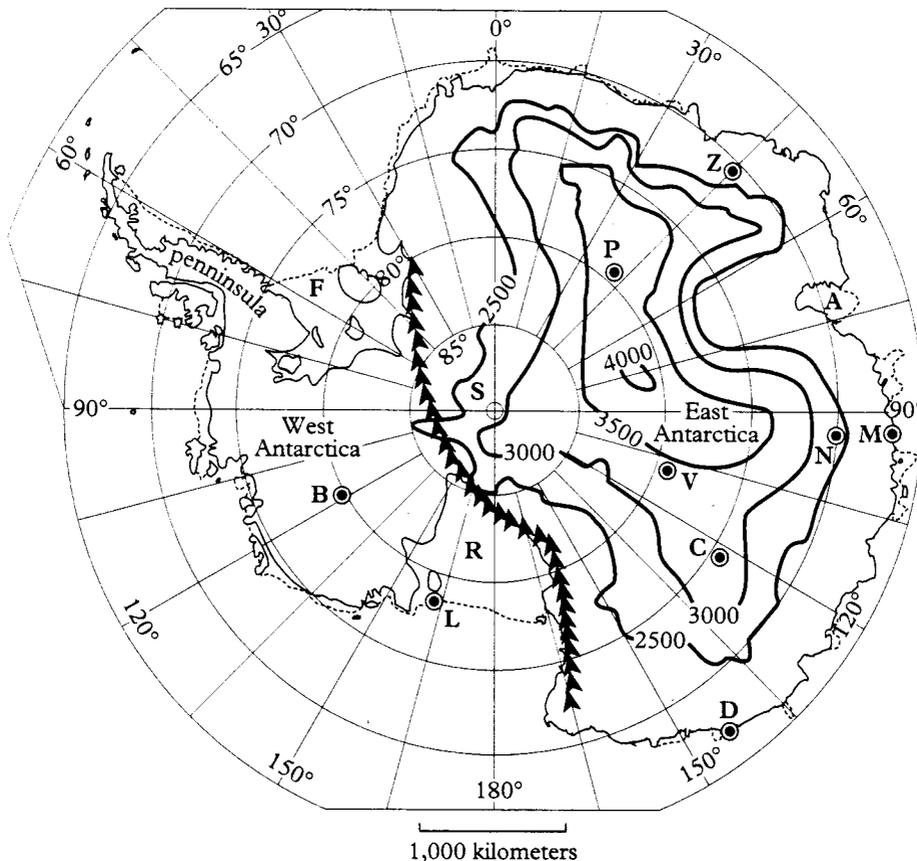


ENCYCLOPEDIA OF CLIMATE AND WEATHER

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ANTARCTICA. The southern polar continent, Antarctica, is Earth's modern-day example of a continental ice sheet. It is about the same size, both in area and in volume, as the ice sheet that covered part of North America during the most recent ice age. Antarctica is larger than Australia and smaller than South America. Its average surface elevation of 2.2 kilometers, greatly exceeding the 0.7-kilometer average for the other continents, is due to the ice sheet, the thickness of which averages 2.4 kilometers and in places approaches 5 kilometers. The amount of ice on Antarctica is 75 meters of sea-level equivalent; this means that if the ice melted completely into the ocean, global sea level would rise by 75 meters. The other great modern-day ice sheet, on Greenland, contains about 7 meters of sea-level equivalent.

Antarctica is divided into two parts by the Trans-Antarctic Mountains (Figure 1). The larger part, mostly in the eastern longitudes, is called East Antarctica; it contains 88 percent of the ice. The smaller part, in the western longitudes, includes the Antarctic Peninsula extending toward South America and is called West Antarctica. The elevation of the ice-sheet plateau is about 2,600 meters in East Antarctica but only 1,800 meters in West Antarctica. If all the ice were removed from Antarctica, and after the bedrock rebounded, only East Antarctica would remain as a continent (about 30 percent larger



