Arctic probably had no concerns about **air pollution**. In the early 20th century, European and North American travelers from cities with polluted air remarked on the clarity of the arctic atmosphere. By the 1950s, scientists flying over the Arctic Ocean were commenting on widespread haze in the atmosphere, which became known as arctic haze (Figure 2.18). This haze is a form of pollution composed of **aerosols**, which are microscopic liquid or solid particles that come from natural and anthropogenic sources.

Figure 2.18. Arctic Haze viewed from an aircraft over Norway near the Arctic Circle, March 2006. (Photo by J. Jacobs)

Much of this pollution, particularly in winter and spring, can be traced to industrial areas within and outside the Arctic Circle. The Arctic is not immune to the effects of long-range transport of air pollutants, which are borne on winds from the south. These, along with pollutants transported by rivers and ocean currents, have led to extensive contamination of arctic terrestrial and marine ecosystems (Figure 2.19).

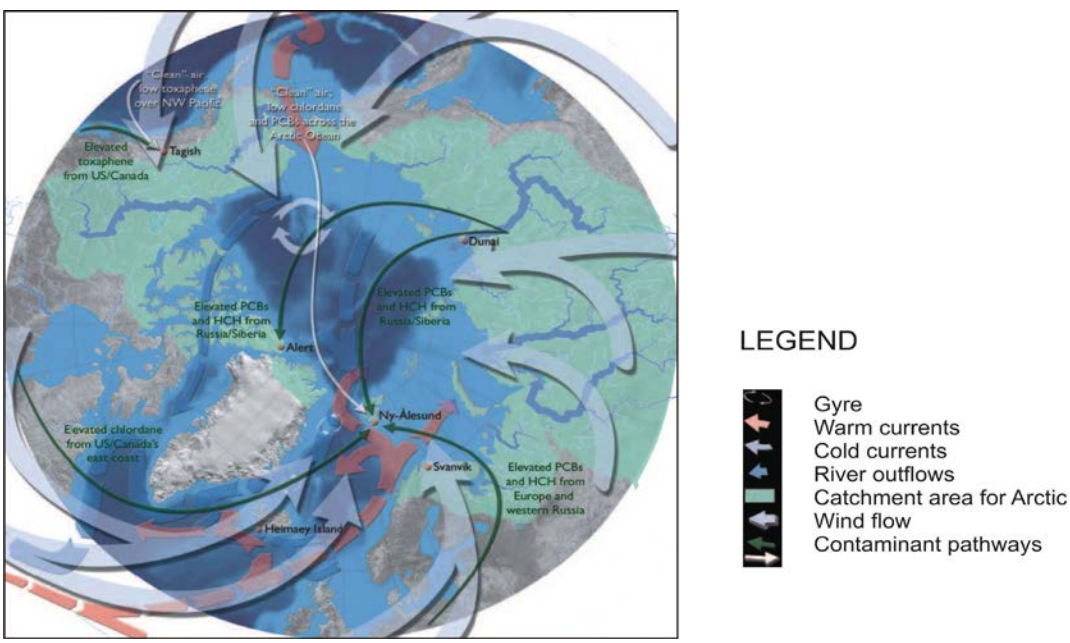


Figure 2.19. Main pathways for long-range transport of contaminants to the Arctic. Broad wind-flow arrows show the main tracks of cyclonic systems entering the Arctic from the south. (Source: Arctic Climate Impacts Assessment, 2004).

Air pollution from local sources is a problem in the North wherever there are industrial activities, heavy use of motor vehicles and stationary engines, e.g., electrical generating plants. In many areas, particularly inland valleys, winter is a season of relatively light winds and low surface temperatures, which produce a **stable atmosphere** near the ground. As a result, emissions composed of gases and particles are trapped near ground-level causing reduced visibility and respiratory problems for people in these areas. Where sufficient moisture is present in the emissions and the temperatures are below – 35 ^{o}C, **ice fog** can form (Figure 2.20). Ice fog can seriously reduce visibility effecting motor vehicle and aviation traffic. Local pollution is less of a problem for coastal locations, especially on main storm tracks where winds mix the atmosphere more effectively and inversions are less common.

Figure 2.20. Ice fog University of Alaska, Fairbanks (Photo R. Watbe).

Conclusion

Climate is a term that refers to the long-term average conditions of several variables in Earth's atmosphere, notably air temperature, atmospheric pressure, humidity, and precipitation, measured over several decades. Earth's climate is driven by energy inputs from the Sun in the form of shortwave radiation and by the emission of longwave radiation back into space from Earth's surface and the atmosphere. Longwave radiation absorbed by gases in the lowermost portion of the atmosphere is converted into heat: this heat contributes to sustaining life in the biosphere. Shortwave and longwave radiation absorbed at the Earth's surface is also converted into other forms of energy. Energy transformations related to the water cycle are particularly important; these energy transformstions facilitate the thawing of frozen soils, warming of the air near Earth's surface, the melting of snow and ice to generate the water supplied to ponds, streams and rivers, and the evaporation and transpiration of water that contributes to the flux of water vapour from the Earth's surface to the atmosphere.

