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ANTARCTICA

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The southern polar continent, Antarctica, is covered by our only modern example of a continental ice sheet. It is about the same size, both in area and in volume, as the ice sheet that covered much of North America during the most recent ice age. Antarctica's average surface elevation of 2.2 km, greatly exceeding the 0.7-km average for the other continents, is due to the ice sheet, the thickness of which averages 2 km and in places approaches 5 km.

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% 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 2600 meters in East Antarctica, but only 1800 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% larger 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 98% of Antarctica is covered with ice, and most of the ice is covered with snow. Temperatures at the snow surface are far below freezing even in summer over most of the continent; melting can occur only in low-elevation regions, and even there it

is rare. About 9% of the continent experiences at least one day of surface melting in a typical year. In the high interior plateau, therefore, the snow 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.

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. 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. At the seaward limit of these ice shelves, icebergs break off owing to stresses induced by waves and currents, and float away. The steady-state mass budget 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. Predictions for the future include more snowfall but also more rapid production of icebergs, so the net contribution of Antarctica to future sea-level change is uncertain.

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°S. 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 about 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.

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 homogeneity of the vast ice-sheet surface. The interior stations with the longest climatic records are South Pole and Vostok, which have been operating year round since the International Geophysical Year (1957-1958). Useful climatic records from the interior of East Antarctica are also available from Plateau Station, occupied continuously for three years in the late 1960s; Dome Fuji Station, established in 1995; and Dome Concordia Station, continuous since 2005. In West Antarctica, Byrd Station was occupied continuously from 1957 to 1970, but now operates only in summer. Mizuho Station, on the East Antarctic "slope" (the transition from the plateau to the coast), was established in 1976. Numerous automatic weather stations are also now operating across the continent.

Surface Temperature. The ice sheet surface is cold at all times. In January, the warmest month of the year, the average 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.

The temperatures of representative stations are summarized in Table 1. The average 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 (1300 kilometers) from the coast.

The winter in Table 1 comprises the 6 months April-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 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 three years that Plateau Station was operating, its average temperature was lower than Vostok's by 0.8 K.

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 surface-based 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. Snow is nearly a blackbody at thermal infrared wavelengths, with an emissivity of 99%, 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%, 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 temperatures 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, when the Sun is circling the horizon continuously at about 20° elevation. In an average year the temperature peaks just 8 days after the summer solstice, a very short lag in comparison with other continents, for which the lag

is closer to 30 days. This short lag is evidence of the small “thermal inertia” of the dry snow surface, which is a good insulator. In autumn (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. In an average year, 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 or is advected 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.

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 surface-based 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 inversion has

diminished somewhat, and the stratosphere has warmed dramatically with the return of the Sun.

Pressure. A consequence of the cold atmosphere is that the atmospheric density is greater at all pressures than in midlatitudes, so that given atmospheric pressure levels occur at lower elevations than they would in midlatitudes. The *pressure altitude* is the altitude in a midlatitude 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% higher than the true altitude in summer and 15% higher in winter.

Surface Energy Budget. An example of 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% 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 74%, but still much larger than the global average of 30%. The high albedo of snow is an important reason for the extreme cold of Antarctica. Another reason is the high altitude of the continent.

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.

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 which form over the ocean and penetrate some distance into the continent, especially in West Antarctica.

The surface winds in the interior are persistent but not particularly strong. At the South Pole the average wind speed is 15.5 km/hr in summer and 25 km/hr in winter. The wind speed increases with surface slope and becomes extreme where the wind is channeled between mountains along the coast. The windiest location yet recorded 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 68 km/hr.

Water Vapor and Precipitation. Because of the high surface elevation and the low atmospheric temperatures, the total column water-vapor amount ("*precipitable water*") over the Antarctic ice sheet in winter is sometimes as low as in the Martian summer. The precipitable water at Plateau Station varied over the course of a year from 0.05 to 0.3 mm, and 0.4-1.6 mm over the South Pole, as compared with 10 to 50 mm typical in the midlatitudes 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 has been established at

South Pole Station, and there is potential for more astronomical observatories at other research stations that are even higher on the plateau (e.g., Dome Concordia 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. Drifting of snow around station buildings causes enhanced accumulation, 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, recording the density profile and the locations of annual layers on the wall of a snow pit. 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 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 annual accumulation measured by these methods is 2-3 cm of liquid equivalent on the East Antarctic Ridge, increasing to more than 40 cm on the Antarctic Peninsula, and averaging about 17 cm for the entire continent.

