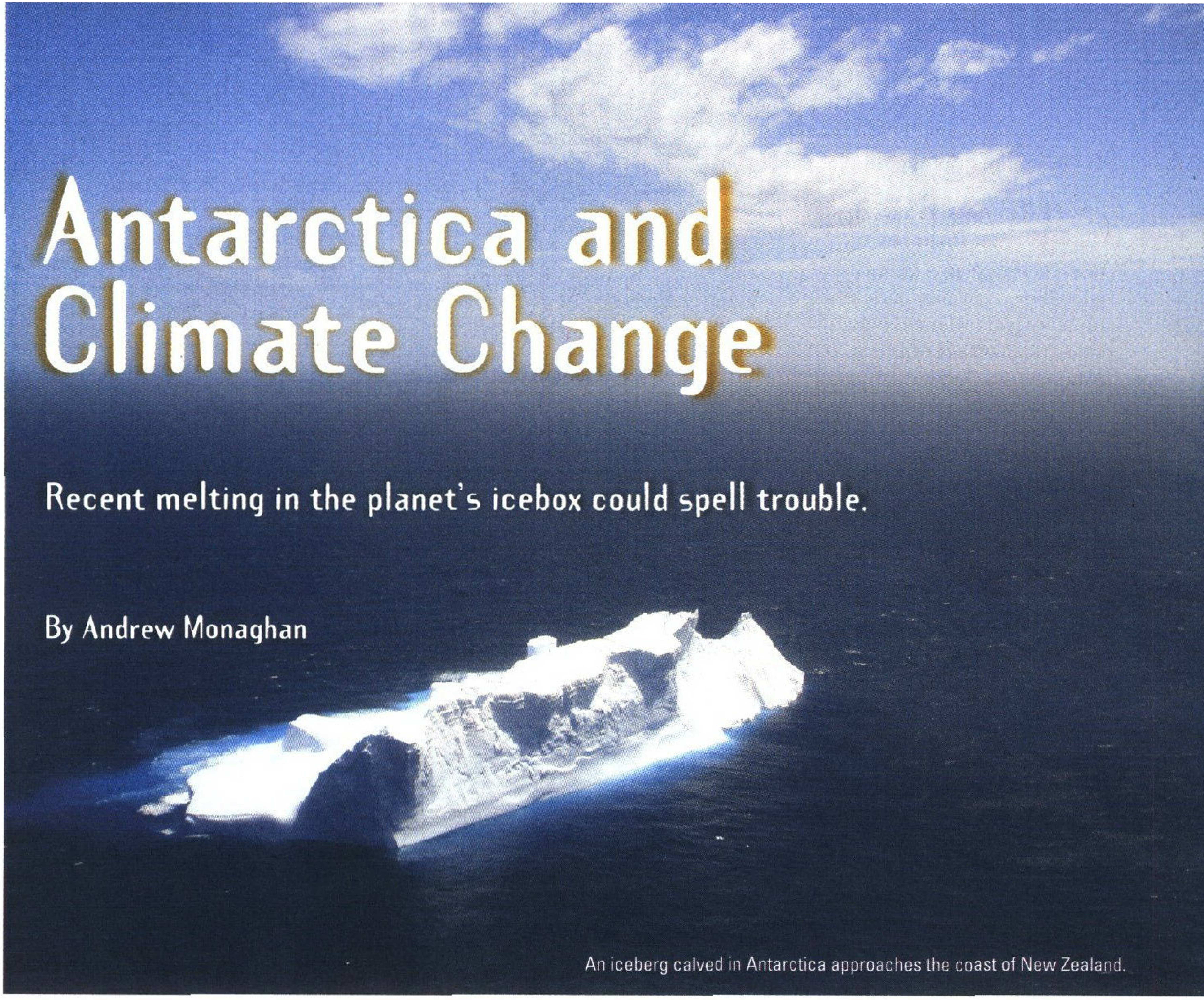
Antarctica and Climate Change

Recent melting in the planet's icebox could spell trouble.

By Andrew Monaghan



An iceberg calved in Antarctica approaches the coast of New Zealand.

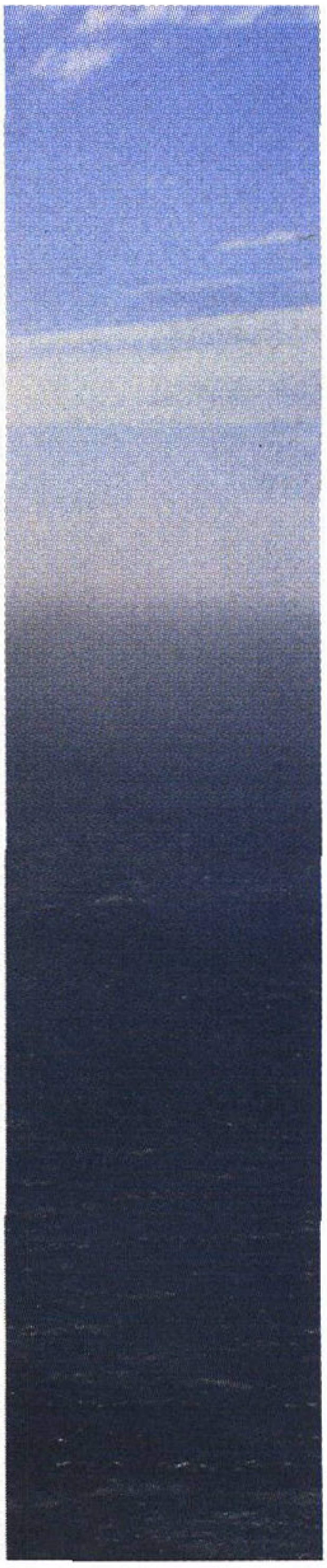
Visiting Antarctica is an incredible, almost unearthly, experience. Icebergs bigger than cities. Glaciers with cracks large enough to swallow a football stadium. A floating ice shelf the size of France. An ice cap thicker in some regions than 10 Empire State Buildings stacked on top of each other. Along with the enormity come the extremes: of the seven continents, Antarctica is the coldest, highest, driest, windiest—and of course iciest—place on Earth. Add to that "remotest," and it becomes clear why teasing the climate record out of this vast continent has been a challenge.

