ARCTIC AND ANTARCTIC

Contents

Antarctic Climate

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Synopsis

Very different climatic regimes are found across the Antarctic, from dry, very cold conditions with few depressions over the interior plateau, to windy and wet maritime environments toward the tip of the Antarctic Peninsula. Although well removed from the other continents, the climate of Antarctica is affected by conditions across the other parts of the Earth, and especially the ocean temperatures in the tropical Pacific Ocean. The climate of the Antarctic has a large interannual variability as a result of interactions between the atmosphere, ocean, and ice. Over the last 50 years the Antarctic Peninsula has experienced a surface warming as large as any in the Southern Hemisphere. This warming extents into West Antarctica, but the rest of the continent has experienced little change. The loss of stratospheric ozone (the ozone hole) has had a major impact on the climate of the Southern Ocean, increasing the surface winds by about 15%. The ozone hole is expected to recover by 2060–2070, but if greenhouse gas concentrations continue to rise there will be a surface warming of several degrees across Antarctica, more precipitation, and a loss of sea ice.

Introduction

Antarctica is the highest, coldest, windiest, and driest continent on Earth, with a climate that varies from extremely cold and dry on the high plateau of East Antarctica to maritime across the northern part of the Antarctic Peninsula. Although remote from the major centers of population, it plays a crucial role in the global climate system and is closely coupled to conditions at lower latitudes via the oceanic and atmospheric circulations.

The Antarctic continent is about 40% larger than the United States, covering an area of 14×10^6 km^2, which is about 10% of the land surface of the Earth. The Antarctic ice sheet contains about 30×10^6 km^3 of ice or about 70% of the world's fresh water, which is equivalent to about 60 m of sea level. The ice sheet is made up of three distinct zones, consisting of East Antarctica (covering an area of 10.35×10^6 km^2), West Antarctica (1.97×10^6 km^2), and the Antarctic Peninsula (0.52×10^6 km^2) (Figure 1).

The orography of the continent has a profound effect on the climate of high southern latitudes, limiting the extent to which depressions can penetrate into the interior and giving rise to the katabatic (downslope) winds that are a major feature of the coastal zone. The elevation of the ice surface rises very rapidly inland from the coast, and the continent has a domed profile, with much of it being above 2000 m in elevation and some parts over 4000 m.

The other landmasses of the Southern Hemisphere are well north of the Antarctic, so that the oceanic and atmospheric flow is much more zonal than in the Northern Hemisphere. However, the highest parts of the ice sheet are found in East Antarctic and are slightly offset from the South Pole, which has implications for the atmospheric circulation around the continent.

The Broad-Scale Synoptic Environment

The Antarctic coastal region is a zone of strong, horizontal thermal gradients (baroclinicity) where cold katabatic winds flow off the continent and meet temperate, maritime air, resulting in the development of many depressions (cyclogenesis). It is also the area where many depressions spiraling south from midlatitudes become slow moving and decline (cyclolysis). The depressions carry warm (cold) air southward (northward) on their eastern (western) flanks and play an important part in the poleward transport of heat.

The large number of depressions in the 60–70° S zone results in a low-pressure belt around the continent known as

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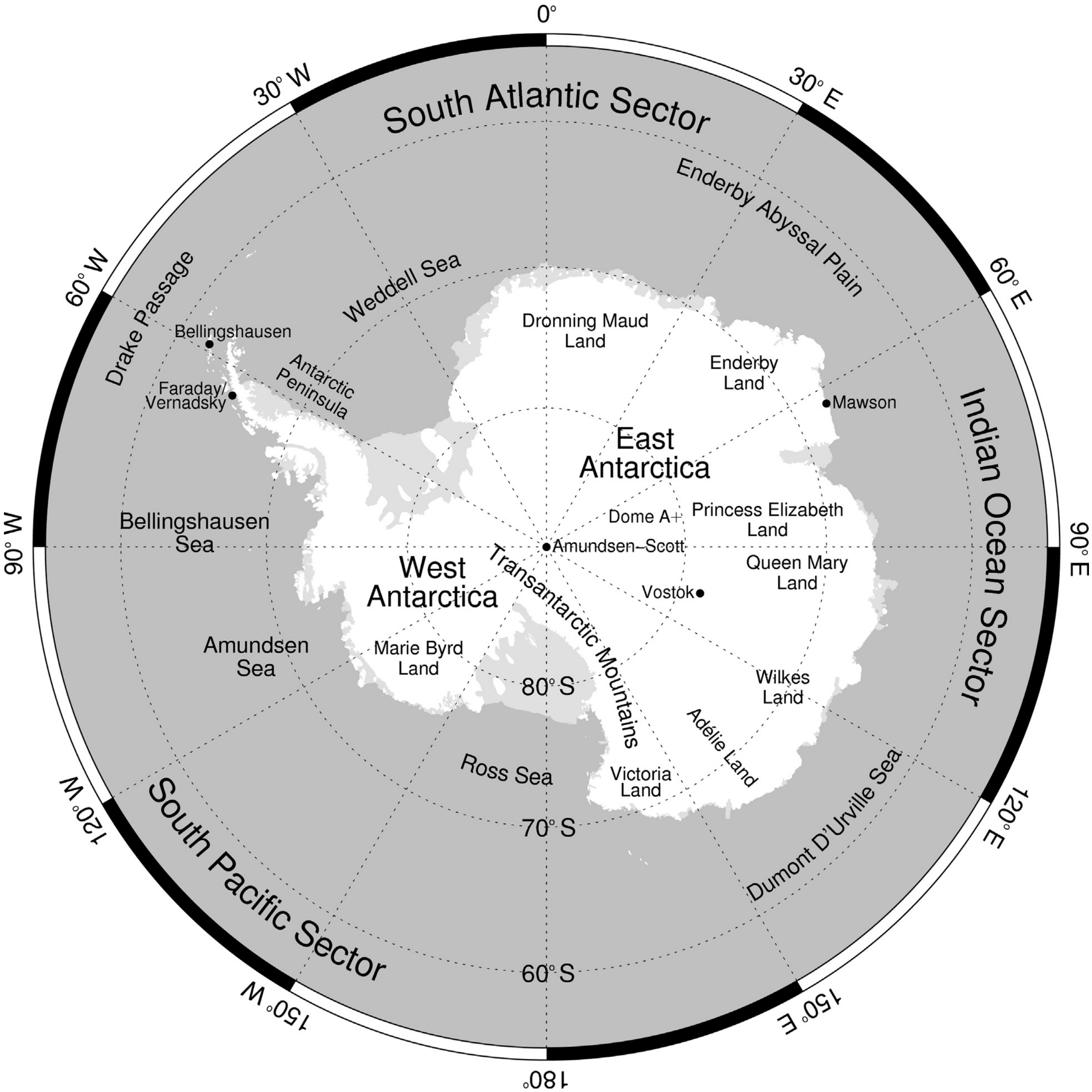