Clouds and 'Diamond Dust'. Clouds are as common over Antarctica as over other continents (about 50% average cloud cover), but the clouds are generally thinner, and convective clouds (cumulus and cumulonimbus) are rare. In very clean air, pure

water droplets can remain liquid down to -37°C . In the interior in winter, most of the atmosphere is colder than this, so ice clouds dominate, but liquid clouds are possible at the top of the temperature inversion. In summer, clouds of liquid water (stratus, stratocumulus, and altostratus) are common, at temperatures around -30°C .

When 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. Diamond dust can account for 50-80% of the snow accumulation along the East Antarctic Ridge, but elsewhere the precipitation is dominated by storms originating at the coasts.

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

Much higher, in the mesosphere at about 80 kilometers, *noctilucent clouds* are occasionally seen, illuminated by the Sun about 10° below the horizon. They form over the polar regions, primarily in summer. 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.

Blowing snow, dunes, and sastrugi. Wind speeds exceeding about 25 km/hr 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*. On the Plateau, blowing snow is primarily restricted to wintertime, for two reasons: the winds are 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 micrometers in diameter, so they can be blown up to great heights, often exceeding 30 meters. Such blizzard conditions occur at the South Pole about 20-50% of the time.

Long periods of drifting snow can cause small barchan dunes to form, the tips of which point downwind. These dunes march slowly downwind along the snow surface until the drifting snow grains sinter together under the stress of the wind and warm temperatures. If strong wind continues, the dunes are eroded into a field of small longitudinal ridges 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.

Megadunes, with wavelengths of a few kilometers and amplitude of only a few meters, are visible from satellites when the sun is low enough to cause shading of the relief. Most deposition of snow occurs on the upwind face of the dunes, while ablation often occurs on the downwind face, so they migrate extremely slowly *into* the prevailing winds. The upwind megadune faces typically are decorated with large sastrugi while the downwind faces are characterized by a smooth glazed surface over depth hoar.

Blue-ice zones. In some mountainous regions, strong winds blow away the newly fallen snow and sublimate the older sintered snow, exposing areas of glacier ice, which are further ablated by sublimation. The exposed surface is often called “blue ice,” but its appearance might be better described as “blue-white” because the ice contains numerous bubbles. It has an albedo of about 60%, much lower than that of snow. The increased absorption of solar radiation raises the surface air temperature and lowers its relative

humidity over the ice relative to the surrounding snow-covered regions, leading to enhanced sublimation during summer.

Synoptic and mesoscale meteorology. In contrast to the Northern Hemisphere, where standing atmospheric waves anchored to continental land masses are responsible for a larger portion of the poleward energy transport, heat and moisture are delivered to Antarctica from lower latitudes primarily by transient eddies: *synoptic* (1000-5000 km) and *mesoscale* (<1000 km) cyclones. The driving force behind the transport of energy to Antarctica from lower latitudes is the equator-to-pole solar radiation gradient. Instabilities in the resulting atmospheric temperature gradient cause the development of large atmospheric eddies (cyclones), which bring warm air poleward and cold air equatorward.

Many of the synoptic-scale cyclones that reach the Antarctic coast originate at latitudes lower than 45°S. *Cyclogenesis*, the creation of cyclones, also occurs at higher latitudes; large temperature gradients occur in the Southern Ocean, at the sea ice edge, and at the boundary between the Antarctic interior and the ice shelves. The combination of these large temperature gradients and westerly flow unobstructed by land masses at 60°S make the Southern Ocean and coastal Antarctica two of the stormiest regions of the world. *Cyclolysis*, the death of cyclones, commonly occurs along the Antarctic coast. However, cyclones can also be rejuvenated there by the strong temperature contrast that occurs when cold katabatic winds are drawn out from the interior by passing depressions.

The temperature gradients at the sea-ice edge and the boundary between the ice shelf and the interior are also responsible for mesoscale cyclones that often have a lifetime of one day or less. These cyclones pose a significant challenge to logistical operations in Antarctica because they form rapidly and often do not contain enough moisture to be visible in satellite imagery (“dry vortices”). Mesoscale cyclogenesis occurs most often in regions of strong katabatic outflow where large temperature gradients can be generated suddenly (e.g. the Ross Ice Shelf).

The strength of the ocean-to-continent pressure gradient, and therefore the strength of the polar vortex, varies from year to year. The location and shape of the polar vortex is maintained in large part by the height and symmetry of Antarctica. The variability in this pressure gradient, or the strength of the westerly winds, is known as the southern annular mode (SAM).