ANTARCTICA. Figure 1. *Map of Antarctica*. Contours of elevation are shown, beginning at 2,500 meters. Locations mentioned in the text are indicated by symbols: Amery Ice Shelf (A), Byrd Station (B), Dome-C (C), Cape Denison (D), Filchner-Ronne Ice Shelf (F), Little America (L), Mirnyy (M), Pionerskaya (N), Plateau Station (P), Ross Ice Shelf (R), South Pole (S), Vostok (V), Mizuho (Z), Trans-Antarctic Mountains (▲).

than Australia), while West Antarctica would be a chain of islands. The West Antarctic Ice Sheet is thus a *marine ice sheet*, with its base resting on the ocean floor rather than on a continental land mass.

About 97.6 percent of Antarctica is covered with ice, formed by compression of snow. There is a gradual transition from snow at the surface to ice below. Temperatures at the snow surface are far below freezing even in summer over most of the continent, so there is very little melting anywhere. The snow therefore builds up year after year, like sedimentary rock, and is compressed under its own weight into ice. Vertical holes have been drilled into the ice sheet at several locations to extract cylinders called *ice cores*. The ice strata are analyzed for isotopes, impurities, and gas content, which give information about the history of local and global climate. [See Cores; Glaciers.]

Ice Shelves. Under the weight of overlying ice and snow, the ice sheet flows downslope and outward to the

coastline. Even on the coast, however, temperatures are too low to allow much melting, so the ice continues to flow out onto the ocean as floating *ice shelves* several hundred meters thick. At the seaward limit of these ice shelves, icebergs break off owing to stresses induced by waves and currents, floating away to melt in the ocean. The steady-state mass balance of the Antarctic ice sheet thus comprises a gain from snowfall balanced by a loss of icebergs, with minor contributions from melting and freezing at the bases of the ice shelves. There are numerous small ice shelves around the perimeter of Antarctica, and two very large ones occupying great embayments of the coastline—the Ross Ice Shelf and the Filchner-Ronne Ice Shelf, each nearly the size of France. The surfaces of these ice shelves are mostly cold snow, but there is melting in places, sometimes forming lakes. [See Icebergs.]

The coastline of East Antarctica closely follows the Antarctic Circle. In West Antarctica the open sea makes its closest approach to the South Pole, at the fronts of the

great ice shelves at 78° south latitude. The explorers Roald Amundsen and Robert F. Scott both docked their ships at this latitude, at the front of the Ross Ice Shelf, to begin their treks to the Pole in 1911.

Sea Ice. The Antarctic continent is surrounded by a cold ocean, the surface of which freezes every winter to form a thin and discontinuous cover of sea ice, averaging less than 1 meter in thickness. At its maximum extent at the end of September, the ice covers an area of 20 million square kilometers, larger than the Antarctic continent itself—in fact, larger than South America. By the end of summer in March, the sea ice has melted away over 85 percent of this area. [See Sea Ice.]

Research Stations. Many research stations have been established along the coast of Antarctica, but only a few in the interior. The climatic records from the interior stations are able to represent much larger areas than those of the coastal stations, because of the greater horizontal homogeneity of the ice-sheet surface. The interior stations with the longest climatic records are South Pole and Vostok, both of which have been operating year round since the International Geophysical Year (1957–1958). Useful climatic records from the interior are also available from Plateau Station in East Antarctica, occupied continuously for 3 years in the late 1960s; Byrd Station in West Antarctica, continuous from 1957 to 1970, and now operating only in summer; and Mizuho Station on the East Antarctic “slope” (the transition from the plateau to the coast), since 1976. Several automatic weather stations are also now operating.

Surface Temperature. The ice-sheet surface is cold at all times. In January, the warmest month of the year, the mean location of the 0°C contour of surface air temperature is far out in the ocean, intersecting the continent only on the western side of the Antarctic Peninsula. A consequence of the cold atmosphere is that the atmospheric density is greater at all pressures than in mid latitudes, so that given atmospheric pressure levels occur at lower elevations than they would in mid latitudes. The *pressure altitude* is the altitude in a mid-latitude atmosphere corresponding to the measured surface pressure at the station. At stations on the high plateau (South Pole and Vostok), the pressure altitude is 10 percent higher than the true altitude in summer and 15 percent higher in winter.