Figure 1 A map of the Antarctic showing regions, topographic features, and the locations of selected research stations.

the circumpolar trough, which is apparent on the mean sea level pressure (MSLP) (Figure 2). Within the trough, depressions mainly move toward the east, with the clockwise flow around these systems giving a climatological easterly wind along the Antarctic coast and westerly winds north of the trough.

The circumpolar trough is present throughout the year, and in the mean fields it has an approximate wave number 3 pattern with low-pressure centers close to 30° E, 90° E, and 150° W. This pattern affects a number of aspects of the Antarctic climate, such as the northward extension of sea ice close to the Greenwich meridian, as a result of the climatological southerly flow at this longitude. Because of the distribution of landmasses in the Southern Hemisphere, the atmospheric planetary waves have a smaller amplitude than their counterparts in the north, so the depressions play a greater role in the poleward transport of heat than in the Northern Hemisphere.

The most marked climatological low-pressure center around the continent is at 150° W and is often referred to as the Amundsen Sea Low. The presence of this low is responsible for the north-to-northwesterly flow on the western side of the Antarctic Peninsula and the relatively mild temperatures that are experienced there. It also gives a mean southerly flow off the Ross Ice Shelf and over the Ross Sea, resulting in this area being a major sea ice production region.

Figure 2 shows that MSLP values within the circumpolar trough are lowest during the spring and autumn and are higher during the summer and winter. This semiannual

