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In this issue . . .

Because this is a special issue, the NSF awards list, covering 1 January to 31 March 1986, for antarctic research and support will appear in the September 1986 issue.

Advances in antarctic geophysical sciences from the IGY to the present

Introduction

In the fall of 1985, members of the Polar Research Board, National Academy of Sciences, National Research Council, presented a symposium summarizing scientific accomplishments in the Antarctic since the International Geophysical Year (IGY). The presentations are one component of a much larger evaluation of past accomplishments, present capabilities, and future antarctic scientific needs that the Polar Research Board is preparing for the National Science Foundation's Division of Polar Programs.

This issue of the *Antarctic Journal* contains written summaries of post-IGY accomplishments in five scientific disciplines: upper atmosphere research, meteorology, physical oceanography, earth sciences, and glaciology. The December issue will contain two additional summaries, terrestrial and marine biology, as well as the latest results of this year's Antarctic Marine Ecosystem Research at the Ice Edge Zone (AMERIEZ) Program.

Post-IGY science in each of the five disciplines has consisted of a combination of manned field studies and an ever-increasing number of instrumented observations, made from antarctic ground stations, ships, aircraft, and satellites. In spite of the explosive increase in technology, the human component in the Antarctic (scientists, technicians, and the staff that support these remote operations) is the single most important factor in our success in unraveling the mysteries of Antarctica and the surrounding oceans.

In the earth sciences, improved marine seismic techniques have permitted researchers to study the sea floor and define the composition and thickness of the upper layers of the Earth. Simultaneously, geologists working on terrestrial outcrops have discovered that the antarctic ice sheet may have been significantly smaller within the past few million years.

In glaciology, the most dramatic advance has been the development of radar

This map shows stations, camps, and other sites that are discussed in the papers in this issue. Currently, the United States operates McMurdo, South Pole, Siple, and Palmer stations.

technologies to determine ice thickness and related properties. As technology evolves, these observations may, in the next decade, be made from orbiting polar satellites. Yet, ice coring and the analysis of ice cores collected from drill holes are still the primary techniques that glaciologists use to unlock the record of changes of world climate that is contained in the Antarctic ice.

In meteorology, the development of sophisticated computer systems has permitted scientists to create models that mirror the complexities of atmospheric circulation and to apply these results to defining antarctic meteorology and climatology. These models are predicated on data collected by field meteorologists.

The United States commitment to antarctic science spans much of this century, and our continuous presence on the continent, beginning with IGY, is approaching its fourth decade. The summaries presented here provide insight into the scope and content of our scientific programs. Progress has been significant, and our knowledge includes far more than just the tip of the iceberg.

Upper atmosphere research

At the time of the International Geophysical Year (IGY), the geographic distribution of many phenomena occurring in the upper atmosphere* was poorly understood. A major thrust of the research during the IGY was to delineate geomagnetic and ionospheric phenomena from various locations on the antarctic continent (Waynick, 1965).

Data acquired during the 30 years that have elapsed since the IGY have revolutionized our understanding of the physics and chemistry of upper atmosphere phenomena. Much of this revolution was brought about by the advent of scientific spacecraft (both earth-orbiting and earth-escaping), which delineated the morphology of the magnetosphere. This region of space around the Earth is where the terrestrial magnetic and electric fields wholly dominate the transport and motion of charged particles (figure 1).

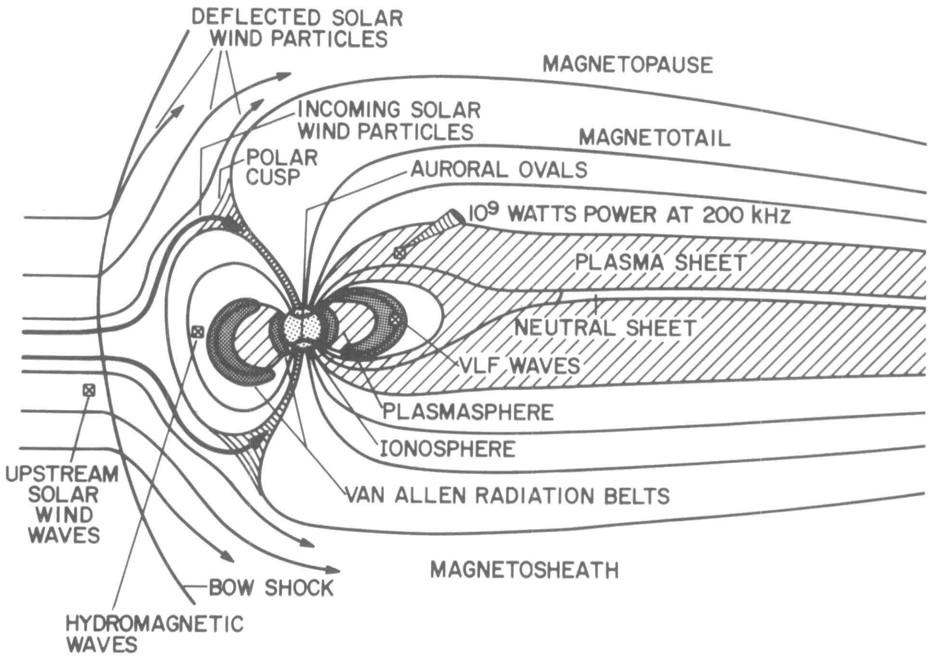
Upper atmosphere research in the Antarctic has changed dramatically from the basic exploration emphasized in the IGY to the use of the continent as a platform for active and passive studies of micro- and macro-scale variations in the Earth's magnetosphere (Lanzerotti and Krimigis, 1985). Studies particularly of interest to upper atmosphere researchers are those associated with the internal magnetospheric boundary (known as the plasmapause) and the auroral and polar cap regions.

Geomagnetic field lines threading through the outer regions of the Earth's magnetosphere (figure 1) intercept the ionosphere and the Earth's surface in high-latitude regions. Because of the approximately 12° offset between the Earth's spin axis and the dipole axis, field lines from the inner magnetosphere also can intersect Earth at rather high geographic latitudes at some locations. Indeed, the antarctic continent encompasses a wide range of geomagnetic latitudes, as illustrated in figure 2 for the case of local geomagnetic noon at the geographic South Pole.

The field lines at about geomagnetic latitude 60°S in the region of Siple Station (SI), Halley Bay (HB), and SANAE (SA) pass through the magnetosphere at the equator at a radial distance of approximately 4 Earth radii near the typical position of

*In this discussion, the upper atmosphere is defined broadly to cover regions from an altitude of about 30 kilometers upwards as far as the sun.

Figure 1. The magnetosphere of Earth, schematically illustrating a number of important morphological features.



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plasmapause. In contrast, stations such as Syowa (SY) and Byrd are in the auroral zone, corresponding to field lines traced to an equatorial altitude of about 6 Earth radii. South Pole Station (SP) is in the magnetospheric cusp region near local geomagnetic noon with field lines tracing close to the magnetosphere boundary. McMurdo (MM) and Vostok (VO) stations are usually deep within the southern magnetosphere polar cap on field lines which are "open" and stretch deeply into the magnetosphere tail. Palmer Station (PA) is normally deep within the plasmasphere.

Magnetic field lines can be traced from one hemisphere to the other through the magnetosphere. Observing locations at opposite ends of a magnetic field line are called "conjugate." The Antarctic has several geographic areas that are connected by magnetic field lines to land regions in the Northern Hemisphere. Presently, the geographic location of Antarctica often is used effectively for conjugate studies in conjunction with simultaneous measurements primarily from Canada, Greenland, and Iceland, as well as on spacecraft. The twin features of the wide geomagnetic coverage of Antarctica and the conjugate relationships of the continent to northern hemisphere sites have been used to optimum advantage in recent years by U.S. upper atmosphere scientists studying the Earth's magnetosphere and ionosphere. Another feature of Antarctica that is important for many investigations is the low ambient noise levels of normal electromagnetic interferences. This feature offers the distinct advantage of high signal-to-noise ratios or greater sensitivity of measurement for many studies.