Geography and topography are paramount to the existence of the Antarctic ice sheets. Antarctica is positioned over the South Pole, which means it receives less of the Sun's energy over the course of a year than any other continent because of the way Earth is tilted with respect to the Sun. Additionally, about 80 percent of the sunlight that reaches Antarctica is reflected by the icy surface. It is buffered from the rest of the globe by the vast Southern Ocean, which surrounds it with an apron of water and sea ice and which enables a belt of perpetual westerly winds to encircle the continent like a gigantic curtain. The steep topography along much of the Antarctic coastal margins acts as a barrier to intense cyclones that would otherwise transport warm, moist air inland, and thus an immense polar desert—vast and incredibly dry for a place that consists of frozen water—exists in the interior of the continent.

Antarctica's shape is relatively symmetrical compared to other continents—a rough circle with the highest topography located near the middle, sloping down toward the ocean on all sides. The cold, thick ice acts as a heat sink, and the air at the uppermost elevations undergoes the most cooling and becomes denser than the air at lower elevations. In turn, the dense air generates persistent, gravity-driven winds that flow down the sloping terrain to the edges of the continent. Thus, Antarctica itself plays a major role in determining—and perpetuating—its own climate (see map). Yet that climate appears to be changing, and its fate is critical to the rest of the Earth as well.

Three Sheets to the Winds

Antarctica can roughly be divided into three regions: East Antarctica, West Antarctica, and the Antarctic Peninsula (see map). East Antarctica accounts for about 75 percent of the sur-



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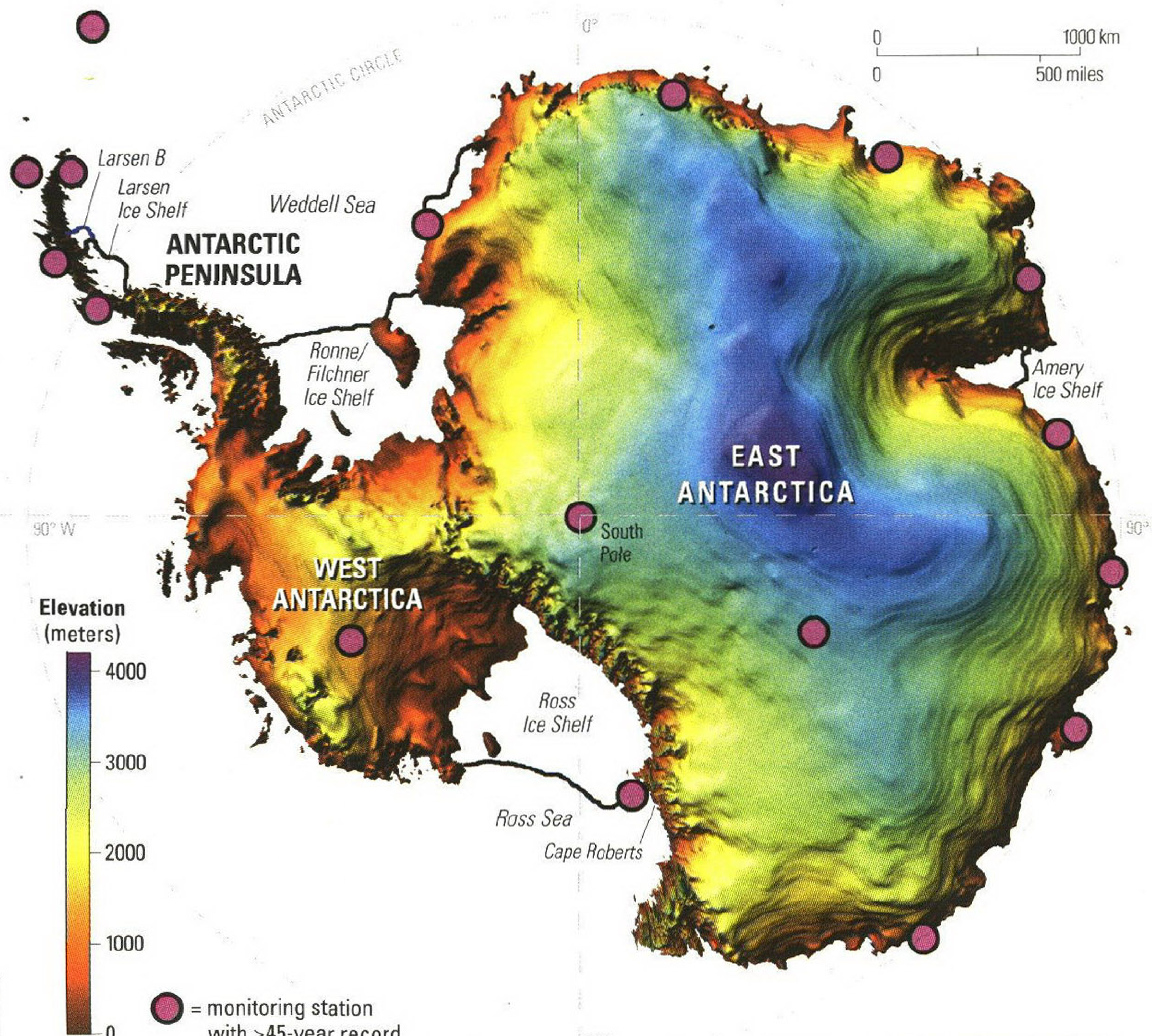