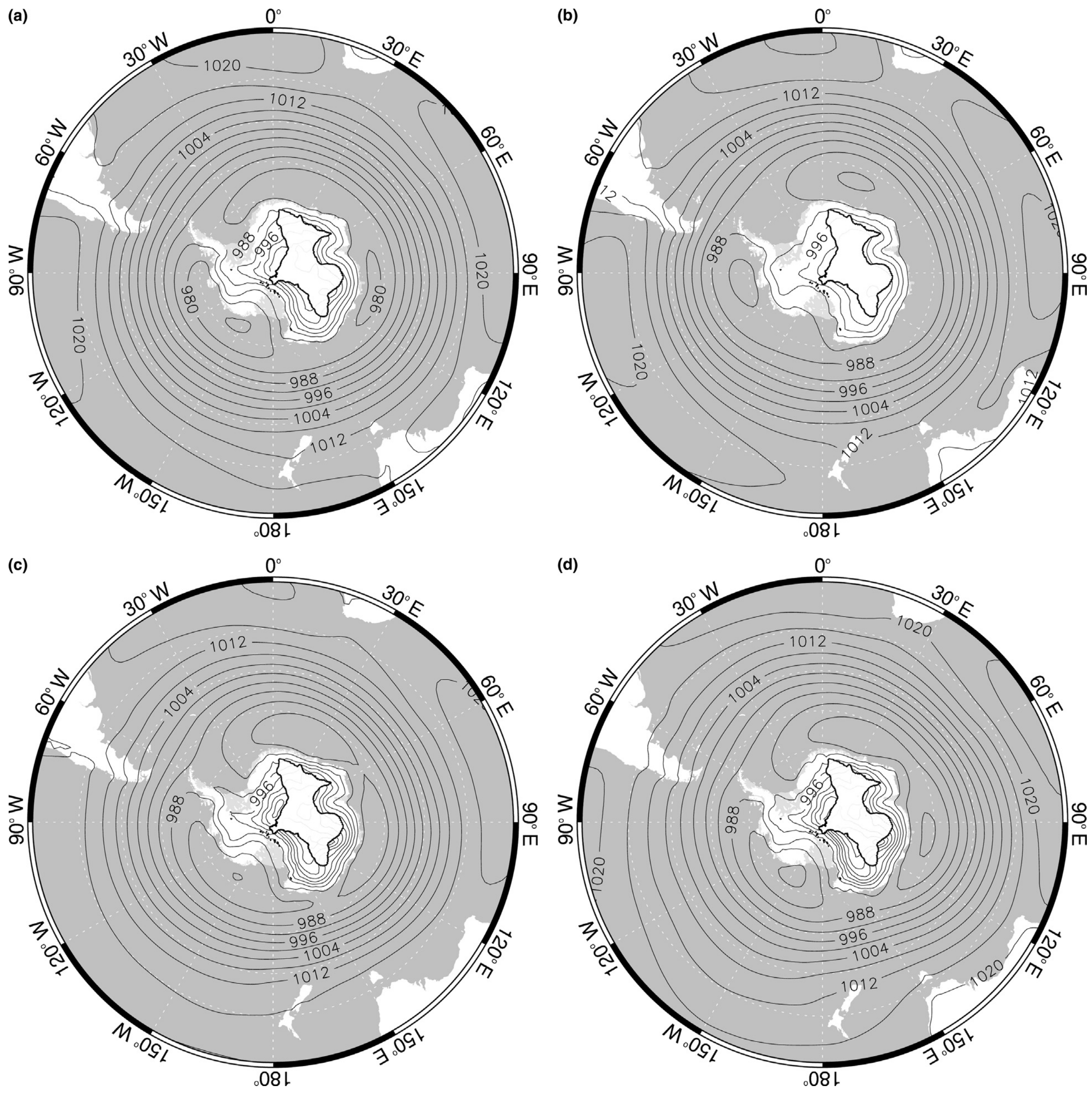

Figure 2 Average mean sea level pressure (hPa) for the four seasons for the period 1979–2010: (a) spring (September–November), (b) summer (December–February), (c) autumn (March–May), and (d) winter (June–August).

oscillation can be seen in the MSLP observations from the coastal stations and also in the number of reports of precipitation. The oscillation is a result of changes in the position and depth of the circumpolar trough over the year, with it being further south (north) and deeper (weaker) in autumn and spring (summer and winter). The oscillation is present because of the phase differences between the seasonal cycles of temperature over the Antarctic continent and Southern Ocean. Across the Antarctic, temperatures drop very rapidly at the start of winter, while over the ocean the minimum is in late winter and early spring. This results in the movement of mass between high latitudes and midlatitudes, giving rise to the semiannual oscillation.

Satellite imagery has revealed that over the Southern Ocean, there are a large number of mesoscale low-pressure systems, which are also known as mesocyclones or polar lows. These have a horizontal length scale of less than 1000 km and a lifetime of less than 1 day, so they are difficult to represent and forecast in numerical weather prediction systems. However, they can have a major impact on the weather experienced at coastal sites and so are important in forecasting processes. At the moment, they tend to be predicted using a 'nowcasting' approach, with the systems being identified on satellite imagery and advected with the low- to medium-level tropospheric flow. Although mesocyclones are rare over the high Antarctic Plateau, they are a common feature on the ice shelves. Here, there is low-level convergence of air that has descended from the plateau, which aids the spin-up of vortices, coupled with the presence of mild, oceanic air masses that provide moisture for cloud formation.

Because of the rapid increase in elevation inland of the coast, few major weather systems penetrate far into the interior of the continent. However, satellite imagery does show that some frontal bands associated with depressions in the circumpolar trough can be identified on the plateau, although automatic weather station data suggest that the pressure signals across these features are small. The conditions that favor depressions having an impact in the interior are amplified planetary waves and strong northerly steering flow aloft. Under such conditions, mild air masses over the plateau can give relatively large falls of precipitation, resulting in a significant fraction of the year's accumulation falling in 1 or 2 days. When the planetary waves are strongly amplified, maritime air masses can affect the South Pole and even Vostok Station on the high plateau of East Antarctica, but such conditions are rather rare.

The Role of Sea Ice

The presence and extent of sea ice across the Southern Ocean have a major impact on the climate of the Antarctic. Unlike in the Arctic, most of the sea ice melts by the late summer, so by February there is on average only about 3.5×10^6 km^2 of ice, most of which is located over the western Weddell Sea and along the coast of West Antarctica. Through the autumn and winter, the sea ice advances in a divergent fashion around the whole continent, reaching a maximum in September, when the mean extent is about 19×10^6 km^2.

The Antarctic sea ice is generally about 1 m thick, with some multiyear ice being 2 m or more in thickness where it has been subject to ridging and rafting. The ice provides an effective cap on the upper layers of the ocean, limiting the fluxes of heat and moisture into the lower layers of the atmosphere. However, the effects of the many weather systems over the Southern Ocean on the sea ice is to open up linear cracks (leads) or larger areas of open water (polynyas), which can provide local sources of heat or moisture, resulting in cloud. This can be important for the climates of the coastal stations during the winter months when the opening up of coastal leads and polynyas can significantly increase the temperature and humidity, sometimes leading to fog formation.

An area that is particularly sensitive to the presence or absence of sea ice is the western side of the Antarctic Peninsula. Here, the sea ice passes north–south along the coast during its annual cycle, and years of extensive (limited) sea ice are notably colder (warmer).

Temperature

Much of the Antarctic is extremely cold because of the combined effects of the long period of winter darkness; the high albedo of the snow surface, which results in the reflection of much of the summer incoming solar radiation back to space; and the high elevation, which limits the penetration of maritime air masses into the interior. The Antarctic atmosphere is characterized by a very strong surface temperature inversion, with temperatures increasing with height over the lowest few hundred meters of the atmosphere. The temperature inversion is strongest in winter on the high plateau and is the result of the intense radiative cooling of the surface and the low wind speeds that give little vertical mixing. The mean strength of the winter inversion (i.e., the temperature difference between the surface and the maximum temperature in the lower troposphere) varies from about 5 °C in the coastal region to more than 25 °C over the highest parts of East Antarctica.