In recent years, South Pole Station, with its continuous daylight conditions during the austral summer, has been used for solar astronomy, especially for studies of the regular, periodic (minutes to hours) oscillations of the Sun as it transfers heat from its internal thermonuclear source to the surface (Grec et al, 1980; Fossat et al, 1981; Duvall et al, 1986). Likewise, interest has begun recently to center on the exploitation of the high-altitude, low-humidity conditions at the South Pole to investigate the potentials of other astronomical research at that location. Clearly, for contemporary upper atmosphere, solar, and astronomical research, the ideal location of Antarctica is the primary motivation rather than basic understanding of the conditions of the continent itself.

Much of antarctic upper atmosphere research following the IGY to the mid-1970's was summarized in the volume edited by Lanzerotti and Park (1978). A major international program in magnetospheric research during the 1976-1980 interval was the International Magnetospheric Study (IMS), in which antarctic studies and several conjugate locations played important roles. Summaries of available data from antarctic sites during this program are contained in papers by Rosenberg (1982), Rycroft (1982), and Nagata and Hirasawa (1982) for U.S., European and worldwide, and Japanese observations, respectively. The following briefly summarizes some of the most recent studies that U.S. researchers have conducted by making use of the excellent locations and facilities afforded by the U.S. Antarctic Program. The included references are only representative of a much broader literature that exists and that can be obtained by contacting the various individual research groups.

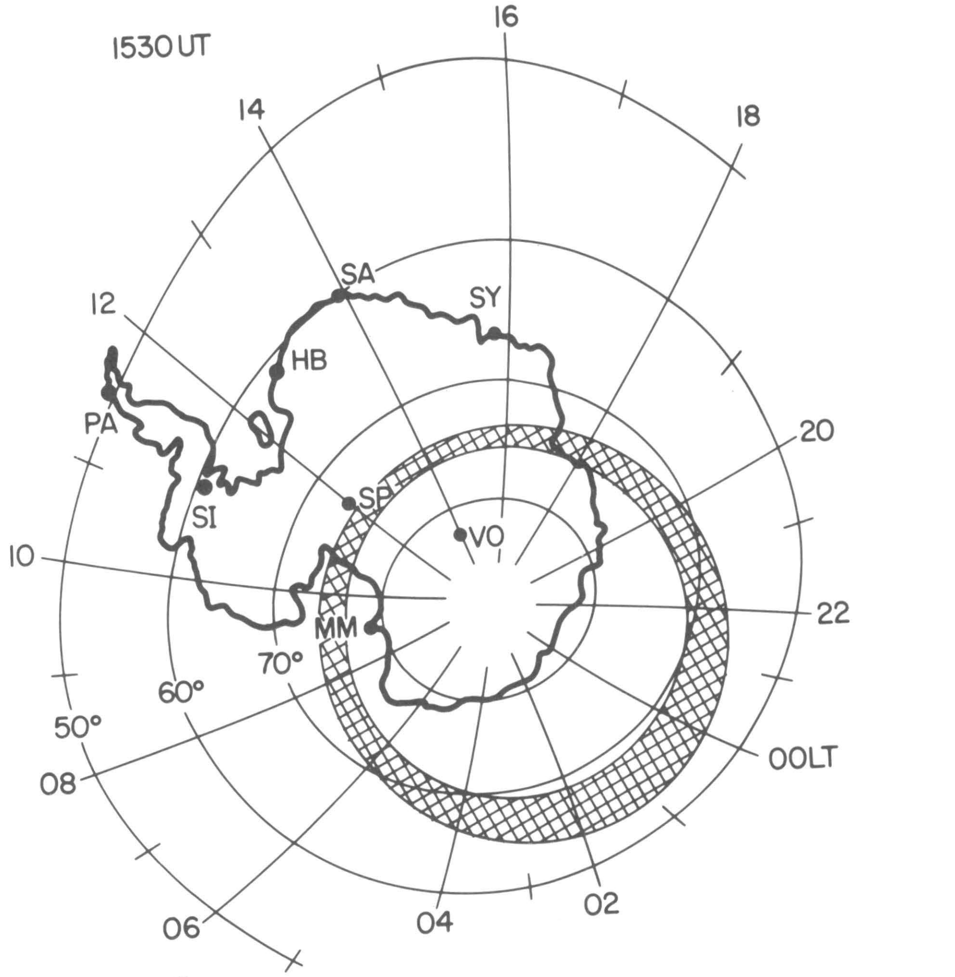

Figure 2. Geomagnetic coordinate system superimposed on the antarctic continent at local magnetic noon at South Pole. The nominal auroral oval is indicated at this local time. The several antarctic stations indicated by two letter codes are identified in the text.

Wave-particle interactions

Trapped particles in the magnetosphere can interact with the various plasma waves that also exist there. These wave-particle interactions can cause trapped particles to be lost from the magnetosphere. The particles impact the ionosphere and produce x-ray and optical emissions, as well as perturb the magnetic and electric fields at and below the site of impact.

Antarctic-based research has significantly contributed to the understanding of wave-induced particle precipitation from the Earth's magnetosphere. Natural plasma waves in the extremely-low-frequency/very-low-frequency (ELF/VLF) bands (approximately 100 to 5,000 hertz) were, for the first time, observed simultaneously with X-rays (Rosenberg et al, 1971, 1981; Foster and Rosenberg, 1976), photoemissions, and D-region ionization enhancements produced by the precipitating particles (Helliwell et al, 1980).

The discovery of the "Trimpi effect" in antarctic data acquired in the mid-1960's provided extensive evidence that whistler waves, which are generated by lightning signals that then propagate in the magnetosphere, can trigger the precipitation of detectable fluxes of greater than 40 kiloelectronvolts electrons (Helliwell et al, 1973). These electrons cause perturbations (the "Trimpi effect") of the phase and amplitude of manmade VLF-waves (most often used as navigation signals) propagating below the ionosphere and reflect off it. The whistler-induced perturbation of these sub-ionospheric ELF/VLF signals is now recognized as a well established technique for studying the physics of the wave-induced scattering process, as well as the ionospheric effects of impulsive particle precipitation (Inan et al, 1985).

In the Antarctic and in the northern hemisphere conjugate regions, upper atmosphere scientists now are studying fundamental questions about what role waves, which are initiated by lightning and thunderstorms, have in the loss of radiation belt particles at mid to low latitudes. Recent findings include the discovery of perturbations in manmade signals with frequencies as high as 800 kilohertz (Carpenter et al, 1984), perturbations in the signal phase with implications for global ELF/VLF navigation (Inan et al, 1985), and discovery of "Trimpi effects" due to whistlers and other natural waves that propagate outside the plasmasphere (beyond an equatorial distance of about 4 Earth radii; see figure 1) (Carpenter et al, 1985).

The experimental results from antarctic research on wave-induced precipitation effects have helped to guide theoretical research and have advanced the capabilities not only for modeling these effects but also for comparing data and theory (Tolstoy et al, 1982, 1986). This observational and theoretical research is applicable to magnetospheric physics as a whole, not just to the antarctic-observed phenomena.

Antarctic research also has been important for related experiments in wave-particle studies. Examples include the successful efforts to stimulate wave-particle interactions artificially with ground-based transmitters (Helliwell and Katsufrakis, 1978) and the SEEP experiment, a satellite project that studied in some detail lightning-generated whistler waves and that made the first direct observations of electrons precipitated by manmade waves (Imhof et al, 1983). These experiments are discussed below.