Climate change in Antarctica. The Antarctic Peninsula is one of the fastest-warming regions in the world, and some warming is seen in West Antarctica, but there has been no significant trend of surface temperature over the last 50 years in East Antarctica. There has also been no clear trend in snow accumulation rate. The increased tropospheric greenhouse gases and decreased stratospheric ozone together are responsible for a strengthening of the westerlies around the continent (positive SAM). This has warmed the Peninsula but has further isolated the Antarctic interior from the rest of the world. If temperatures over the continental interior do increase in the future, then snow accumulation is expected to increase because of the increased capacity of warmer air to carry water vapor inland.

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Table 1. Surface air temperatures at representative Antarctic stations.

Region	Low- latitude coast	High- latitude coast	West Antarctica	East Antarctica	
Station	Mirnyy	Little America (Framheim)	Byrd	South Pole	Vostok
Latitude ($^{\circ}$ S)	66	78	80	90	78
Elevation (meters)	30	40	1500	2800	3500
Station pressure (millibars)	980	980	800	680	620
Mean summer temperature ($^{\circ}$ C)	-2	-7	-15	-28	-33
Mean winter temperature ($^{\circ}$ C)	-16	-33	-34	-58	-66
Extreme maximum temperature ($^{\circ}$ C)	+8	+6	-1	-14	-21
Extreme minimum temperature ($^{\circ}$ C)	-40	-61	-63	-81	-89

Table 2. Surface energy budget at Pionerskaya (70°S, 95°E, 2700 meters). 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).

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

Figures

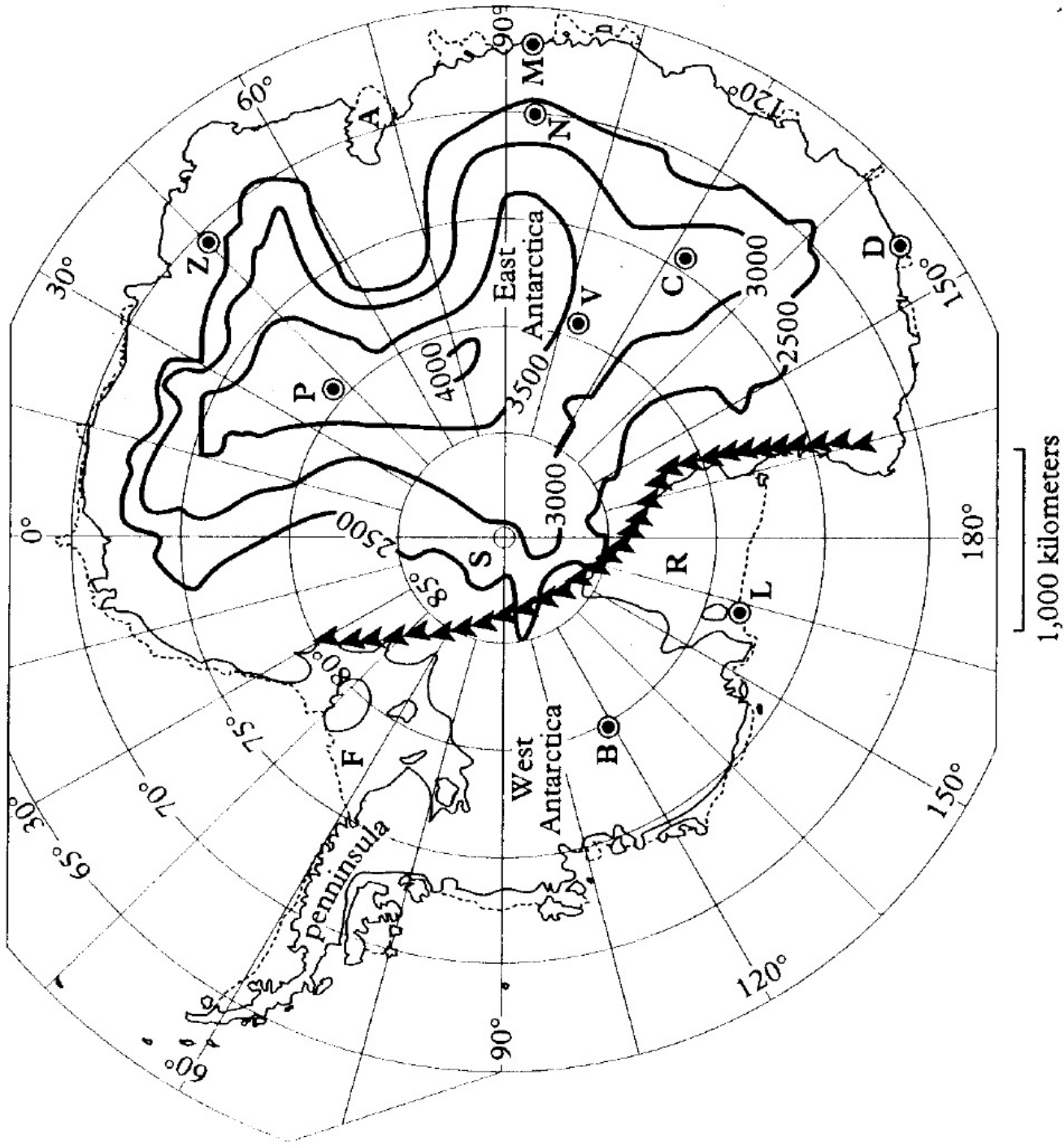
Figures are unchanged from the 1996 version, except that on Figure 1 there is one misspelled word: change “Penninsula” to “Peninsula”.