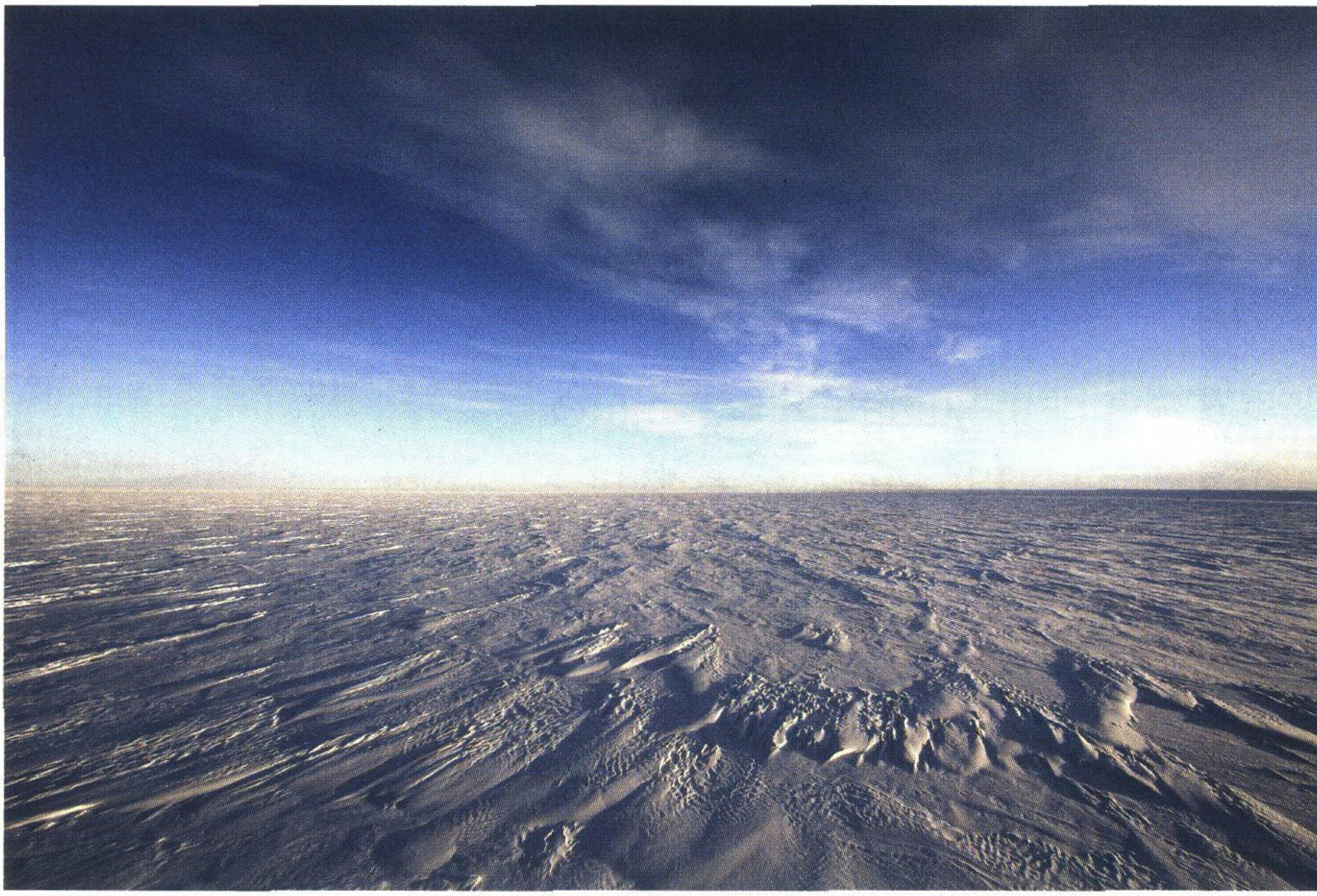
Courtesy *Bulletin of the American Meteorological Society*