Across the Antarctic, there is a very large range of annual mean surface air temperatures, although it is only in the northernmost part of the Antarctic Peninsula that mean summer temperatures rise above freezing. Over the Antarctic Peninsula and along the coast of East Antarctica, the annual cycle of temperature is similar to those found in midlatitudes, with a broad summer maximum and a minimum in July or August. However, at more southerly latitudes, the cycle is different, with a sharp summer maximum and a 'coreless' winter, during which temperatures vary by only a small amount. This form of the annual cycle comes about for a number of reasons, including the abrupt change in solar radiation at the start and end of the period of austral darkness, the effects of the semiannual oscillation on the annual cycle of advection of warm air into the Antarctic, and the heat reservoir effect of the Antarctic snow pack.

The plateau of East Antarctica experiences the lowest temperatures on Earth, with Vostok Station (78.5° S, 106.9° E, 3488 m elevation) having an annual mean temperature of −55.4 °C. The station has recorded the lowest temperature measured at the surface of the Earth, when on 21 July 1983 the temperature dropped to −89.6 °C. This occurred during a period when there was very little cloud, the wind speed was very low, and the winds blew around the station, limiting the advection of warmer maritime air. A station has recently been established at Dome Argus at an elevation of 4083 m above sea level, and early observations suggest that it is typically 5–6 °C colder than Vostok. It therefore has the potential to record an even lower extreme surface temperature than Vostok.

At higher levels in the troposphere the Antarctic atmosphere is strongly stratified, much more so than in the midlatitude areas of the Southern Hemisphere. This is the case in all seasons, with the stability being strongest below about 4 km during the winter. Temperature data from radiosonde ascents usually show a tropopause in summer, but it can become very indistinct during the winter when the stratosphere cools rapidly.

The Wind Field

The strong, persistent, and directionally constant near-surface winds recorded at a number of sites around the Antarctic are one of the most remarkable features of the continent's climate. Many of the winds at stations around the coast of East Antarctica are katabatic in origin and occur because of the drainage of cold, dense air at low levels from the interior plateau to the coast. Figure 3 shows the near-surface streamlines across the continent derived from the output of a high-resolution weather-forecasting model. These show that much of the flow originates in the higher parts of East Antarctica and flows

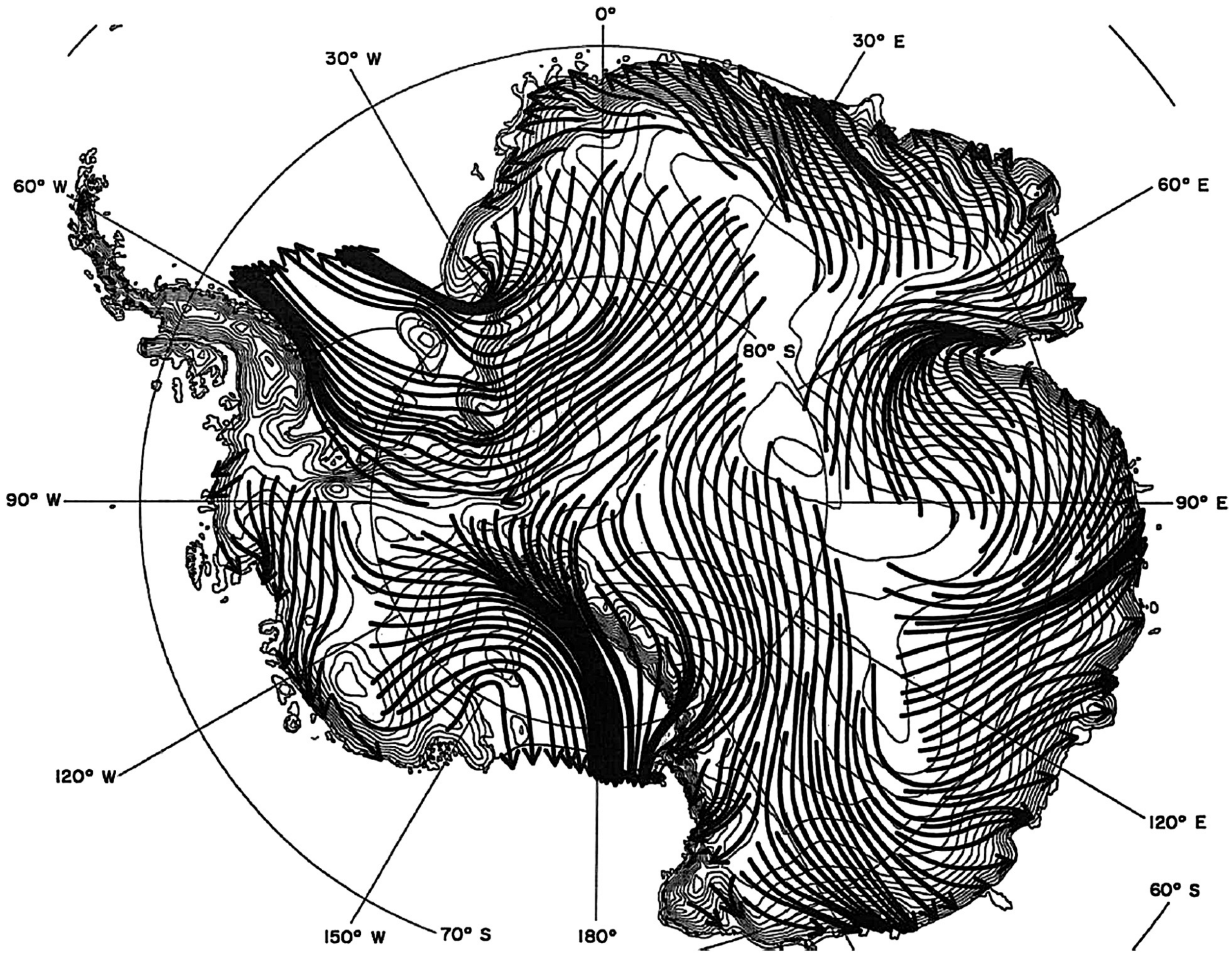

Figure 3 Near-surface mean streamlines for the period June 2003–May 2004 from the Antarctic Mesoscale Prediction System. Reproduced from Parish, T.R., Bromwich, D.H., 2007. Reexamination of the near-surface airflow over the Antarctic continent and implications on atmospheric circulations at high southern latitudes. Monthly Weather Review 135, 1961–1973. Used by permission of the American Meteorological Society.