The temperatures of representative stations are summarized in Table 1. The mean summer (December–January) temperature is below freezing at all locations, but on occasion there is some melting at the coastal stations. At Byrd Station the record high temperature almost reached the melting point. On the East Antarctic Plateau the temperatures are lower at Vostok than at South Pole, mostly because of the difference in elevation, since these stations are the same distance (1,300 kilometers) from the coast.

The winter in Table 1 comprises the 6 months April through September. The monthly mean temperature at South Pole Station is close to –58°C for each of these 6 months. The extreme minimum temperature at Vostok, –89.2°C, recorded in July 1983, is a world record. The

ANTARCTICA. Table 1. *Surface air temperatures at representative antarctic stations*

Region	Low-Latitude Coast	High-Latitude Coast	West Antarctica	East Antarctica	
	STATION	MIRNYI		LITTLE AMERICA (FRAMHEIM)	SOUTH POLE
Latitude(°S)	66	78	80	90	78
Elevation (meters)	30	40	1,500	2,800	3,500
Station pressure (millibars)	980	980	800	680	620
Mean summer temperature (°C)	–2	–7	–15	–28	–33
Mean winter temperature(°C)	–16	–33	–34	–58	–66
Extreme maximum temperature (°C)	+8	+6	–1	–14	–21
Extreme minimum temperature (°C)	–40	–61	–63	–81	–89

coldest place on the Earth's surface is probably somewhere along the topographic ridge of East Antarctica. Both Vostok Station and Plateau Station are near this ridge. During the 3 years that Plateau Station was operating, its average temperature was lower than Vostok's by 0.8 K, so Plateau Station might someday break Vostok's world record.

The extreme low temperatures in winter occur under conditions of light winds and clear sky, when a strong temperature inversion develops. The temperature in the inversion typically rises by 25 K in the lowest 300 meters of the atmosphere, but on occasion it can rise this much in the lowest 30 meters. At South Pole Station a near-surface temperature inversion is present on average in 10 months of the year, all except December and January.

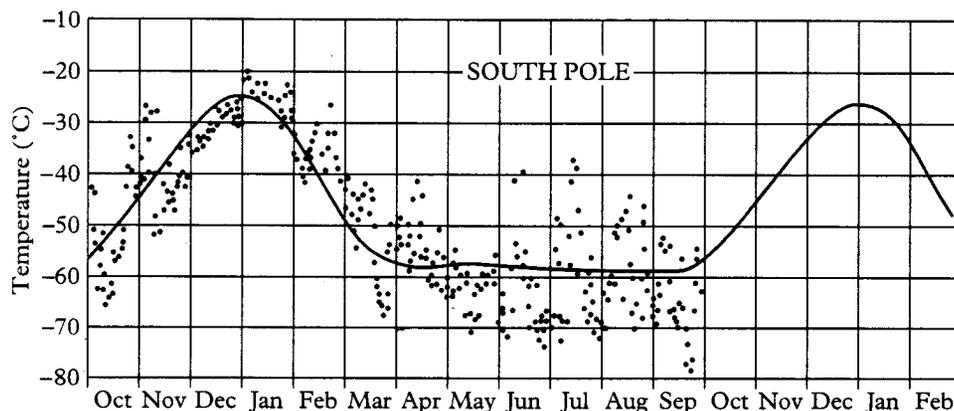
The wintertime temperature inversion near the Antarctic surface is an extreme example of a more widespread phenomenon common at night and in winter at lower latitudes. At night, when there is no solar radiation, by far the largest terms in the surface energy budget are the downward and upward longwave (infrared) radiation. In East Antarctica these average about 100 and 125 watts per square meter, respectively. The snow is nearly a black body at thermal infrared wavelengths, with an emissivity of more than 99 percent, so emission of 125 watts per square meter is consistent with a temperature of about -56°C . The atmosphere, however, is far from opaque, with an effective emissivity of only about 50 percent, so to emit 100 watts per square meter it requires a higher temperature.