Digital elevation model of Antarctica. Topography plays a first-order role in determining Antarctic climate, so maps of annual mean near-surface temperature, snowfall accumulation, and wind speed have spatial patterns that closely follow terrain elevation. The coldest, driest, and least windy regions are located at the highest reaches of East Antarctica (blue and purple), while warmer, wetter, and windier regions generally are located along the coastal margins (orange and red).

face area and is slightly larger than the United States. It is covered by the East Antarctic Ice Sheet (EAIS, pronounced to rhyme with "fleece"). EAIS is astounding, reaching a height of more than 4,000 meters at its apex and holding the water equivalent of 60 meters of global sea level. (The deepest ice core on Earth was recently drilled on EAIS at Dome C, yielding an 800,000-year record of climate history.) Like all ice sheets, the total mass of frozen water that makes up EAIS is the result of a balance between the growth of ice due to snowfall, and the loss of ice due to melting at the edges and the calving of icebergs. Changes in the "mass balance" of ice are of great concern to scientists because of the important implications for sea level. If an ice sheet is growing, it tends to lower sea level due to the additional storage of frozen water; if it is shrinking, it tends to raise sea level. Collectively, recent estimates of the mass fluctuations of EAIS suggest that it is approximately in balance.

The Greenland-sized West Antarctic Ice Sheet (WAIS; rhymes with "race") makes up about 20 percent of Antarctica's surface area and stores the frozen water equivalent of six meters of global sea level. Despite being only one-tenth the size of EAIS, WAIS is the ice sheet that has scientists chewing their fingernails. Why? First, the average elevation of WAIS is much lower than EAIS, and thus WAIS is more susceptible to inland penetration by the relentless succession of cyclones that encircle the continent and transport warm, moist air from lower latitudes. If these cyclones become more frequent or more intense, as many climate models project, WAIS may become much warmer.

Second, and more importantly, WAIS is a marine-based ice sheet. Unlike the primarily land-based EAIS, the bottom of WAIS rests below sea level, and therefore ocean water is constantly in contact with the edges of WAIS. Studies of the responses of marine-based ice sheets to past climate fluctuations suggest that they can retreat quickly when ocean temperatures rise because of increased melting at the ocean-ice interface. (The ocean is effective at melting ice because water has a large capacity for storing and conducting heat.) In addi-



Keith Vanderlinde, National Science Foundation

Landscape typical of the East Antarctic Ice Sheet. Bedrock is more than two miles (3.2 kilometers) below this surface.

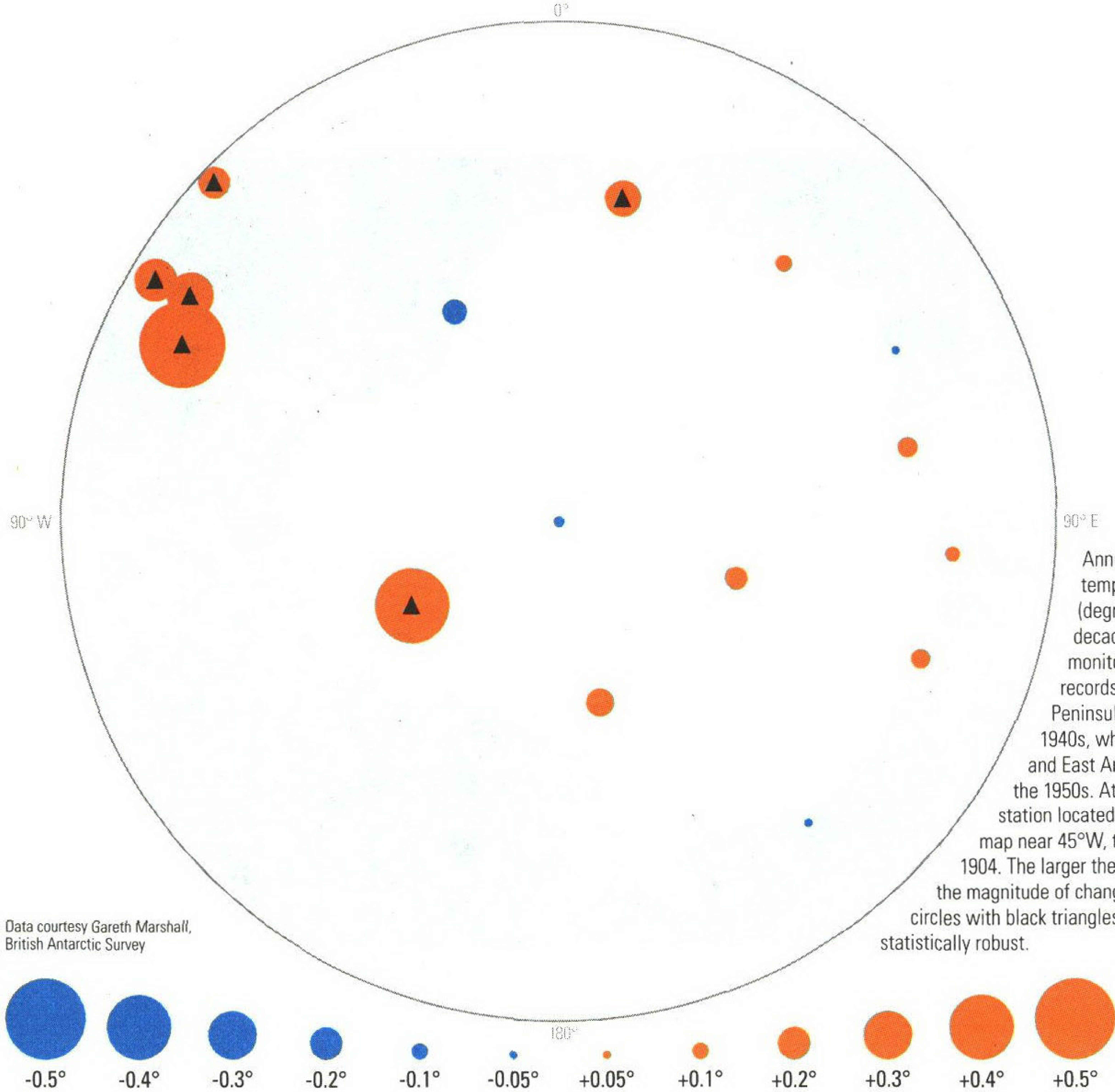
tion, the ocean water may begin to work its way underneath the base of the ice, which can accelerate melting and lead to greater instability. In recent years, regional ocean warming is thought to be the cause for the acceleration of several of the major glaciers that comprise WAIS due to enhanced melt at their edges. WAIS is shrinking overall and therefore contributing to sea-level rise.