Planetary-scale circulation of air in the Earth's atmosphere plays an important role in maintaining a global energy balance. Cold air formed over the polar regions is transported equatorward while warm air formed over the equatorial region is transported poleward. The result is a net import of heat to the polar regions.

Large-scale industrialization of regions outside the circumpolar North, and increasingly in the North itself, has contributed to air pollution in the form of various gases and particulate matter. These materials, upon release into the atmosphere, are transported for great distances from their sources and contribute to the extensive contamination of terrestrial and marine ecosystems.

Discussion Questions

1. Discuss the combined influence of solar declination, day length and surface albedo on the seasonal surface energy budget of the alpine tundra landscape illustrated in Figure 2.12.

2. Discuss the spatial variation of January and July precipitation illustrated in Figure 2.18 with reference to both the radiation and energy budgets.

Study Questions

1. Study the climatic data (climagraphs) from Sisimiut and Nuuk (Figure 2.1). Note the seasonal patterns in temperature and precipitation as well as annual averages and describe any differences between the two records. Find Sisimiut and Nuuk on a map and examine the geographic characteristics of the region. Discuss the factors that shape the climate at both locations and the reasons for the differences between them.

2. In the climate system, the albedo effect of snow cover is considered a feedback to the climate. The condition that makes precipitation fall as snow – low air temperature – is reinforced by the albedo of the snow on the ground. Is this a case of positive or negative feedback? Give other examples of feedbacks in the climate system.

3. Consult an atlas (e.g., http://map.uarctic.org) to find the main biomes of the North, the location of the northern treeline and the distribution of permafrost. Find and discuss spatial patterns in the distribution of vegetation zones in relation to patterns of elements such as mean annual temperature, mean summer temperature, solar radiation and precipitation.

4. The following towns in northern Canada all have local sources of pollution, such as motor vehicles, diesel-powered electrical generators and plants related to mining or oil and gas industries. Find climatic information for Wabush, Labrador; Iqaluit, Nunavut; Whitehorse,Yukon and discuss the climatic potential for air pollution in terms of:
    1. location on main pathways for long-range transport,
    2. wind speed and wind direction,
    3. extreme low temperatures associated with surface inversions, and
    4. other important factors.

Glossary of Terms

Biomes: are climatically and geographically defined as similar climatic conditions on the earth, such as communities of plants, animals and soil organisms and are often referred to as ecosystems.

Cyclonic Depression: an area of low atmospheric pressure characterized by inward spiraling winds that rotate anticlockwise in the northern hemisphere and clockwise in the southern hemisphere.

Greenhouse Effect: a process by which radiation emitted from the earth's surface is absorbed by atmospheric greenhouse gases (e.g., water vapour, carbon dioxide) and is re-emitted in all directions.

Heat Capacity: a measurable physical quantity that characterizes the amount of heat required to change a substance's temperature by a given amount.

Lapse Rate: in physical geography, the rate of change of any atmospheric variable with altitude, especially atmospheric temperature.

Latent Heat of Vaporization: the amount of heat required to convert a unit mass of a liquid at its boiling point into vapour without an increase in temperature.

Longwave Radiation: electromagnetic radiation with wavelengths greater than 4 microns (1 micron = 1 µm = 1×10^{-6} metres).

Planetary Albedo: the fraction of solar radiation that is reflected by the earth atmosphere system and returned to space mostly by back scatter from clouds in the atmosphere.

Shortwave Radiation: electromagnetic radiation with wavelengths between 0.4 to 4.0 microns.

Stable Atmosphere: the atmosphere is considered stable when it does not support, in any way, the movement of air molecules upward for a defined area or location.

Transpiration: a process in which the water vapour escapes through plant leaves into the atmosphere.

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Online Primers and Self-instruction:

U.S.A. National Weather Service: http://www.srh.weather.gov/srh/jetstream/index.htm
UCAR (U.S.A.): http://www.eo.ucar.edu/
U.K. Meteorological Office: http://www.metoffice.gov.uk
U.K. Science Weather Resource Site: http://weatherfaqs.org.uk/
National Snow and Ice Data Centre (USA): http://www.nsidc.org/cryosphere/index.html
NSDIC Primer of Arctic Weather and Climate: http://www.nsidc.org/arcticmet/
USGS Water Science for Schools http://ga.water.usgs.gov/edu/index.html
and http://ga.water.usgs.gov/edu/dictionary.html
University of the Arctic Environmental Atlas: http://map.uarctic.org/
Wikipedia – Climate of the Arctic: http://en.wikipedia.org/wiki/Climate_of_the_Arctic

Online weather and climate glossary:
http://www.srh.weather.gov/srh/jetstream/append/glossary_a.htm
Links to weather services of the world through the World Meteorological Organization:
http://www.wmo.int/pages/index_en.html