Related wave-particle interaction studies include the detailed measurements on the ground of magnetic pulsations produced by impulsive electron precipitation (e.g., Arnoldy et al, 1982; Engebretson et al, 1983, 1984; Lanzerotti and Rosenberg, 1983). The incident electrons produce transient variations in the conductivity of the ionosphere, which in turn lead to the observed geomagnetic variations. These studies provided insight into how frequently the phenomena occur and on how the phenomena could be used to deduce important parameters of the ionosphere where the electrons stop.

Rocket payloads have been used at Siple Station by U.S. investigators to study directly the electrons involved in wave-particle interactions and X-rays (Benbrook et al, 1983; Roederer et al, 1985; Sheldon et al, 1985). These investigative tools have added important capabilities to antarctic research and have contributed to understanding magnetosphere processes.

Particles impacting the upper atmosphere also produce variations in the optical emissions where the atoms are excited and return to their ground states. The most important results associated with optical studies followed from the identification of the unique character of dayside aurora and its association with the magnetospheric cusp (see figure 2) (Eather and Mende, 1971).

The geographic South Pole is one of the best ground-based locations from which to study dayside aurora. Studies at this station since the early 1970's have led to a clear description of dayside aurora and its differences from nightside aurora (Eather, 1984). In addition, and more importantly, studies of the movements of dayside aurora as a function of geomagnetic latitude and the close association of these movements with geomagnetic disturbances (substorms) have had important implications for magnetospheric physics. These include the fundamental question of whether the substorm is directly driven by the solar wind or by a storage/release process, in which energy from the solar wind is first stored for a lengthy interval before being released to cause the substorm.

Active VLF experiments

The antarctic ice sheet is an ideal location for establishing long antennas to monitor passive signals and to be connected to powerful transmitters for broadcasting signals into the ionosphere and magnetosphere (Helliwell and Katsufrakis, 1978). At Siple Station controlled experiments using a 42-kilometer-long dipole antenna that transmits coherent VLF signals (about 2 to 5 kilohertz) have revealed the existence of a highly nonlinear, narrowband wave-growth process. Called the "coherent wave instability" (CWI), this mechanism appears to be based on doppler-shifted, cyclotron wave resonance between the input waves and the counter-streaming electrons near the equatorial plane of the magnetic field line along which the wave is propagating.

For input signals exceeding a certain threshold, the CWI causes coherent waves to grow at large exponential rates of 25 to 240 decibels per second (Helliwell et al, 1980). Following saturation, typically at 20 to 40 decibels above the input signal level, narrowband wave emissions are usually spontaneously triggered, lasting a few tenths of a second and rising or falling in frequency by several hundred hertz or more according to the input frequency. These triggered emission signals may be suppressed or entrained by other injected signals from ground VLF transmitters (such as Navy navigation satellite transmitters) or northern hemisphere power grids.

Two-frequency input signals from the Siple transmitter can produce strong sidebands up to 100 hertz from the carriers. Noise simulation experiments show that the elements of the noise can coalesce into longer, quasi-coherent wave trains (Helliwell et al, 1986b). These two results suggest that hiss and chorus, two of the most important wave emissions from natural magnetospheric plasma, may simply be different aspects of the CWI.

The large gains found in these artificial wave-injection experiments can account in a natural way for several recently discovered connections between naturally-occurring VLF waves and precipitating electrons. For example, investigators have demonstrated that such natural VLF events produce X-rays, light emissions, and perturbation of the intensity and phase of waves reflected from the ionosphere. Recent discoveries of similar wave phenomena in the magnetosphere of Jupiter suggest that this wave-particle interaction process may be a prominent feature of most astrophysical plasmas.

Artificial wave transmissions from Siple Station have revealed a new type of plasma instability that affects coherent VLF signals propagating at low altitudes in the subauroral ionosphere. The effect involves energetic particle precipitation from the magnetosphere with the resultant creation and maintenance of ionospheric irregularities, the scattering and amplification of electromagnetic and electrostatic waves, and the enhanced scattering of energetic electrons (Bell and Katsufrakis, 1985). Joint international experiments involving VLF transmissions from Siple Station and measurements from Canadian, Japanese, French, and Soviet satellites have revealed important new features of VLF wave-particle interactions both in the ionosphere and in the high-altitude magnetosphere (e.g., Bell et al, 1983; Kimura et al, 1983).

Besides using satellites to monitor VLF broadcasts from Siple Station, scientists have launched sounding rockets from that station to study in detail the propagation of VLF signals across the neutral atmosphere-ionosphere boundary. The instruments on the sounding rockets measured the transmission efficiency of the Siple transmitter into the ionosphere to be about 0.0001 (Kintner et al, 1983). Because all previous VLF signal diagnostics were ground-based, the sounding rocket receivers provided a "truth test" of the assumption that the ground-based results represented the signal in the overhead ionosphere. On some occasions scientists observed significant differences between rocket and ground measurements; natural whistler waves and nonlinear effects on the Siple transmissions observed by the sounding rockets were not observed by the ground-based VLF receivers. These differences were most likely caused by sharp density gradients in ionization in the ionosphere E-region which were consistently observed to reflect downward-propagating natural waves from the plasmasphere back into the magnetosphere (Brittain et al, 1983).

Structure of the magnetosphere

Data acquired in the Antarctic was key in defining the plasmasphere (figure 1), the region of cold plasma that approximately co-rotates with the Earth as the Earth turns (Carpenter, 1963). Inside the plasmasphere, the plasma densities can be several thousand ions and electrons per cubic centimeter whereas outside the densities can be much less—1 to 10 per cubic centimeter or less. The transition region (the plasmapause) can be quite sharp, less than 0.5 Earth radius at the equator on occasion.

Naturally-occurring VLF signals measured at Eights, Byrd, Siple and Palmer stations have revealed many aspects of the plasmapause and plasmasphere (Carpenter and Park, 1973). On the average, the plasmapause is fixed in sun-earth coordinates with a dawn-dusk asymmetry involving a dusk-side bulge. The equatorial radius of the plasmapause roughly varies inversely with the level of magnetic disturbance.

Antarctic research has also provided important results on many dynamic features of the magnetosphere. Decreases in the nightside plasmasphere radius and sunward surges of the dusk-side bulge have been measured during substorms. The multi-day refilling time of depleted regions of plasma following magnetic storms was found in antarctic data and led to overall descriptions of a cyclic plasmaspheric process of fast plasma loss and slow replenishment from the ionosphere (Carpenter and Park, 1973). Features of the ionosphere near the plasmapause have been studied by using ionosond techniques (Berkey and Jarvis, 1985).

Several important propagation features of whistler waves in the magnetosphere plasma were described from antarctic data. These include

- the half-gyrofrequency cutoff of whistler propagation in magnetospheric plasma ducts
- the triggering action of whistlers in producing bursts of waves that scatter particles into the ionosphere (Rosenberg et al, 1971)
- the coupling between nearby whistler paths at the time of reflection from the ionosphere (Smith and Carpenter, 1982)
- amplification of whistlers in the magnetosphere that depends on their frequency-time characteristics (Carpenter et al, 1986).

Hydromagnetic waves

Data from antarctic stations (particularly Siple Station) and the Siple conjugate area have helped to define the field-line resonance nature of hydromagnetic waves with frequencies in the range of approximately 0.05 to 0.001 hertz (Lanzerotti, 1978). In particular, scientists have found that the density gradient at the plasmapause significantly influences how hydromagnetic waves produced by the solar wind are coupled to specific geomagnetic field lines and why this causes them to resonate like a guitar string (e.g., Chen and Hasegawa, 1974; Southwood, 1974). Such waves can cause considerable energy transfer to the ionosphere under certain conditions.

X-ray and extreme ultraviolet (EUV) radiation from solar flares produce sudden conductivity changes in the ionosphere. Siple data and data from the conjugate area show that such conductivity changes can apparently launch hyrdomagnetic waves into the magnetosphere (Rosenberg et al, 1981).