The third region, the Antarctic Peninsula, is a California-sized finger of West Antarctica that projects northward into the Southern Ocean. The Peninsula is about 4 percent of Antarctica and has a milder climate that is strongly influenced by the ocean that surrounds it on three sides. The northern half of the Peninsula spans latitudes analogous to Scandinavia in the Northern Hemisphere, and temperatures frequently reach the melting point during the summer months. The landscape is largely glaciated, and the mountainous spine that defines the northern Peninsula is characterized by alpine glaciers like those found in Norway or Alaska. The volume of ice on the Antarctic Peninsula is small compared to that of WAIS and EAIS. However, due to strong warming and additional factors discussed below, glacial retreat there is widespread and therefore is contributing to sea level rise. Perhaps more alarmingly, recent reports indicate that the pattern of glacial retreat is migrating southward toward continental Antarctica and WAIS.

Temperature Trends

Near-surface temperature trends are a widely used proxy of climate change, in part due to the broad global availability of long-term records. In contrast to widespread increases worldwide, instrumental records, augmented by satellite and computer-modeled records, suggest that annual near-surface temperatures over most of East Antarctica have only changed modestly since the 1950s. Over West Antarctica, where several large glaciers have accelerated during the past decade, the instrumental record of near-surface temperature is poor, and satellite measurements are less reliable because of problems that arise due to the cloudier conditions there.

To fill the gaps, records of oxygen isotopes from newly collected ice cores extracted across the WAIS have been employed to reconstruct West Antarctic temperatures, indicating that the region has probably warmed by 2°C since 1950. What's more, the ice core records show that large temperature fluctuations over West Antarctica are tied to ocean temperatures in the tropics, indicating that the WAIS is much more vulnerable to global climate changes than its higher, drier East Antarctic counterpart. The WAIS warming is consistent with large temperature increases on the adjacent Antarctic Peninsula, where good instrumental records yield highly reliable results. Strong