Figure captions

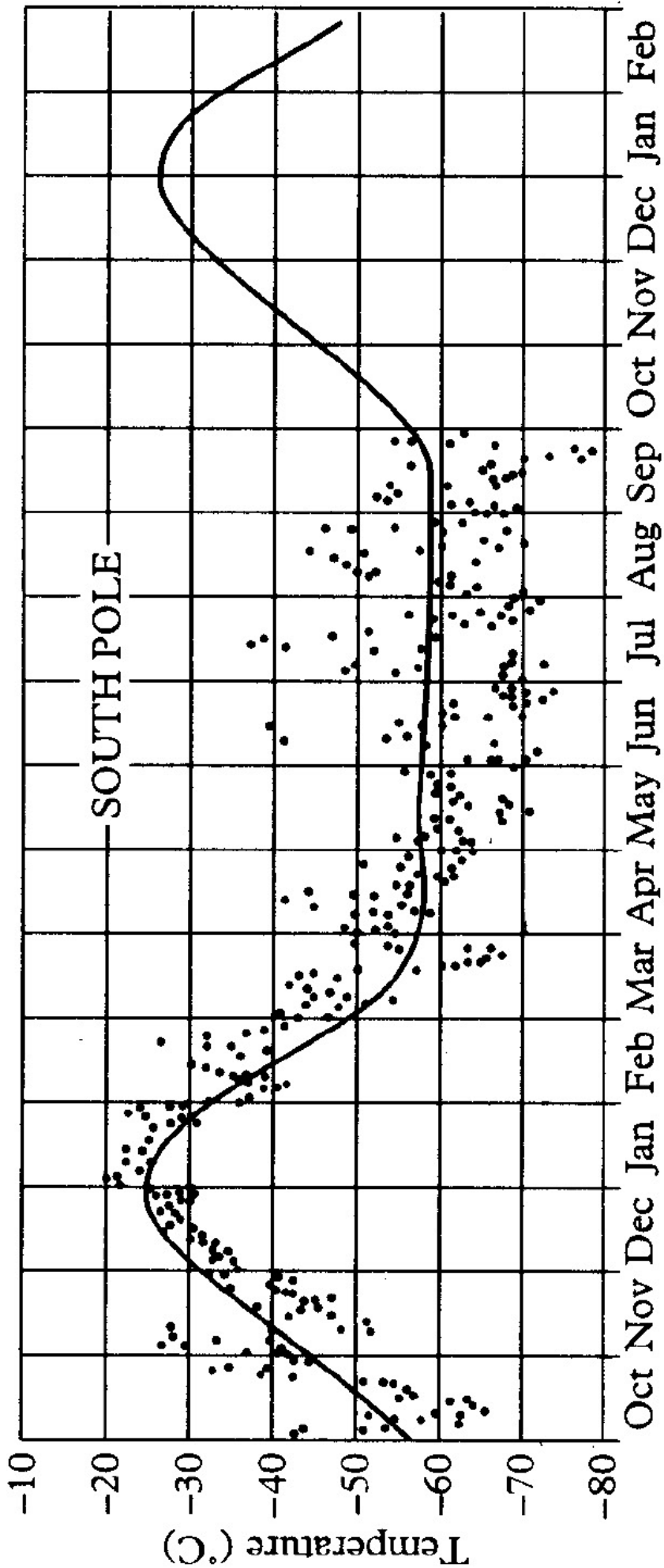
Figure 1. Map of Antarctica. Contours of elevation are shown, beginning at 2500 meters. Locations mentioned in the text are indicated by symbols: Amery Ice Shelf (A), Byrd Station (B), Dome Concordia (C), Cape Denison (D), Filchner-Ronne Ice Shelf (F), Little America (L), Mirnyy (M), Pionerskaya (N), Plateau Station (P), Ross Ice Shelf (R), South Pole (S), Vostok (V), Mizuho (Z), Trans-Antarctic Mountains (^).