Waves in the range of 10 to 0.1 hertz are often produced by the spiraling of protons and helium ions around the geomagnetic field lines. Measurements of magnetic field changes in this frequency range at Siple Station and in the conjugate area have shown that the polarizations of these waves apparently identify the location of wave generation in the magnetosphere (Arnoldy et al, 1979).

Cosmic rays

U.S. studies in the Antarctic of solar and galactic cosmic rays have concentrated on measurements at McMurdo and South Pole stations. The asymptotic cone of acceptance for cosmic rays at McMurdo Station is nearly perpendicular to the ecliptic plane. Measurements at McMurdo, in conjunction with those from Thule, Greenland, (almost perpendicular to the north ecliptic plane) are important for determining north-south anisotropies of cosmic-ray fluxes. The altitude of South Pole (with an asymptotic cone of acceptance approximately in the ecliptic plane because of the tilt of the geomagnetic dipole axis) means that the cosmic-ray counting rates are higher and the energies detected directly are lower than at a comparable station, for example, on the coast.

A number of specific recent discoveries relate to measurements of the north-south (n-s) cosmic ray asymmetries. These include

- measurements of transient (Pomerantz and Duggal, 1972) and long-term (Pomerantz et al, 1982) n-s anisotropies
- the study of the solar cycle variation of the n-s asymmetry and its implications for the galactic cosmic-ray radial gradient in the solar system (Bieber and Pomerantz, 1986)
- two classes of periodicities in cosmic-ray anisotropy related to solar rotation (Jacklyn et al, 1984)
- cosmic-ray intensity waves extending over the energy range from 1 to 200 gigaelectronvolts, (Duggal et al, 1981).

The data also have been used to analyze and understand the effects of various types of interplanetary disturbances (produced by solar activity) on cosmic-ray fluxes (e.g., Duggal et al, 1983). Finally, observations of relativistic solar cosmic rays have provided new insights into the propagation of energetic solar particles in the corona and in interplanetary space (e.g., Bieber et al, 1986).

Analytical studies of these and numerous other effects, which manifest themselves as temporal variations of the antarctic cosmic-ray intensity, coupled with theoretical investigations of physical processes that can produce them have provided new insights into the large-scale structure of the solar system and its control by the sun, as well as fundamental aspects of solar physics.

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Meteorology

The weather and climate of Antarctica and how it influences the rest of the globe have fascinated explorers and scientists from the "Heroic period" of antarctic exploration that started with the first wintering on the *Belgica* in 1898-1899, through the "Mechanical expeditions" that began with Admiral Byrd's first expedition in 1928, and finally into the period of airplane-, satellite-, and computer-supported permanent scientific stations in the second half of the 20th century. In the *Compendium of Meteorology*, Court (1951) summarizes what had been learned about antarctic weather and climate from expeditions up to World War II. He lists about 100 antarctic meteorology books and papers, which were published between 1930-1950.

Two major post-war expeditions before the International Geophysical Year (IGY) in 1957-1958 added substantially to the knowledge of antarctic weather and climate. One of these was the French expedition to Port Martin (66°49'S 141°24'E) from which Loewe (1956) provided the first detailed account on the energy, mass, and water budgets of the continent. The second was the Norwegian-Swedish-British expedition to Maudheim (71°3'S 10°56'W). Participants of this expedition obtained detailed climatic data for a climatically vulnerable ice shelf, along with a detailed analysis of polar boundary-layer processes by Liljequist (1957). The results of these expeditions contributed substantially to the pre-IGY knowledge of the antarctic climate.

Convincing synoptic studies of weather and climate were not possible before the IGY, although the South African Weather Bureau attempted to produce hemispheric charts based in part on whaling ship reports. Conclusive analysis, however, could not be accomplished until the advent of manned stations, automatic weather stations, buoys, and satellites during and after the IGY. Our understanding of antarctic meteorology has advanced rapidly since then.

Antarctic observational systems

The long-term occupation of manned stations in Antarctica began during the IGY. In recent years, 25 meteorological stations have operated year-round in the 35 million square kilometers south of 60°S. This compares with 340 such stations in the United States, an area less than a third in size but with about 50 times more stations per unit area. Most of the stations ring the Antarctic; only two of them operate all year on the high interior antarctic plateau—the U.S. Amundsen-Scott South Pole Station at the geographic South Pole and the U.S.S.R. Vostok Station (78°28'S 106°48'E) which is also on the polar plateau.

Other observational systems are beginning to fill the gaps. Automatic weather stations with improved power supplies that include radioisotope generators, long-term storage batteries, and solar cells have become quite reliable. These are now used in the Ross Sea and on the Ross Ice Shelf, inland from the French station Dumont d'Urville (66°40'S 140°1'E) up to Dome C (74°50'S 120°E) to measure katabatic winds, inland from Casey Station (66°16'S 110°32'E), and on the Antarctic Peninsula. The southern oceans remain the most poorly observed region on Earth with only a few buoys periodically deployed in the open ocean and in the pack ice. However, satellites now provide much information about the southern oceans in such forms as cloud mosaics and passive microwave observations of sea ice (Zwally et al, 1983).

A number of special observation periods and facilities have supplemented the low-density observational systems in Antarctica. During the First GARP (Global Atmosphere Research Program) Global experiment (FGGE) in 1978-1979 several hundred ocean buoys were deployed. Also, constant-level balloons circled the southern oceans and crossed the continent. These provided atmospheric data and ice-sheet elevations. The U.S. station Plateau, built at an altitude of 3,600 meters, operated for 3 years and provided fascinating new insights into atmospheric boundary-layer structure and processes. Deep drilling and recovery of ice cores, which were done at Byrd Station (now Byrd Surface Camp) and are continuing at Vostok, are laying a basis for reconstructing Antarctica's climatic record. A clean-air facility at South Pole continues to provide data on snow and atmospheric chemistry.

New nations now are venturing into Antarctica. The stations built by these nations are not necessarily established in locations best suited for scientific purposes but are located where access is convenient. Improvements in the meteorological observational network therefore are most likely to come from improved technology and to a lesser extent from additional stations.