toward the coast, often converging toward certain preferred coastal locations. The katabatic winds are most pronounced during winter, when there is no incoming solar radiation, and a large pool of cold air over the interior is formed to feed the katabatic flow.

Surface winds over the interior show a high directional constancy, indicating that they are dictated by the local orography. The wind speeds are closely related to the slope of the orography, with the strongest winds being measured at stations on the coastal escarpment and the weakest on the parts of the plateau with the smallest orographic gradient. Along the coast of Adélie Land, the orography channels the katabatic flow onto a small stretch of coast, resulting in very strong and persistent winds with a very high directional constancy. It was in this area that Douglas Mawson's 1912–13 expedition recorded the Earth's highest annual mean wind speed of 19.4 m s^{-1} and gale-force winds on all but one of 203 consecutive winter days.

As the katabatic winds descend from the plateau, they interact with the synoptic-scale weather systems within the circumpolar trough. The northerly winds to the east of the lows tend to suppress the southerly katabatic flow, while the katabatics are enhanced by the southerly flow to the west of the depressions. The Coriolis force also affects the katabatic winds, tending to turn them to the left so that they merge with the coastal easterlies on the southern side of the circumpolar trough. The near-surface flow therefore appears as an anticyclonic vortex, with cold air outflow from the continent. In some parts of the coastal region, such as south of the Weddell Sea, the coastal easterly flow comes up against high orography, and the cold, stably stratified air at low levels does not have the kinetic energy to cross the barrier. The air is then dammed up against the barrier until a pressure gradient develops that results in the air moving north as a 'barrier wind.' With the strong static stability encountered at low levels in the Antarctic, barrier winds are relatively common in the coastal areas of the continent.

Clouds and Precipitation

Clouds are very important in the Earth's climate system as they can reflect a high proportion of incoming solar radiation back to space. However, since the surface of the Antarctic already has a high albedo by virtue of its year-round snow cover, clouds over the continent tend to have less of an effect on the incoming solar radiation because the surface and cloud have similar albedos. Nevertheless, clouds play a very important part in controlling surface temperatures through their effect on the long-wave radiation budget. In cloud-free conditions, the dry atmosphere allows most of the emitted terrestrial radiation to escape to space, resulting in very low temperatures. However, when thick cloud cover is present, surface temperatures are much higher because of the downward long-wave radiation emitted from the cloud.

Since most of the research stations are located in the coastal region, it is difficult to get an accurate picture of the cloud distribution across the continent. However, using in situ data and satellite imagery, climatologies of cloud cover have been prepared. These suggest that the highest fractional cloud cover is found over the ocean areas north of the edge of the continent, with about 85% cloud cover throughout the year near 60° S. In the coastal area near 70° S, the surface observations indicate that the total cloud cover is about 45–50%, with little seasonal variability and only a small decrease during the winter months. Inland of the coast, the amounts of thick cloud decrease rapidly, since few synoptic-scale weather systems are found over the interior. However, the inland areas are characterized by extensive, very thin cirrus cloud, which gives a semipermanent veil of ice crystals. This type of cloud causes problems for observers, who have to decide whether to report no cloud or 100% cloud cover. The mean annual percentage cloud cover at the South Pole is 45%, but anyone using such statistics has to be aware of the nature of the cloud that occurs there and the problems facing observers of how to report the thin cirrus.

The amount of precipitation across the Antarctic generally follows the distribution of thick cloud. In other words, the highest precipitation totals are found in the coastal region, with a rapid decrease inland. Figure 4 shows the mean annual net accumulation (precipitation–evaporation) across the continent as estimated from ice cores. These glaciological