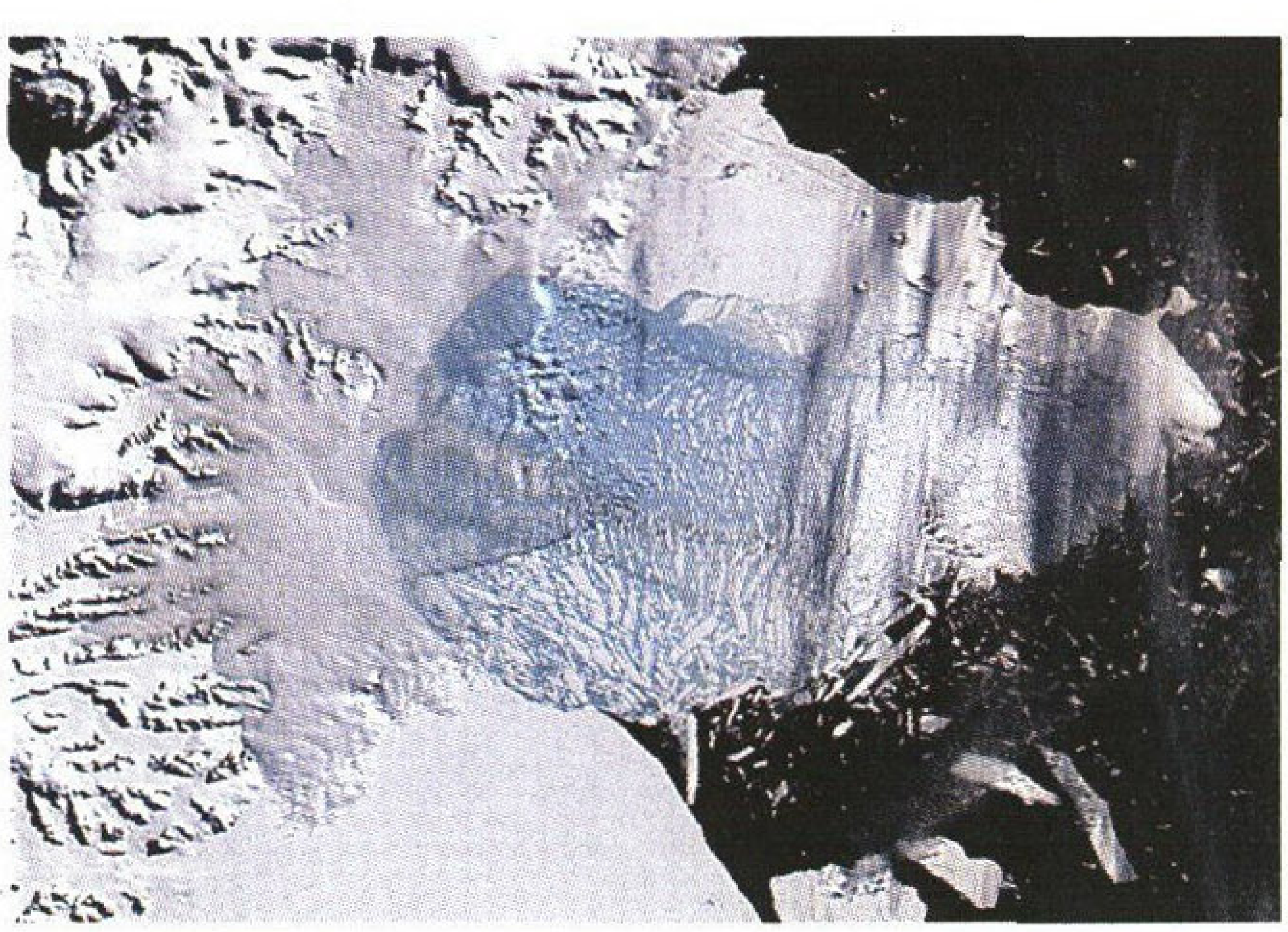
Data courtesy Gareth Marshall, British Antarctic Survey

Annual near-surface temperature trends (degrees Celsius per decade) at Antarctic monitoring stations. The records on the Antarctic Peninsula began in the 1940s, while those in West and East Antarctica began in the 1950s. At Orcadas, an island station located at the edge of the map near 45°W, the record began in 1904. The larger the circle, the greater the magnitude of change. Only for those circles with black triangles is the trend statistically robust.

temperature increases of up to 3°C since the 1950s have been among the largest warming signals on Earth. The substantial warming on the Peninsula has been cited as a contributor to the dramatic breakup of a Rhode Island-sized portion of the Larsen B Ice Shelf in 2002, which ocean-bottom sediment records suggest existed for at least the prior 10,000 years.

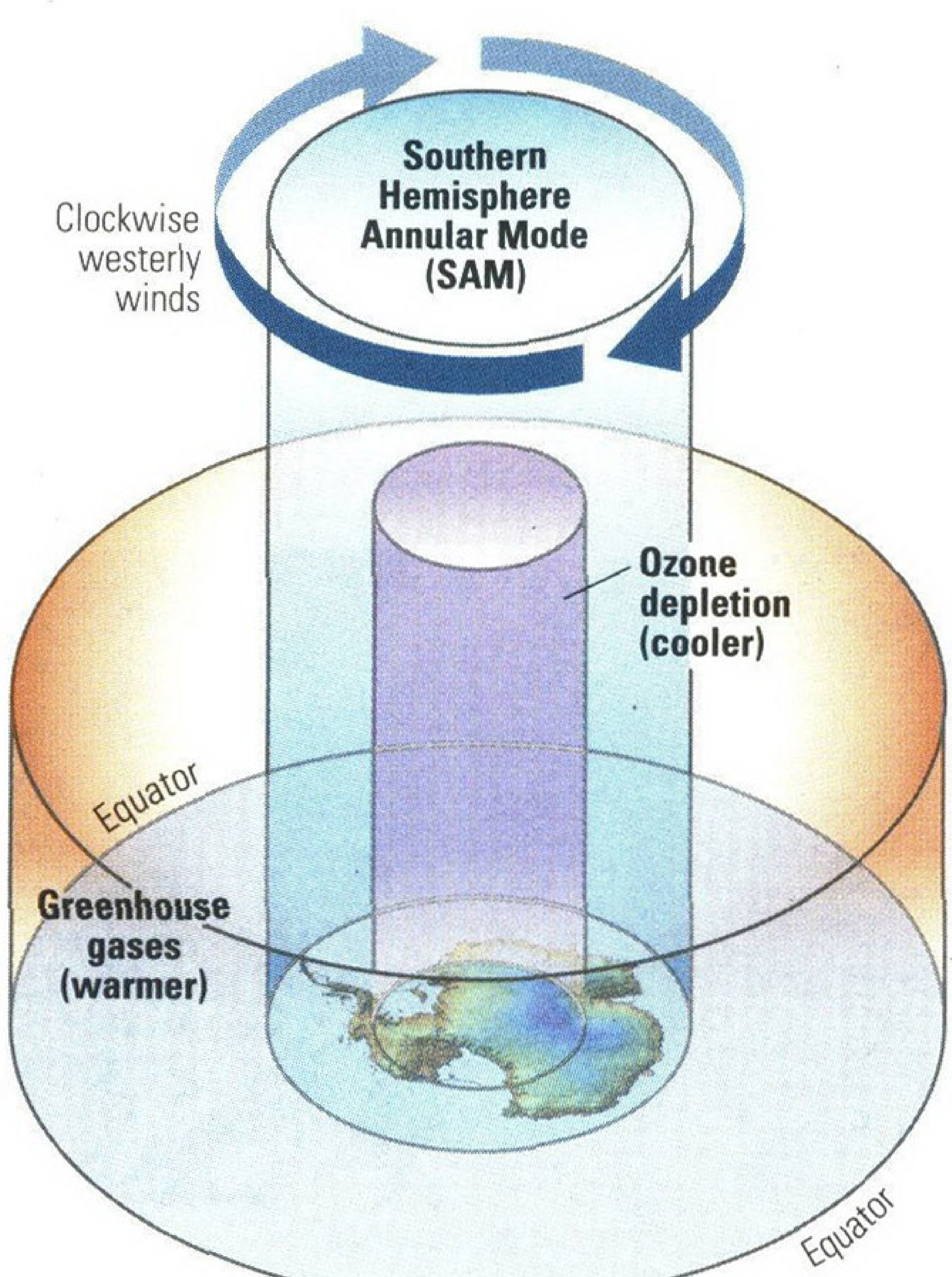
The uneven pattern of temperature trends over Antarctic land surfaces during the past half-century—muted change at the East Antarctic stations, but strong warming on the Peninsula that extends inland over WAIS—has been attributed partly to a strengthening belt of westerly winds (*from* the west) that encircles the continent and is called the Southern Hemisphere Annular Mode (SAM; see figure, p.10). This "donut" of winds extends from the surface to more than 20 kilometers aloft. The strength of the winds is determined by the atmospheric temperature gradient (the difference in temperatures) between the middle-and-tropical latitudes and the south polar region. The gradient has increased during certain seasons in recent years, causing the winds to strengthen.