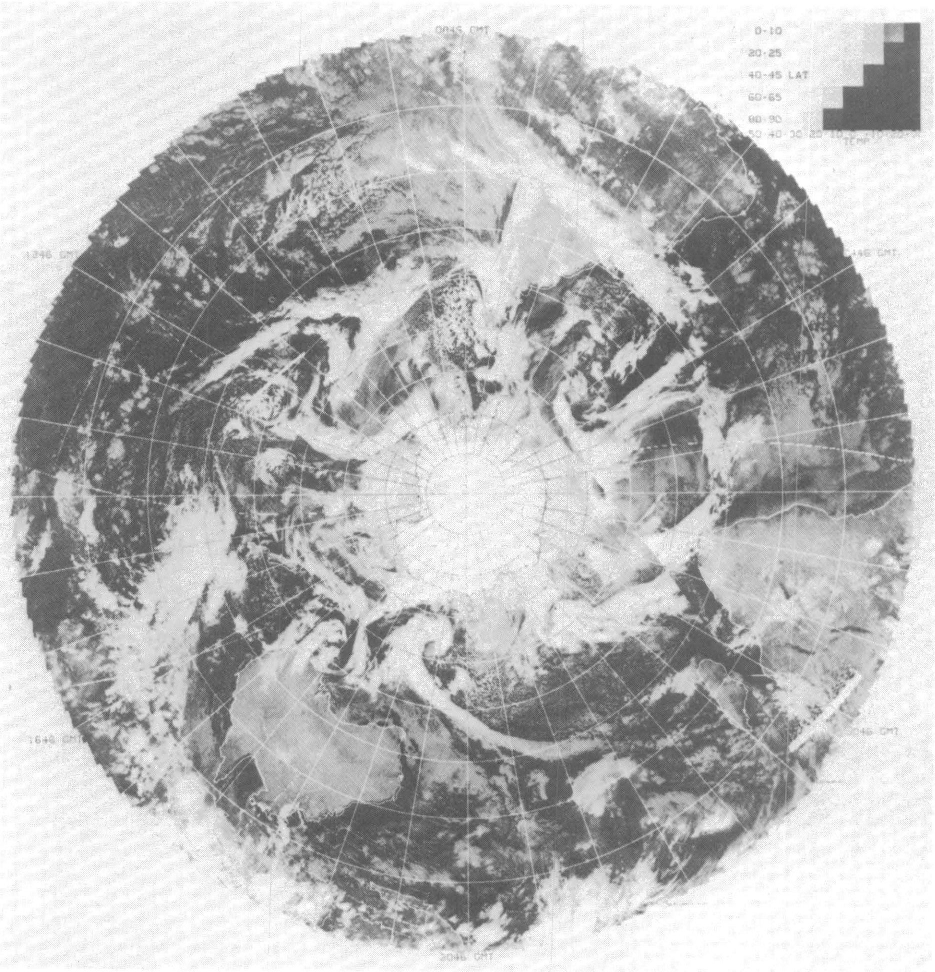


Figure 1. NOAA-1 infrared photo mosaic of the Southern Hemisphere, June 18, 1971. Note that the continents are depicted lighter (colder) than the warmer ocean, and that the brightest (highest and coldest) clouds appear in the southern ocean depression vortices and the tropical systems over Indonesia. The gray scale shows approximate temperature values in °C.

Large-scale circulation

Before the IGY relatively little was known about the large-scale circulation of the atmosphere of the southern hemisphere. Palmer (1945) described its observed broad features, but the precise position and movement of air masses and fronts were largely conjecture. Satellites have improved observation capabilities drastically (figure 1) and are now essential for weather prediction. Cloud-vortex observations and classification by Streten and Troup (1973) have made possible the first truly synoptic climatology for the southern oceans.

In a book published just before his death (Schwerdtfeger, 1984), Werner Schwerdtfeger summarized the present knowledge of the weather and climate of Antarctica. Meteorologists now recognize that the main features of antarctic circulation are a katabatic boundary-layer regime over the continent that is only weakly coupled to the air flow above it, and, in contrast, a strongly coupled and very energetic wind regime over the southern oceans in which winds and sea state surpass those of other oceans. This latter feature was, of course, well known even 100 years ago to the crews of large sailing ships. The seasonal change in the circumpolar vortex up to the stratosphere and its cyclonic and anticyclonic systems are relatively well understood through the efforts of many, including Palmer, Schwerdtfeger, Streten, van Loon, and Taljaard.

The boundary-layer katabatic wind regime is a unique large-scale circulation feature on Earth. Radok (1973) has compared some aspects of this regime with the trade wind regime. Katabatic winds display an extraordinarily high degree of persistence and are a function of the surface-temperature inversion and terrain slope angle. In the initial models for these winds, the energetics invoked to cause air flow differed. Although these differences have not been resolved entirely, Parish and Bromwich (1986), using a model developed by Ball (1960), successfully reproduced the high spatial irregularity and strong topographic channeling of the flow that characterizes the observed wind regime (figure 2). An observation program, presently running in Adelie Land and using automatic weather stations in a profile from the coast up to Dome C, should enhance understanding of the temporal change in the katabatic drainage.

Climate

Antarctica is the coldest and driest continent on Earth. Since the IGY, scientists have studied in detail the climate and its various geographic regimes. From the results of these investigations a fairly complete picture has emerged. The Soviet atlas of Antarctica (Bakaev, 1966), the American Geographical Society *Antarctic Map Folio Series* (Weyant, 1966, 1967), a contribution by Schwerdtfeger (1970) to the published World Series of Climatology, and several volumes in the American Geophysical Union Antarctic Research Series provide a comprehensive picture of the climate of Antarctica and its surrounding oceans.

The central antarctic plateau is a cold desert with annual mean temperatures between -50°C (South Pole) and -60°C (Plateau Station). The lowest temperature (-89.2°C) on Earth was recorded on the

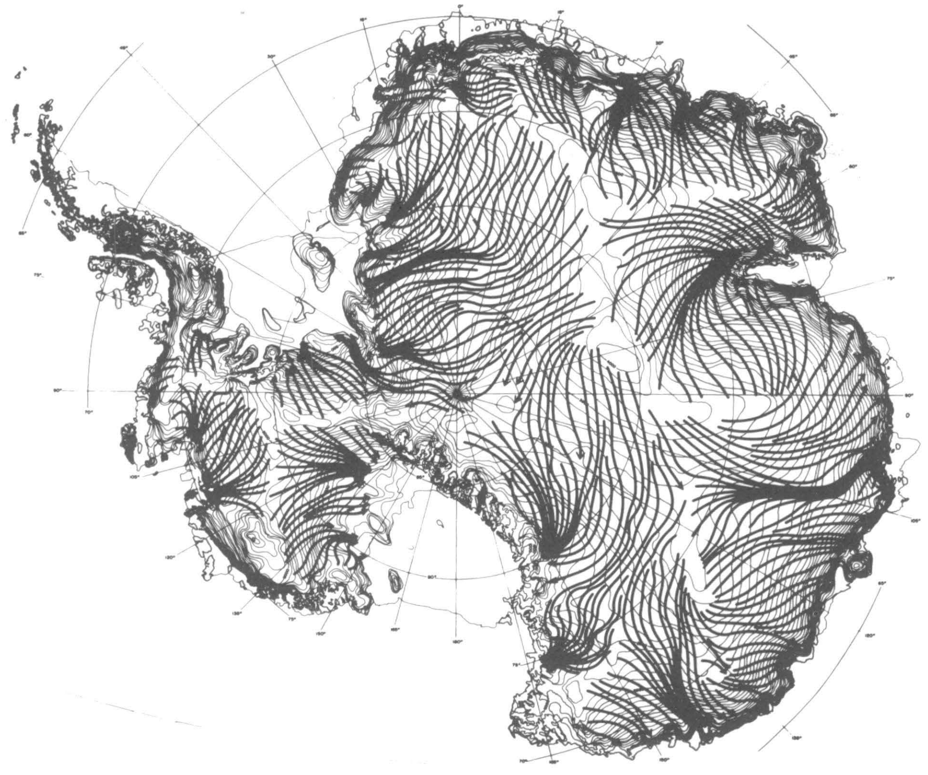


Figure 2. The surface wind field over the antarctic ice sheet. The heavy lines represent the streamlines of time-averaged surface air motion derived from solution of the Ball model over a square grid with 50 kilometers spacing (From Parish and Bromwich, 1986).

east antarctic plateau at Vostok Station in July 1983. Annual precipitation is about 7 centimeters water equivalent at geographic South Pole and 3 centimeters at Plateau Station. The coastal regions are much warmer (-10°C to -20°C), receive more precipitation, and have much stronger (katabatic) winds.

Few direct measurements are available from the extensive pack-ice zone that annually surrounds Antarctica, but clearly the ice modifies the antarctic climate considerably by reflecting solar radiation and by suppressing sensible and latent heat exchange between the ocean and the atmosphere (Fletcher, 1969). Satellite and buoy measurements are beginning to quantify this effect, which depends strongly on such ice characteristics as thickness and concentration. The sea ice distribution around Antarctica also affects cyclonic activity and vice versa—a greater ice extent in one sector or zone increases cyclogenesis there (e.g., Carleton, 1981).

Soon after the IGY, meteorologists recognized (Wexler, 1960) that the seasonal temperature variations in the stratosphere are much larger than those in the troposphere. Intense horizontal advection of maritime air frequently ventilates the interior of Antarctica and gives rise to the flat "coreless" winter temperatures* there instead of sharp winter minima. On the other hand, the antarctic stratosphere cools continuously until the sun returns and then warms as much as 50°C in a month. Explosive stratospheric warmings often occur much earlier than the Sun's return. These are caused by subsidence associated with changes in the circulation patterns of the stratospheric circumpolar vortex.