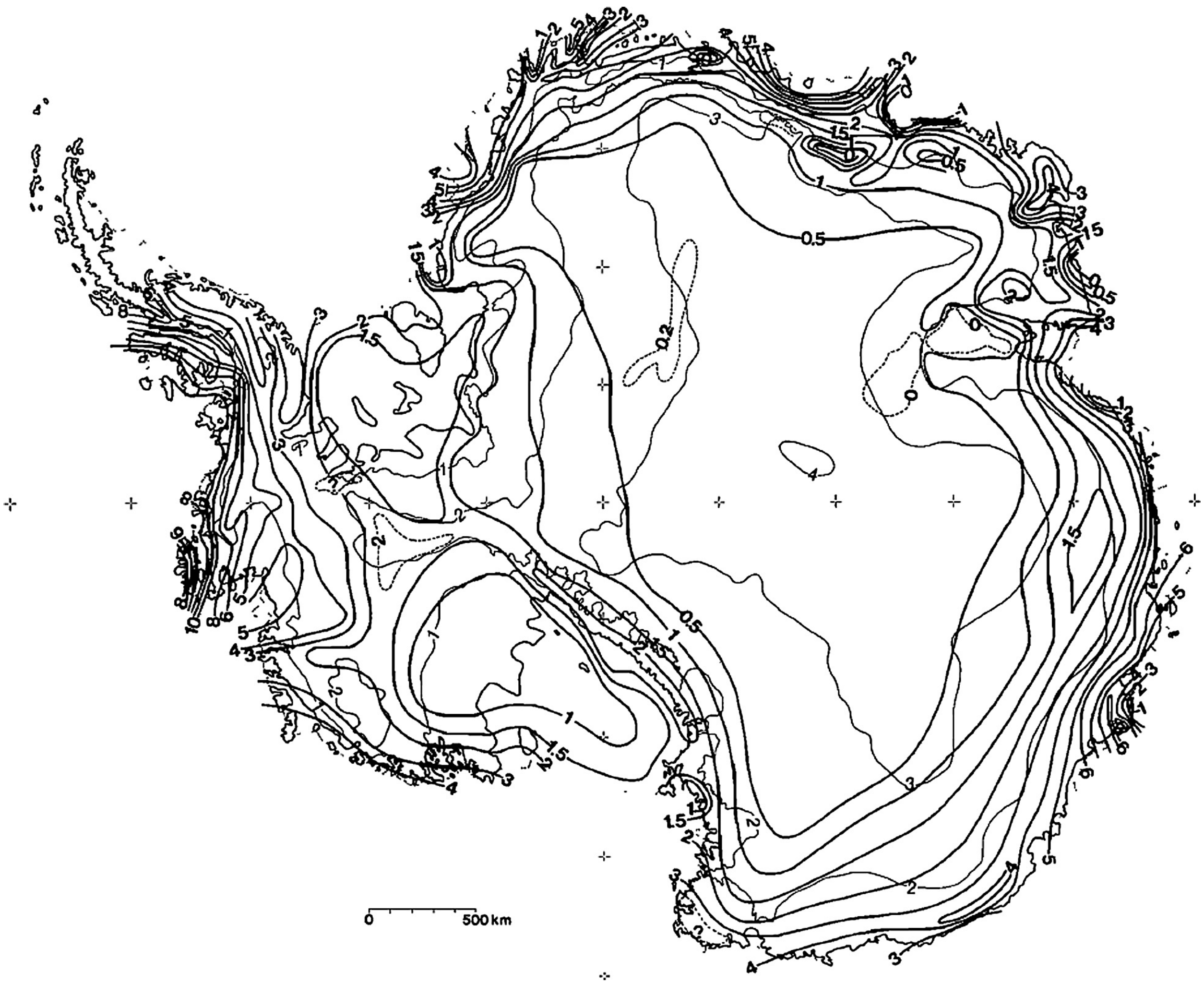

Figure 4 An estimate of snow accumulation across the Antarctic based on ice core data. Isopleths are in units of 100 kg m^{-2} $year^{-1}$ (or, equivalently, 100 mm $year^{-1}$). Reproduced with permission from Bromwich, D.H., 1988. Snowfall in high southern latitudes. Reviews in Geophysics 26, 149–168. © American Geophysical Union.

measurements of accumulation are very similar in magnitude to those of precipitation, since there is little evaporation in the interior. However, they are not identical, because of the effects of blowing snow and summer melt in some areas. But with so few in situ measurements of precipitation, they have been used extensively as a proxy for precipitation. In Figure 4, it can be seen that no data are presented for the northern part of the Antarctic Peninsula because precipitation varies so rapidly in this area. The area of greatest precipitation is along the coast of the southern Bellingshausen Sea, where there is over 1 m water equivalent per year. This peak is found because of the high frequency of northerly airstreams bringing mild, moist air onto the coast. Other areas of high precipitation are found where there is frequent cyclonic activity, such as north of Enderby Land and along the coast of East Antarctica. Some of the smallest amounts of accumulation are found on the low-lying Ross and Ronne Ice Shelves. Inland of the coast, the amounts of accumulation drop very rapidly, so over most of East Antarctica there is less than 50 mm of accumulation per year.

A number of estimates have been made of the mean and total snow accumulation across the whole of the Antarctic ice sheet using glaciological data gathered in situ. Studies suggest that the mean accumulation is about 160 mm water equivalent per year, which is equivalent to a total input of approximately 2205 Gt year^{-1}.

The mechanisms behind precipitation are different across the Antarctic, with most precipitation in the coastal area coming from synoptic-scale weather systems. In the interior, most falls in the form of clear-sky precipitation, also known as 'diamond dust.' This is an almost continuous fallout of ice crystals from a thin veil of cirrus cloud covering the sky. Clear-sky precipitation has not been investigated extensively, but is thought to result from the cooling of air over the plateau and the formation of ice crystals as the precipitation descends into the cold near-surface layer. Just inland of the coast, there is a zone where both synoptic-scale weather systems and clear-sky precipitation play a role. Over Queen Maud Land, studies have shown that clear-sky precipitation falls on most days, but that a few major weather systems can give a significant fraction of the year's accumulation in a few days.

Climate Variability and Change

The high-latitude areas exhibit a greater degree of interannual and interdecadal climate variability than locations in the tropics or midlatitudes. This is a result of the complex interactions between the atmospheric circulation and the cryosphere, including a number of positive-feedback mechanisms that amplify climate variability. However, our understanding of climate variability and change is limited in the Antarctic because of the shortness of the in situ records and the fact that most research stations are on the coast, with only the Vostok and Amundsen-Scott stations providing long records from the interior.