Figure 2 shows the 20-year average of the seasonal cycle of surface air temperature at South Pole Station as a solid line, with dots indicating the individual daily tem-

peratures for one particular year (October 1985–September 1986). The temperature rises rapidly in the spring (October and November), then averages -28°C for the summer months of December and January. The normal peak temperature comes only 8 days after the summer solstice, a very short lag in comparison with other continents, for which the lag is closer to 30 days. In fall (February and March) the temperature drops rapidly by nearly half a degree Celsius per day. When the Sun sets on the March equinox, the temperature is already down to its winter level and does not drop much more (on average) throughout the next 6 months. This phenomenon, peculiar to Antarctica, is called the *coreless winter*. In winter the energy budget of the Earth–atmosphere system over Antarctica consists of a loss of about 110 watts per square meter of infrared radiation to space, balanced by an equal import of heat from lower latitudes, carried by tropospheric winds. This import is apparently maintained at a rather constant rate throughout the 6-month winter.

The day-to-day variations in temperature (dots in Figure 2) are much larger in winter than in summer. The lowest temperatures occur on calm, clear days with a strong temperature inversion. The inversion can be destroyed within a few hours when a cloud forms overhead (because clouds, like snow, have high emissivity at thermal infrared wavelengths), or when strong winds mix the warmer air down to the surface. In the summer, by contrast, the atmosphere has nearly constant temperature in the lowest few hundred meters, so clouds and wind are unable to change the surface temperature significantly.

Surface Energy Budget. An example of the surface



ANTARCTICA. Figure 2. Surface air temperatures at South Pole Station. Solid line: 20-year mean for each day. Dots: daily mean temperatures for the year October 1985–September 1986.

ANTARCTICA. Table 2. *Surface energy budget at Pionerskaya (70° south latitude, 95° east longitude, 2,700 meters)**

	June	December
Downward shortwave (solar) radiation	0	372
Upward shortwave radiation	0	-312
Downward longwave (infrared) radiation	106	173
Upward longwave radiation	<u>-134</u>	<u>-209</u>
Net radiation	-28	+24
Sensible heat	23	-16
Latent heat	<u>1</u>	<u>-2</u>
Sum	-4	+6

*Energy fluxes are in watts per square meter; a positive number means that the flux is in the downward direction (from the atmosphere to the surface).

energy budget on the Antarctic Plateau is given in Table 2 for Pionerskaya Station. Quite large amounts of solar radiation, exceeding the global average at the top of the atmosphere (334 watts per square meter) are received in December, but 84 percent of the radiation is reflected. This value, the *albedo* of the snow surface, is higher on the Antarctic Plateau than anywhere else on Earth. Water vapor, ozone, and carbon dioxide in the atmosphere absorb some solar radiation, so the albedo at the top of the atmosphere over Pionerskaya is less than this—probably about 72 percent—but still much larger than the global average of 30 percent. The high albedo of snow is an important reason for the extreme cold of Antarctica.

In June there is no incident solar radiation, and the loss of infrared radiation from the surface (134 watts per square meter) is not quite balanced by the downward radiation from the atmosphere, leaving a net radiation loss of 28 watts per square meter. The sensible heat flux is downward because the air is warmer than the snow surface; the latent heat flux is also downward, indicating deposition of frost. These fluxes still do not balance the loss of longwave radiation; the residual 4 watts per square meter deficit results in a cooling of the snowpack.

In December the net radiation is positive because the absorption of solar radiation exceeds the net longwave loss. The result is that a square meter of snowpack is gaining 6 watts of heat during this month and is, therefore, warming. After a complete annual cycle, the snow gains no net heat. The -4 watts per square meter in June, together with the deficits in the other winter months, is balanced by the net gain in the shorter summer.