Over East Antarctica, the stronger westerly winds counteract the prevailing winds that drain from the continent and which blow partially eastward due to the rotation of the Earth (the Coriolis effect). The result is weaker near-surface winds. In turn, the weaker winds have less capacity to erode the strong temperature inversion at the Antarctic surface (the layer of very cold air just above the Antarctic ice). The weaker winds cannot mix the relatively warm air above the inversion



http://visibleearth.nasa.gov/

March 5, 2002: the large blue area shows where the previously solid Larsen B ice shelf has broken up into icebergs and smaller "bergy bits."



Above: View from near Cape Roberts on the Ross Sea. The Transantarctic Mountains run from the Ross Sea to the Weddell Sea, dividing East and West Antarctica.
Left: Schematic of the Southern Hemisphere Annular Mode (SAM) over Antarctica (not drawn to scale).

down toward the surface as effectively as they previously did, and thus the surface of East Antarctica has not warmed as it may have otherwise.

Over the Antarctic Peninsula and WAIS, the impacts of the strengthening westerly winds on near-surface temperatures appear to be more variable compared to EAIS. For example, the SAM has enhanced summer warming on the eastern side of the Peninsula by increasing the occurrences of relatively warm winds that descend from the nearby mountain slopes; on the other hand, it has suppressed warming slightly on the western side, for reasons that are not well understood. Overall, the effect of the SAM on temperature changes over the Antarctic Peninsula and WAIS has been weaker than for EAIS. Thus, other causes also appear to play prominent roles. Recent findings suggest that the heat-trapping effect of increasing greenhouse gases is also contributing to the strong warming on the Antarctic Peninsula.

To determine the cause of recent and future temperature trends in Antarctica it is critical that scientists understand why the latitudinal temperature gradient has increased and in turn strengthened the SAM. This is especially true for EAIS, by far the largest region of Antarctica, and where the SAM has exerted a strong influence on climate variability. Studies using

Courtesy Eric Cravens (USGS/NICL, 2007)

Processing an ice core from the West Antarctic Ice Sheet.

computer models of the atmosphere suggest that the SAM is due partly to human causes, including increases of industrial greenhouse gases and ozone depletion high above Antarctica due to chlorofluorocarbons. The formation of the ozone "hole" over Antarctica each spring decreases the absorption of solar energy and cools the high reaches of the atmosphere that lie poleward of the SAM. Equator-ward of the SAM, the enhanced heat-trapping effect of greenhouse gases has caused net warming in the middle and lower atmosphere. Internal (mainly natural) fluctuations in the climate system, such as ocean temperature oscillations, also play a key role in driving the SAM trends.