Antarctica affects and is affected by global climate. Potential changes in the antarctic environment, induced by carbon dioxide, are beginning to be assessed (NAS, 1984). Stratigraphic, isotopic, particle, and entrapped gas (e.g., carbon dioxide) data derived from the deep ice cores taken at Byrd Station and Dome C and especially from the more than 2,000 meters of ice extracted so far at Vostok provide for the first time details of the most recent global glaciations that have been only outlined in ocean sediment cores.

Boundary-layer processes

Lettau (1971) has called the antarctic plateau a "test tube for meteorological theories" because its surface is flat and exceptionally uniform and because diurnal variations due to changes in solar elevation are small or absent. Numerous boundary-layer experiments conducted in Antarctica since the IGY have proved this to be true. Following the pre-IGY studies at Port Martin and Maudheim, Rusin (1961) produced the first major summary of the meteorological and radiational regime of Antarctica, based primarily on data from the Soviet stations established during the IGY.

Radiation is the most important component of the surface energy balance to strongly influence climate. Measurements at several plateau stations (cf. Weller, 1980) confirmed Rusin's largely negative radiation balances, but later comparison with coastal stations showed that the surface energy exchanges are more intense on the coast than over the interior of Antarctica. This runs counter to the popular view of the ice sheet as the main global heat sink, which in fact lies in the higher layers of the antarctic atmosphere (Radok, 1981). Carroll (1982) made the most recent energy balance measurements at South Pole Station with more modern equipment over 3 years. Even during the polar night, these measurements showed a high degree of short-term variability due to the frequent influx of maritime air.

The strong radiational cooling of the surface, on the other hand, produces the katabatic wind regime and associated extensive snow drifting, which was studied in detail by Budd et al (1966) at Byrd Station. Radiational cooling also produces extraordinarily stable stratifications, wind shears, and associated optical phenomena. The vertical profiles of temperature and wind through the inversion layer were described by Kuhn et al (1977). They are highly complex (figure 3), represent the most stable stratification found anywhere on Earth, and provide a major challenge to turbulence theory.

Atmospheric and snow chemistry

The concept that the polar regions are pollution-free areas was abandoned after long-term environmental monitoring stations were installed in both regions. While cleaner than the Arctic, the Antarctic nevertheless has anthropogenic substances present in its atmosphere, despite the long transport from industrial sources across the stormy southern oceans.

The GMCC (Global Monitoring for Climate Change) station at the geographic South Pole has contributed substantially to our knowledge of global atmospheric chemistry. The rising levels of carbon-dioxide, measured at South Pole since about 1958 by Keeling (1984), show the same global trends as at lower latitudes (figure 4). Halocarbons are present in the antarctic atmosphere (Robinson et al, 1983), but their increase appears to be slowing down. Also their concentration is lower than in the Arctic. Aerosols include sea salt (even

*"Coreless" winters are winters in which the mean monthly temperatures during a number of months differ little from each other. This pattern is common in the Arctic as well as the Antarctic.

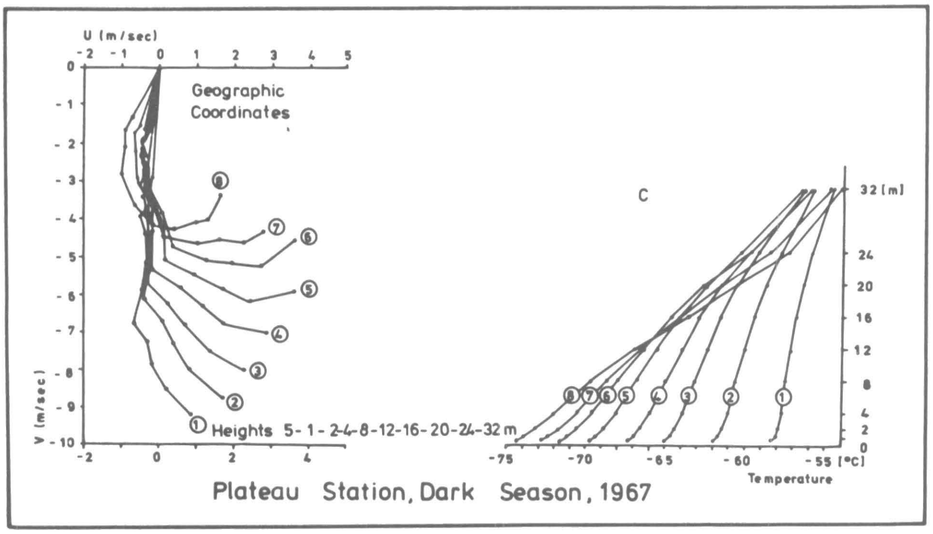


Figure 3. Features of the polar night boundary layer at Plateau Station, Antarctica. The vertical profiles of temperature and wind are shown for eight different sets of observations (From Kuhn et. al. 1977).

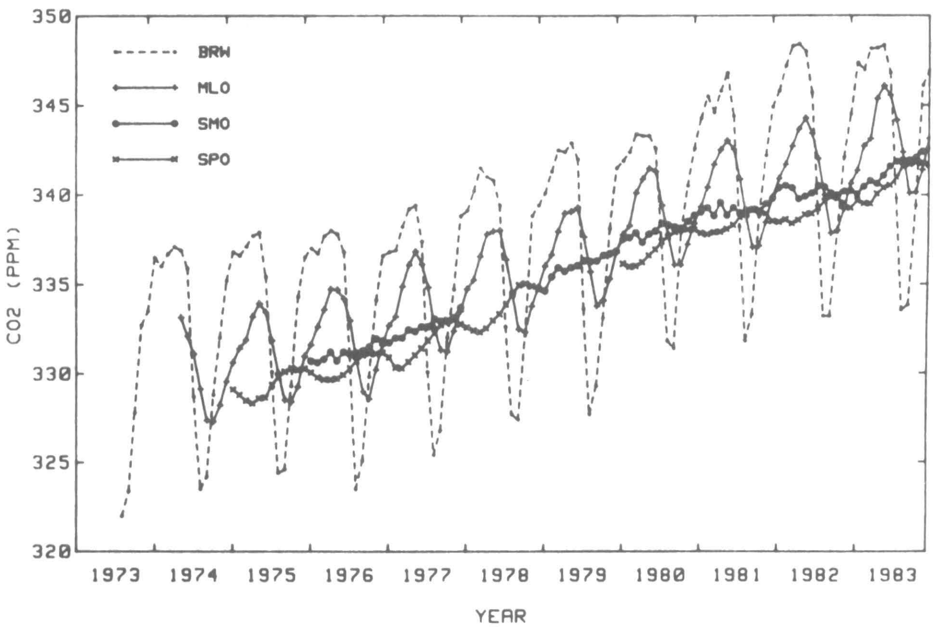
at the South Pole), crustal material, and sulfur compounds. Some of the latter originate from the volcanoes of Antarctica, particularly Mt. Erebus on Ross Island.

Both gases and aerosols have been used to examine the long-range transport and mixing of tropospheric and stratospheric air. Modern techniques employed include lidars, balloons that can ascend up to 30 kilometers to sample nitrous oxide and aerosols, and scanning photometers on satellites such as the Nimbus-7 sun photometer SAM II (Stratespheric Aerosol Measurement) to examine aerosol layers.

The snow surface is a convenient filter that collects and stores all the material that falls onto it. Snow stratigraphy studies have, therefore, allowed a glimpse into the past chemical conditions that existed over the ice sheet. Radionuclides show nuclear test horizons. Lead and other trace metals are present, although the concentrations indicate that Antarctica is still little affected by industrial lead pollution (Boutron and Patterson, 1983). The most spectacular results come from analyzing the oxygen isotopes of deep cores to reconstruct paleoclimates (Robin, 1983) and gas samples encapsulated in bubbles in the ice to show the low pre-industrial levels of carbon-dioxide (Neftel et al, 1982).