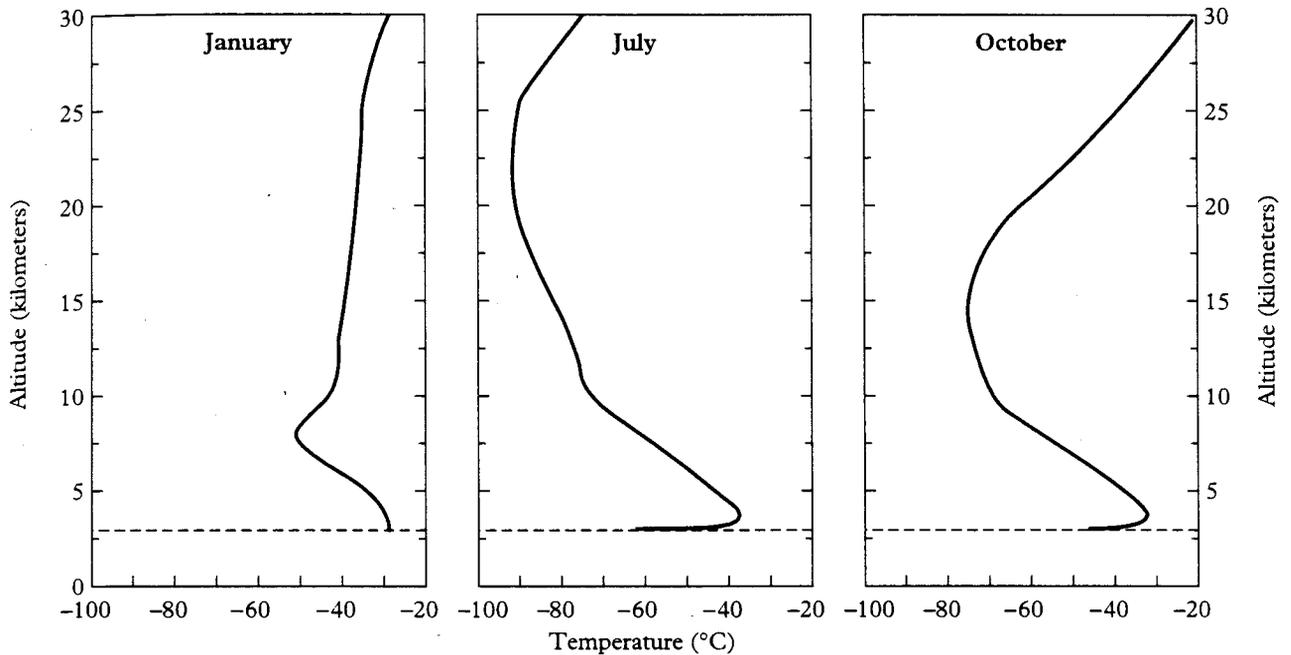
Upper-Air Temperatures. Atmospheric temperatures from the surface up into the stratosphere, to about

10 millibars pressure, are available from radiosondes launched daily by balloon at South Pole Station (Figure 3) and at several coastal stations. In summer (January) there is little or no near-surface inversion. The temperature decreases with height to a well-defined tropopause, then increases slowly through the stratosphere due to heating by ozone's absorption of ultraviolet sunlight. In winter (July) a strong inversion is present. The Sun has set on the ozone layer, so there is no well-defined tropopause in the temperature profile. In the October profile, the near-surface inversion has diminished somewhat, and the stratosphere has warmed dramatically with the return of the Sun.

Water Vapor and Precipitation. Because of the high surface elevation and the low atmospheric temperatures, total water-vapor amounts over the Antarctic ice sheet in winter are sometimes as low as those on Mars. Total *precipitable water* at Plateau Station varied over the course of a year from 0.01 to 0.3 millimeters, as compared with 10 to 50 millimeters typical in the mid latitudes and tropics. Water vapor absorbs strongly at infrared and longer wavelengths, so infrared and microwave astronomy can best be carried out where the precipitable water is small. A large astronomical observatory is now under construction at South Pole Station.