Rising Seas

Whether the SAM will continue strengthening in the coming decades is still unknown because the relative importance of greenhouse gases, ozone, and the internal variability of the Antarctic climate system is uncertain, as is how each factor may change. For example, it is unclear how quickly greenhouse gases will increase during the twenty-first century due to ever-shifting global political and social factors. It is also unclear how quickly the ozone hole will recover as a result of the Montreal Protocol to phase out ozone-depleting substances. However, the annual springtime minimum ozone amounts that define the ozone hole have leveled off during the past decade, and over roughly the same period the upward SAM trend has weakened. It is still unknown whether this is due to coincidence, but if the SAM trend continues to weaken (or reverses), other influences that in recent decades have taken a back seat to the SAM may play a more dominant role in determining temperature trends over all of Antarctica. These include the direct effect of heat-trapping greenhouse gases, possible reductions in sea ice, and the increase of ocean temperatures near Antarctica and in the tropics. There is already proxy evidence that widespread warming may occur over Antarctica if and when the SAM subsides; a recent study found that extensive temperature increases have occurred in the middle atmosphere (above the Antarctic surface) since the early 1970s during winter, a season during which the SAM trends are weak.

Getting a handle on the magnitude and extent of Antarctic climate change during the twenty-first century is a top priority of scientists, largely because of the potential implications for sea level rise and the subsequent impacts on heavily populated coastal areas. During the twentieth century, sea level rose by about 18 centimeters. However, during the past decade, as global warming has become stronger and the retreat of the Greenland and West Antarctic ice sheets has accelerated, so has the rate of sea level rise. Thus, projections for twenty-first century sea level rise are higher than for the twentieth century, but the range of estimates is large because the response of the ice sheets to warming is not well known.

Increased snowfall over the ice sheets due to global warming is one factor that contributes to uncertainty in sea-level rise projections. More snowfall means that EAIS and WAIS will

Background photo: DJ Jennings, National Science Foundation

The Challenge of Determining Antarctic Climate Trends

A network of about 17 human-occupied stations has provided a more-or-less continuous instrumental climate record for Antarctica since the mid-1950s, when global atmospheric monitoring was given a boost during the International Geophysical Year. If that seems like a reasonable number, consider that Antarctica's surface area is about 1.5 times that of the United States, and that most of the stations are along the coast. The rough U.S. equivalent would be to have five monitoring stations along each of the East and West Coasts, but perhaps only one station in the interior, despite the unique climates of the Great Lakes, the Great Plains, and the Rocky Mountains. (In reality there are at least 350 stations throughout the United States.)

The problem of elucidating recent climate change from the handful of instrumental climate records in Antarctica has been exacerbated by their short length. Whereas over the six inhabited continents there are reliable instrumental records for at least 100 years that clearly indicate warming trends, over Antarctica there is only a 50-year record which is confounded by year-to-year climatic variability that is larger than on the other continents. It has been challenging to extract the Antarctic climate change "signal" from the "noise" of the limited record.

The shortcomings of the instrumental record have inspired scientists to devise innovative techniques for investigating Antarctic climate variability. Chemical signatures recorded in the annual layers of ice cores document the history of Antarctica's climate over the past few hundreds to thousands of years, providing bounds for the timing and magnitude of current climate change. Satellite records during recent decades have allowed scientists to monitor changes in sea ice and the movements of ice sheets over huge swaths of Antarctica for which there are no instrumental observations. Advances in numerical modeling of the ocean, sea ice, atmosphere, and land surface with powerful computers have provided insight into the mechanisms that drive polar climate.

The unique framework of the Antarctic Treaty has fostered an environment of collaboration among nations that has enabled coordinated data collection efforts that would otherwise be unthinkable. Together, collaboration and innovation are rapidly advancing scientists' understanding of climate variability and change in Antarctica.

Glenn Grant, National Science Foundation

Palmer Station, just off the coast of the Antarctic Peninsula on Anvers Island. It is one of three research stations operated by the U.S. Antarctic Program.

grow faster, and therefore offset some of the enhanced loss of ice at the edges of Antarctica due to warmer atmospheric and ocean temperatures. Additionally, the current generation of global climate models—the tools used by the United Nations Intergovernmental Panel on Climate Change (IPCC) to project future climate—do not include the effects of climate change on the flow of the polar ice sheets. This has caused considerable debate about whether the IPCC sea-level projection for the end of the twenty-first century (18–59 centimeters) is too low. A growing body of evidence suggests that ice sheets respond rapidly to climate change in a manner that causes an accelerating contribution to sea-level rise during warming. Therefore, some leading scientists assert that the amount of sea-level rise by the end of the twenty-first century will be much higher, perhaps as much as 80–200 centimeters. And their concern is not just based on the fact that the IPCC climate models currently do not simulate ice sheet processes. Records of past climatic variability suggest that during the last interglacial period, about 130,000 years ago, sea level was several meters higher during a time when global average temperatures were only a few degrees warmer than they are now. The IPCC models collectively project that global climate will be about 3–4°C warmer by the end of the twenty-first century.

Although the magnitude is disputed, there is wide agreement that global sea level will continue to rise during the twenty-first century. More than 100 million humans live within a meter of sea level, many of them in developing countries that are ill equipped to deal with the problem. Actions on the part of industrial nations to curb greenhouse gas emissions will set an example for rapidly developing nations and will be an important step toward mitigating the impacts of ice sheets on future sea level rise and humans worldwide.

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More on Climate Change

Worldwatch Institute's *State of the World 2009: Into a Warming World* focuses on meeting the challenge of climate change from a variety of perspectives and will be released in January. For more information, go to www.worldwatch.org/node/5658.

For more information about issues raised in this story, visit **www.worldwatch.org/ww/antarctica**.