These results have shown that Antarctica is not isolated from the rest of the globe, but that processes and human activities as far away as the Northern Hemisphere affect conditions in the Antarctic. Nowhere is this more evident than in the startling discovery that antarctic snow and penguin eggs contain DDT.

Figure 4. Monthly mean carbon-dioxide concentrations from continuous measurements at Barrow, Alaska (BRW), Mauna Loa, Hawaii (MLO), Samoa (SMO) and South Pole (SPO). Values are in parts per million with respect to dry air (From NOAA/GMCC-Boulder, Colorado).



Conclusion

Great progress has been made since the IGY in understanding antarctic meteorology and climatology. Basically, we now understand the major seasonal features of atmospheric circulation, the climate of the continent, the radiation and energy balance that affect climate and circulation (including the katabatic wind regime), and the transport of gases and aerosols to Antarctica.

Interest in antarctic meteorology and climatology has increased substantially, as exemplified by the growing number of scientific papers listed in the quadrennial U.S. national reports on polar meteorology to the International Union of Geodesy and Geophysics (Robinson, 1983; Radok, 1979; Weller, 1975 and earlier ones). The problems of climate research, as part of the World Climate Program, have put a new focus on the polar regions and have brought polar meteorologists and climatologists together with other atmospheric scientists, oceanographers, and glaciologists. Improvements in modern measuring techniques, which include satellites, buoys, radars, automatic weather stations, and other tools, will provide better coverage of the polar regions in the future.

Although we have a much better understanding now than before the IGY of the broad features and processes of the antarctic atmosphere, many questions remain. Some of the major problems that wait to be solved include the large-scale nature of the antarctic heat sink and its variations (i.e. the changes of the energy budget on synoptic time-space scales), coupled air-ice-sea interactions, antarctic teleconnections (i.e. how does Antarctica affect global processes?), and the response of Antarctica to climate change (e.g. carbon-dioxide warming). These are broad, interdisciplinary problems in the context of which antarctic meteorology will become part of a truly global research enterprise.

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Physical oceanography

During the last 30 years, circumpolar and regional surveys have significantly advanced scientific understanding of the oceans surrounding Antarctica. More recently, research has focused on specific elements or processes within the southern oceans. During all phases of this research, international collaboration has been an important component, as has the application of state-of-the-art technology including moored and drifting instrumented arrays and sensors aboard satellites.

International Geophysical Year programs

The antarctic programs for the 1957-1958 International Geophysical Year (IGY) included an extensive southern oceans component (Gordon and Baker, 1969). Taken over 3 consecutive austral summers, the IGY data set, which marked renewed interest in the region, is a comprehensive, nearly synoptic representation of the southern oceans. Because most data were taken along supply routes to antarctic stations, the data set is not uniformly distributed, but it does permit time variability studies during the 3 years and studies over decades by comparison with the 1930's data collected by the British *Discovery* expeditions.

Use of the mechanical bathythermograph, which was newly available to scientists during the IGY, was a key factor in the scientific success of the IGY oceanography effort. The mechanical bathythermograph, which gives a continuous record of water temperature and depth as the instrument is lowered and raised, provided a high spatial resolution picture of the thermal structure of frontal zones and indicated where eddies exist within the polar front zone (Wexler, 1959).

Oceanography during the 1960's and 1970's

Since the IGY, antarctic supply ships have continued to obtain bathythermograph data and have extended this valuable, although spatially and temporally incomplete, time series. More recently, oceanographers, working from research ships and some supply ships, have used expendable bathythermograph (XBT) probes to measure temperature more precisely to deeper levels. For example, XBT probes were an important part of the late 1970's International Southern Oceans Studies (ISOS). During ISOS oceanographers used the observation capabilities of the supply ship to obtain a set of repeated XBT lines along various routes. Such measurements have been fundamental to the study of the southern oceans frontal zonation structure and heat storage.

Between 1961 and 1979, most of the circumpolar belt was surveyed. From 1962 to 1972 during 55 cruises, the ice-strengthened U.S. research ship *Eltanin* covered 410,000 miles and obtained a comprehensive multi-disciplinary data set within some 80 percent of the southern oceans. Renamed the *Islas Orcadas* and operated jointly with Argentina, the *Eltanin* continued the circumpolar survey from 1974 to 1979 and carried the survey into the South Atlantic. Part of the southwest Indian Ocean sector was surveyed in 1974 by the research ship *Conrad*, which is part of the University-National Oceanographic Laboratory System supported by the National Science Foundation.

The *Eltanin/Islas Orcadas* hydrographic data greatly enhanced our picture of the thermohaline stratification, water masses, fronts, and currents within the circumpolar belt and continental margins of Antarctica. *Eltanin* data allowed more accurate mapping and volumetric determination of temperature-salinity modes of water masses. This has generated a number of new concepts about water mass formation processes and rates. New sites where bottom water is formed were located, as well as evidence for deep convection of the Weddell Gyre. The *Eltanin/Islas Orcadas* hydrographic data are a primary component of the *Southern Ocean Atlas* (Gordon and Molinelli 1982; Gordon and Baker 1982).

During the period of the *Eltanin* observations, technology continued to evolve. Serial hydrographic stations were replaced with continuous *in situ* measurements of the thermohaline stratification. These systems (STD and then the CTD) produced far better resolution of the vertical stratification and enabled oceanographers to detect relatively intense fine structure in the frontal zone and continental margin stratification.

While hydrographic technology advanced, the use of tracer geochemistry also evolved. Tracer distributions (such as stable isotopes of oxygen, tritium, carbon-14, and freon) provide a view of the integrated effects of ocean, ocean-glacial ice, and ocean-atmosphere exchange processes at various scales. With these data oceanographers are able to estimate the time scale of phenomena as well as give more "control" of the water types forming specific water masses.

In the austral summers of the late 1960's and 1970's, the western segment of the Weddell Gyre was surveyed as part of the International Weddell Sea Oceanographic Expedition (IWSOE). During this work, which was staged from icebreakers and included scientists from the United States and Norway, oceanographers collected data within the fringes of the summer and multi-year sea-ice fields. Similar studies were conducted in the Ross Sea from U.S. icebreakers and lead to much improved resolution of the characteristics of the oceanic regime along continental margin south of the New Zealand/Australian sector. These studies improved our concepts of formation and production rates of Antarctic Bottom Water, intensity and structure of the shelf-slope front, continental shelf oceanography, and the role of the ocean in the glacial ice balance.

During the 1970's the International Southern Ocean Studies (ISOS) program focused on the Antarctic Circumpolar Current (ACC). This program concentrated on the Drake Passage but included some observations southeast of New Zealand.

With data from the ISOS program, oceanographers established a reliable value for the total baroclinic and barotropic transport of the ACC (125,000,000 cubic meters per second with about 70 percent of the net in the baroclinic mode) and for its variability (roughly 20 percent). This variability seems closely related to the zonally average wind stress acting on the circumpolar belt with a lag-time of about 1 week. The hydrographic data reveal a multi-filament structure for the ACC as it passes through the Drake Passage. These alternating jets of eastward flow with zones of weak flow or counterflow are associated with thermohaline frontal zones. The fronts display meanders or wave-like structures and generate eddies and rings. If the Drake Passage results are indeed typical of the circumpolar belt, these time varying features, which accomplish significant meridional heat flux, may be the primary mechanism to balance the oceanic heat loss south of the ACC.