Near the coast the air is warmer and moister, and the snow accumulation is correspondingly greater, than in the interior. Snowfall is not normally measured because it cannot be distinguished from blowing snow in precipitation gauges. Instead, the net accumulation is estimated by measuring the snow surface rising against a thin stake, as well as the vertical profile of snow density. This measured accumulation is the net result of gains from snowfall, frost deposition, and drifting, and losses from sublimation and drifting. Deposition of *rime* (supercooled cloud droplets that freeze on contact with the surface snow) also is important in some regions, especially on the ice shelves. Station buildings cause enhanced accumulation due to drifting, so the measurements are ideally made several kilometers distant from the buildings to ensure that they represent the natural surface.

Average annual snow accumulation has also been measured at numerous locations during tractor-traverses of the ice sheet. The traditional method is to dig down a few meters and record the locations of annual layers on the wall of a snow pit, also measuring the density profile. Annual layers are visible in spite of the absence of melting, because in autumn a frost layer (called *depth hoar*) about 1 to 2 centimeters thick forms just below a harder



ANTARCTICA. Figure 3. Monthly average atmospheric temperature, as a function of altitude above sea level, obtained from balloon-borne radiosondes launched at South Pole Station in 1992. The horizontal dashed line marks the surface elevation at 2,835 meters. (Data and figure provided by Ash Mahesh and Von Walden, University of Washington.)

surface crust about 5 millimeters thick. This pair of structures is preserved for many years in the cold snowpack. Many more sophisticated stratigraphic techniques are now used, which make use of the seasonal cycles of oxygen isotopes, dust, and chemical impurities. The net accumulation measured by these methods varies from 25 kilograms per square meter per year on the East Antarctic Ridge, to more than 400 on the Antarctic Peninsula, averaging about 170 for the entire continent.

Continuing measurements of snow accumulation are important for determining the role of Antarctica in global sea-level change. The sea level is expected to rise during the next century as a result of global climatic warming caused by anthropogenic (human-generated) greenhouse gases. The ocean water is expected to expand as it warms, and the Northern Hemisphere glaciers are expected to retreat, adding meltwater to the ocean. By contrast, the Antarctic ice sheet is expected to grow because more precipitation will probably fall from warmer, more humid air. An increase in snow accumulation during the next century would not be balanced as quickly by any change in ice flow rates, so increases in Antarctic accumulation may actually diminish the expected sea-level rise. Analysis of an ice core at Dome C

indicated that the snow accumulation rate increased by 30 percent as the temperature increased by 3 K at the end of the last ice age.

Clouds and Diamond Dust. Clouds are as common over Antarctica as over other continents (about 50 percent average cloud cover), but the clouds there are generally thinner, and convective clouds (cumulus and cumulonimbus) are rare. In the interior, only ice clouds are possible in the winter, but in summer, clouds of liquid water (stratus, stratocumulus, and altostratus) are also common, at temperatures around -30°C . In very clean air, pure water droplets can remain liquid down to -40°C .

Whenever there is a strong temperature inversion, a thin ice cloud usually forms near the surface owing to slow downward mixing of warmer air. The cloud is so thin that it is not even called a cloud. With a clear blue sky above, small ice crystals, called *diamond dust*, form in the near-surface air, sparkling in the sunlight or moonlight and often creating spectacular halos and arcs.

Wind. The general circulation of the Antarctic troposphere comprises poleward flow in the middle troposphere, subsidence over the ice sheet, and downslope outward flow (turned to the left by the Coriolis force) at

the surface. The surface winds have high directional constancy, especially in regions of significant slope. The *inversion wind* of the interior results from a balance of pressure gradient, Coriolis force, and frictional force. As the slope steepens nearer the coast, the inversion wind transitions to a *katabatic wind*, which is a down-slope drainage wind resulting from gravity acting on the dense layer of air just above the sloping snow surface. Modifying this general pattern are numerous cyclonic storms that form over the ocean and penetrate some distance into the continent, especially in West Antarctica.