Standard deviations of the annual mean surface air temperatures for a number of stations are given in Table 1. These stations are located in different climatic regimes: at the South Pole (Amundsen-Scott Station), on the high interior plateau (Vostok), on the coast of East Antarctica (Mawson), and on the Antarctic Peninsula (Faraday/Vernadsky and Bellingshausen). Most of the stations have very similar variability of temperature, which is perhaps surprising considering the very different environments in which they are located. Variability of depression activity in the coastal area is to be expected, which would vary the temperatures. However, the figures show that conditions in the interior also vary from year to year as a result of changes in atmospheric circulation. But the station with the largest variability is Faraday/Vernadsky station on the western side of the Antarctic Peninsula. This station is located close to an area of large sea ice extent variability, and small changes in ice extent are amplified into much larger surface temperature variations.

The primary mode of Antarctic climate variability is the southern annular mode (SAM), which consists of synchronous pressure anomalies of opposite signs in midlatitudes and high latitudes. Thus, the SAM can be considered an index of the strength of the midlatitude westerlies. When pressures are below (above) average over Antarctica, the SAM is said to be in its high (low) index or positive (negative) phase. The SAM contributes a significant proportion of Southern Hemisphere climate variability (typically ~35%) from high-frequency to very low-frequency timescales. The SAM shows a high level of intrinsic variability, but is also affected by the amount of volcanic aerosol in the atmosphere, the concentration of greenhouse gases, and the Antarctic 'ozone hole.' The SAM has shown significant positive trends during autumn and summer over the past few decades, resulting in a strengthening of the circumpolar westerlies by about 15%. It has been suggested that the more positive SAM since about 1980 has mainly been a result of the 'ozone hole,' although during the first decade of the twenty-first century, the SAM

Table 1 Mean temperature data for selected Antarctic stations

Station	*Latitude*	*Longitude*	*Elevation (m)*	*Period*	*Mean annual temperature (°C)*	*Standard deviation of the annual mean temperature (°C)*	*Mean January temperature (°C)*	*Mean July temperature (°C)*
Vostok	78.5° S	106.9° E	3488	1958–2010	−55.3	0.9	−32.1	−66.8
Amundsen-Scott	90.0° S	–	2800	1957–2010	−49.4	0.7	−28.1	−60.0
Mawson	67.6° S	62.9° S	16	1955–2010	−11.2	0.7	+0.1	−18.0
Faraday/Vernadsky	65.4° S	64.4° W	11	1951–2010	−3.7	1.6	+0.7	−8.7
Bellingshausen	62.2° S	58.9° W	16	1969–2010	−2.3	0.8	+1.5	−6.5

became more neutral at a time when the ozone hole was still showing no clear sign of recovery.

The near-surface air temperature trends since 1951 at selected Antarctic stations are presented in Figure 5. The data show a strong dipole of change, with significant warming across the Antarctic Peninsula but with very small trends across the rest of the continent. The largest warming trends in the annual mean temperatures are found on the western and northern parts of the Antarctic Peninsula. Here, Faraday/Vernadsky station has experienced the largest statistically significant (<1% level) trend in annual mean temperature of +0.54 °C per decade for the period 1950–2009. The rate of warming decreases away from Faraday/Vernadsky, with the long record from Orcadas on Signy Island, South Orkney Islands, having experienced a warming of only +0.20 °C per decade. However, it should be noted that this record covers a 100-year period rather than the 60 years for Faraday/Vernadsky.