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.

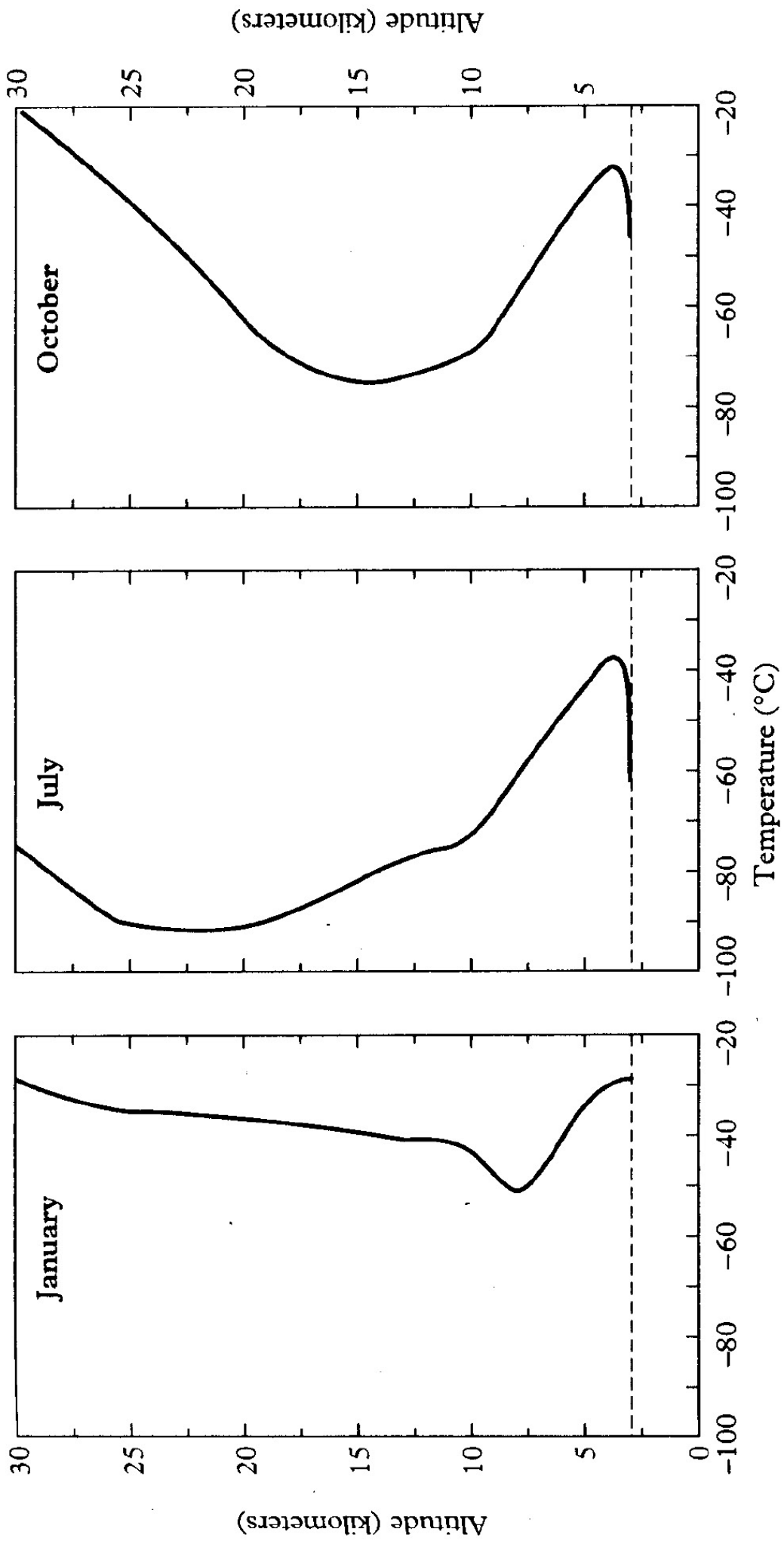
Figure 3. Monthly average atmospheric temperature, as a function of altitude above sea level, obtained from balloon-borne radiosondes launched at South Pole Station in 1992. The horizontal dashed line marks the surface elevation, 2835 meters. [Data and figure provided by Ash Mahesh and Von Walden, University of Washington.]



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 (▲).



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. 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.)