The winds at the surface are persistent but rather weak in the interior. At the South Pole the average wind speed is 4.3 meters per second in summer and 7 meters per second in winter. The windspeed increases with surface slope and becomes extreme where the wind is channeled between mountains along the coast. The windiest location yet recorded in Antarctica is at Cape Denison, where Douglas Mawson established the base of the first Australian expedition to Antarctica in 1911, recording an annual average wind speed of 19 meters per second.

Wind speeds exceeding about 7 meters per second are sufficient to loosen snow grains from the surface and start them drifting. When the snow grains reach eye level, they are called *blowing snow* instead of *drifting snow*. On the Plateau, blowing snow is restricted to wintertime, for two reasons: the winds are on average stronger in winter, and the snow grains are smaller and more easily lifted. The falling snow crystals are smaller in all dimensions in winter, because they grow much more slowly in the colder air. Blowing-snow particles in winter are typically 30 microns in diameter, so they can be blown up to great heights, often exceeding 30 meters. Such blizzard conditions were encountered about one-third of the time during the winter of 1992 at South Pole Station.

The drifting snow causes a roughening of the surface, eroding the snow surface into a field of small longitudinal dunes called *sastrugi*, aligned with the wind that created them. On the Plateau they are typically 3 meters long, 1 meter wide, and 10 to 50 centimeters high, but they can grow much higher in the windier regions on the steeper coastal slopes.

Stratospheric and Mesospheric Clouds. Over most of the Earth, clouds do not form in the stratosphere because it is so dry. In the Antarctic winter, however, the stratosphere can cool to temperatures below -83°C , allowing *polar stratospheric clouds* to form at about 20 kilometers height. These clouds, which act as a catalyst for the destruction of ozone in September and October, are normally too thin to be visible from the ground. How-

ever, they can grow much thicker over mountainous terrain to become visible as *nacreous clouds*, most evident when illuminated by the Sun from about 5 degrees below the horizon.

Much higher, in the mesosphere at about 80 kilometers, *noctilucent clouds* are occasionally seen, illuminated by the Sun about 10 degrees below the horizon. They have been mapped from a satellite and found to be less common in the Antarctic than in the Arctic. An important source of water vapor for the mesosphere is the oxidation of methane, so the increase in frequency of reported sightings of noctilucent clouds over the past few decades has been attributed to the increase in atmospheric methane. [See Clouds.]

Watching the Sky. Here is a description of sky observations for a year at the South Pole Station, starting in the summer. The Sun cycles once around the sky over the course of a day, with imperceptible vertical motion. It reaches 23.5 degrees elevation on the December solstice and slowly spirals down to the horizon at the March equinox. Sunset lasts 30 hours from the time the bottom of the Sun touches the horizon until the upper limb finally sets. The slow sunset, together with the large near-surface temperature inversion, allows leisurely observation of atmospheric refraction phenomena; the green flash, normally a split-second blink elsewhere on Earth as the Sun's upper limb sets, can last for hours at the South Pole.

After sunset, the twilight fades slowly for 6 weeks and is still faintly visible until early May. In the dark winter, auroras are visible on most clear days, usually just as broad white streaks but sometimes as swirling colors. During most years there is a lunar eclipse sometime during the winter. The moon circles above the horizon for 2 weeks, then sets for 2 weeks, allowing the constellations to dominate the sky: the Scorpion, the Centaur, the Southern Cross, and the Magellanic Clouds, with Orion chopped in half by the horizon. The bright stars Sirius, Canopus, Achernar, Fomalhaut, Alpha and Beta Centauri, and Spica compose a familiar pattern unchanging throughout the winter.

The twilight begins again in early August; the sky-brightness then doubles every 2 days, increasing by a factor of 100,000 from 15 August to 21 September. Two weeks before the polar sunrise, nacreous clouds can occasionally be seen in the direction of the Trans-Antarctic Mountains. With conditions of extreme temperature inversion, a rare treat to watch for—seen in polar regions a few times each century—is the Novaya Zemlya Solar Mirage; the Sun may rise briefly as much as 2 weeks

early, then set again after just a few minutes. The September equinox finally brings back the Sun for the next 6 months, ending winter.

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STEPHEN G. WARREN