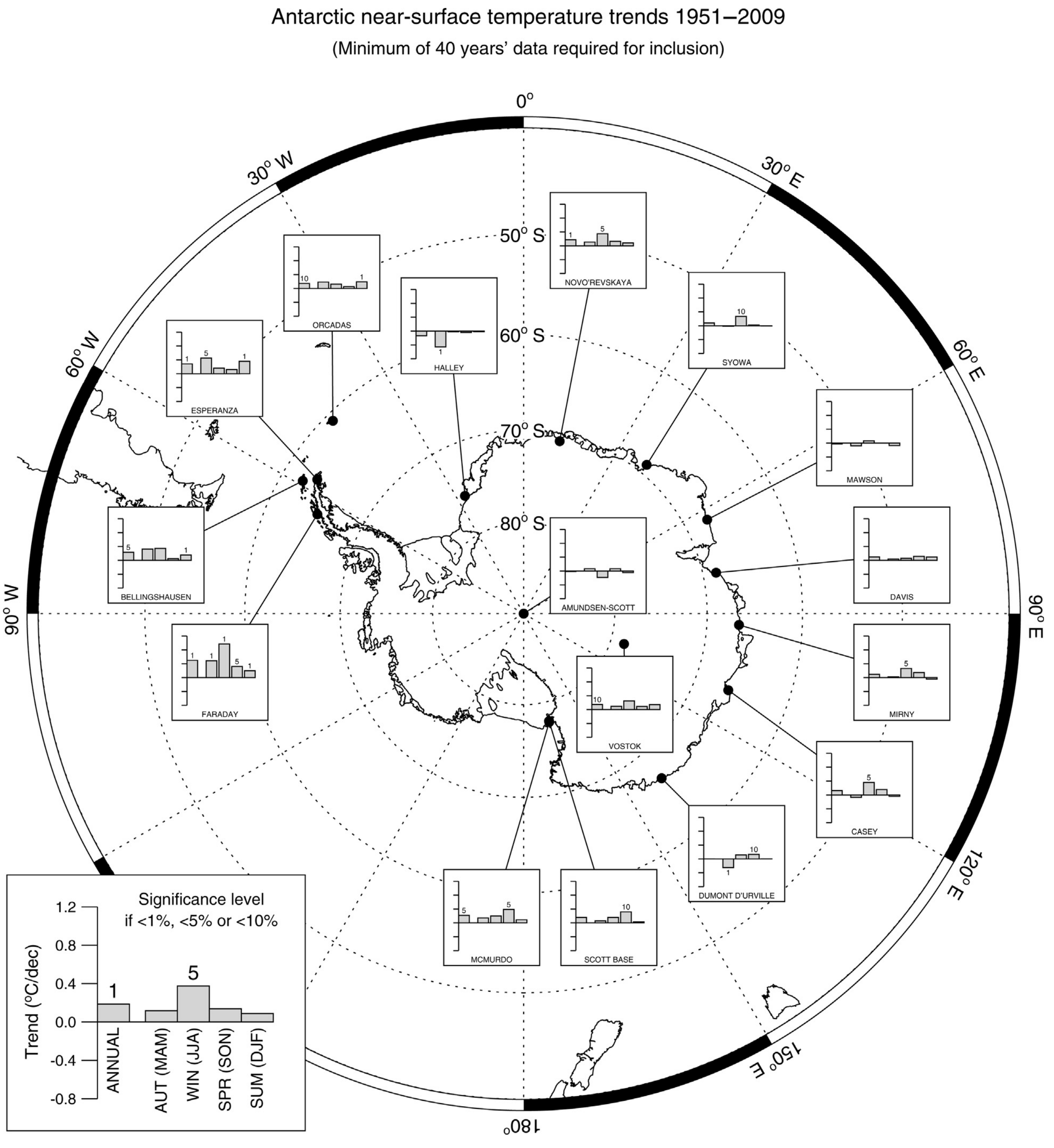

Figure 5 Antarctic near-surface temperature trends for 1951–2009. The scale in the bottom left corner indicates the warming or cooling over the full length of the station records. The numbers above the bars indicate the statistical significance by percentage.

The warming at Faraday/Vernadsky has been largest during the winter, with the temperatures increasing during that season by +1.03 °C per decade over 1950–2009. In this area, there is a high anticorrelation during the winter between the sea ice extent and the surface temperatures, suggesting that more sea ice was present during the 1950s and 1960s, with a progressive reduction since that time.

Temperatures on the eastern side of the Antarctic Peninsula have risen most during the summer and autumn months, with Esperanza having experienced a summer increase in annual mean temperature of +0.42 °C per decade over 1945–2009. This temperature rise has been linked to a strengthening of the westerlies as the SAM has shifted into a more frequent positive phase. Stronger winds have resulted in more relatively warm, maritime air masses crossing the peninsula and reaching the low-lying ice shelves on the eastern side.

Estimating temperature trends across the remote interior of the Antarctic is difficult because of the lack of staffed stations, and there has been an active debate over how far into West Antarctica the warming observed on the Antarctic Peninsula extends. With no long-term in situ records available, attempts have been made to estimate trends here using data from the coastal stations and knowledge of the spatial pattern of temperature variability. At the moment, it is thought that there has been a small warming across West Antarctic since the 1950s, but the magnitude is smaller than on the Antarctic Peninsula.

The Antarctic radiosonde temperature profiles suggest that there has been a warming of the troposphere and cooling of the stratosphere over the last 30 years, which is the pattern of change that would be expected from increasing greenhouse gas concentrations. However, the midtroposphere has warmed more in winter than anywhere else on Earth at this level. The radiosonde data show that regional midtropospheric temperatures have increased most around the 500 hPa level, with statistically significant changes of 0.5–0.7 °C per decade. The exact reason for such a large midtropospheric warming is not known at present. However, it has been suggested that it may, at least in part, be a result of greater amounts of polar stratospheric cloud during the winter.

Possible Future Change

The twenty-first century will be a period when we expect the Antarctic 'ozone hole' to recover, and we will possibly see stratospheric ozone levels returning to normal levels by 2060–70, but with greenhouse gas concentrations increasing. The 'ozone hole' has in many ways shielded the Antarctic from the impact of greenhouse gas concentration increases, but this will diminish over the coming decades.

Various scenarios of how greenhouse gas concentrations will increase during the twenty-first century have been considered by the Intergovernmental Panel on Climate Change (IPCC), but here we will examine how the Antarctic climate might evolve if CO_2 concentration increases to 720 ppm by 2100, which is one of the most frequently considered scenarios.

With a doubling of CO_2 over the twenty-first century, we expect the SAM to be even more predominantly positive in the future during all four seasons, further increasing the speed of the westerly winds over the Southern Ocean. Although a positive SAM has resulted in little warming around the coast of East Antarctica in recent decades, a doubling of greenhouse gas concentrations would result in a general warming across the continent and Southern Ocean. Estimates from the output of IPCC Fourth Assessment report models suggest that the surface warming averaged over the continent would be of the order of 3–4 °C, which is approximately the same magnitude as that over other land areas of Earth. However, the models suggest that the largest warming in the Antarctic will be across the high-latitude areas of the Southern Ocean in winter as a result of the loss of sea ice and the greater fluxes of heat into the atmosphere. Here, the models suggest a temperature increase in excess of 0.5 °C per decade.

Although the extent of Southern Hemisphere sea ice has increased slightly in recent decades, it is expected to decrease markedly during the coming century. Modeling studies have suggested that the ice extent could decrease by about 25% for the year as a whole, with a loss of around 50% in March and 20% in September.

If temperatures rise across the Antarctic over the next century, the air will be able to hold a greater amount of moisture. Since air masses are advected southward and forced up onto the Antarctic Plateau by depressions over the Southern Ocean, we can expect greater amounts of precipitation, especially in the coastal region. Estimating the increase in precipitation is difficult, but models suggest this could be of the order of 20% by 2100.

Further Reading

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