During the 1978-1979 First GARP Global Experiment (FGGE), oceanographers used the experiment's extensive drifter array that was tracked by satellites to conduct a circumpolar study of southern oceans circulation. The FGGE drifters provided air pressure data, which enabled scientists to calculate better the geostrophic wind over the ocean. The trajectories of the FGGE drifters addressed the distribution of the circulation variability at various spatial scales including that of the mesoscale eddy field within the ACC. These factors also were detected from space in 1978 from the altimeter aboard the satellite SEASAT. SEASAT allowed synoptic determination of the wind stress on the ocean surface and of the wave field.

Weddell Sea study, 1981-1982

The *Discovery, Eltanin/Islas Orcadas* and *IWSOE* data sets included only the ice-free areas or, at best, the edges of the summer sea-ice fields. Until the 1981-1982 austral summer, these areas of the southern oceans were the only areas that had been studied extensively. In October and November 1981, the 137-meter Soviet icebreaker *Mikhail Somov* supported a joint U.S.-U.S.S.R. program in the Weddell Sea. During this cruise along the Greenwich meridian, U.S. and Soviet scientists obtained oceanographic data from well within the sea-ice cover, close to the time of its maximum extent. The *Somov* data set revealed for the first time the condition of the ice-covered ocean after the cumulative effects of winter.

These data have improved estimates of deep- to surface-water heat flux and have enabled oceanographers to describe some of the basic properties that are responsible for generating polynyas. However, the oceanic conditions under the extensive seasonal sea-ice cover around Antarctica remain the biggest "blind spot" in our view of the southern oceans structure. Observation within the sea-ice cover, particularly during the winter, represents an aspect of southern oceans research for which we are still essentially in a survey phase.

Satellites and oceanography

During the past decade, satellites have contributed greatly to our knowledge and understanding of the southern oceans and promise to be a major factor in future advances. Passive microwave data allow us to map sea-ice characteristics and the advance and retreat of sea ice without cloud interference. Visible and infrared radiation sensors have been developed to define the locations and variability associated with the frontal zones under cloud-free conditions.

The brief SEASAT mission of 1978 demonstrated the potential application of the scatterometer (for sea-level winds) and the altimeter (for sea-surface elevation). With only 3 months of data, circumpolar mapping of surface temporal variability of the Antarctic Circumpolar Current revealed coherent features over large scales, specifically ocean basins.

Conclusion

Progress has been impressive since the IGY. This paper cannot possibly provide a complete literature review, but some key papers, which review various segments of the field, are listed below. For review of general oceanography and water mass formation: Warren, 1981; Gordon, 1983; Killworth, 1983; and Carmack, 1984; Jacobs, Fairbanks, and Horibe, 1985; and the SCOR Working Group 74 Report, in press. For review of the Antarctic Circumpolar Current and fronts: Bryden, 1983; Gordon, 1983; Hofmann, 1985; Whitworth, 1985; Nowlin and Klinck, (submitted to *Reviews in Geophysics and Space Science*). For recent application of satellite technology: Zwally et al, 1983; Fu and Chelton, 1984; Garrett, 1961; and Cheney, Marsh, and Beckley, 1983.

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Earth science

Although only continental geophysics was included as an official part of the International Geophysical Year (IGY), geological observations were made by scientists participating in the oversnow traverses. Soon after the IGY, geology, as well as marine geology and geophysics, became an integral part of the U.S. research program. The accomplishments of the IGY have been followed by many others in the earth sciences; some of the major accomplishments are presented here.

Marine geology and geophysics

The marine program was conducted primarily from the ice-strengthened research ship *Eltanin*, which during its 10 years of continuous service crisscrossed more than two-thirds of the southern oceans (figure 1). Thirty-three of the 55 cruises included marine geology and geophysics. The results (*Antarctic Journal of the U.S.*, 1973; Hayes, 1972; Heirtzler, 1971; Heezen et al, 1972; Goodell et al, 1973), together with a number of cruises on the *Islas Orcadas* (formerly the *Eltanin*) and other ships, have contributed fundamental information on bathymetry, sediment distribution and type, Neogene biostratigraphy and paleontology, and patterns of sea-floor magnetic anomalies. The Deep Sea Drilling Project Antarctic Legs (28 and 35) and Sub-Antarctic Legs (29, 35, 71, 90) have provided the data base for the record older than that attainable with piston cores.

Eltanin cores provided material for an important early contribution on the correlation of microfossil assemblages and the paleomagnetic record in deep-sea cores (Hayes and Opdyke, 1967). From studies of deep-sea cores, proceeding from piston cores to the Deep Sea Drilling Project cores, scientists have developed a high-latitude biostratigraphy. This biostratigraphy has helped to establish important reference sections for much of the late Mesozoic and Cenozoic in the Sub-Antarctic (Legs 29, 36, 71, and 90) but only for parts of the latest Paleogene and Neogene for the Antarctic (Legs 28 and 35). From micropaleontologic studies of floras and faunas of these sections, earth scientists have been able to recognize biogeographic patterns for the Cenozoic (Kennett, 1978a). The pattern shows marked changes at the Eocene-Oligocene boundary and at the transition from the Oligocene to the Miocene. The former records the establishment of assemblages with distinct polar characteristics; the latter shows a transition to the present-day pattern of steep gradients of faunal and floral diversity. The transitions are interpreted in terms of ice formation around or on the antarctic continent.

Paleoenvironmental studies also have used the record of ice-rafted debris (IRD) and disconformities. Watkins et al (1974) presented a model of preferential IRD deposition in high latitudes during interglacials and in lower latitudes during glacial maxima. Subsequently, Keany et al (1976) took into account the common occurrence of manganese nodules with IRD maxima. Another model proposed by Watkins et al. (1982) uses the rates of accumulation of manganese micronodules to

- remove the effects of bottom-current winnowing
- establish the true IRD accumulation rate
- estimate the relative changes in iceberg transport of debris.

Marine geologists also have shown that IRD can be correlated with the position of the Polar Front and that the first major northward migration of the IRD maximum occurred in late Miocene time (Ciesielski et al, 1982). Widespread disconformities in the cores are thought to reflect variations in the intensity of bottom water circulation and may be associated with manganese-nodule pavements (Kennett and Watkins, 1976). From detailed investigation of disconformities, scientists have been able to interpret these features in such terms as the influence of the Antarctic Circumpolar Current on sedimentation on the Falkland Plateau (Ciesielski et al, 1982; Ciesielski and Weaver, 1983) and the effects of Circumpolar Deep Water and Antarctic Bottom Water on the Pliocene through Holocene record of the deep oceans (Osborn et al, 1983; Ledbetter and Ciesielski, 1986). The record demonstrates significant temporal variations in water mass activity through time.

Biometric analysis (e.g., Malmgren and Kennett, 1972) has proved useful in deriving paleoenvironmental information. In these studies, analysis of foraminifera from surface sediment established frequency and coiling characteristics that relate to latitude (water temperature). Such data can be used for down core interpretation of paleoenvironments.

Quaternary paleoenvironments have been the object of much investigation under the stimulus of the CLIMAP project. Cores from the Sub-Antarctic in the Indian Ocean were used by Hays et al (1976a) to demonstrate a relationship between the Earth's orbital parameters and glacial maxima, thus providing the geological support for the Milankovitch theory of ice ages. Further, Hays et al (1976b), using cores from the Atlantic and southwest Indian Oceans, developed a radiolarian-based, high-resolution biostratigraphy linked to changes in isotopic oxygen-18 values for the last 150,000 years. They established that at the last glacial maximum (18,000 years ago) the Polar Front was displaced northwards as much as 7° latitude from its present position, but the apparent lack of change in the position of the Subtropical Convergence led them to infer a contraction in the width of the Sub-Antarctic waters and an increase in the thermal gradient in those latitudes. In subsequent work based on diatom assemblages and preservation, Burckle (1984) has shown that 18,000 years ago

- a northward shift in the late-spring to early-summer annual maximum extent of the sea ice occurred, but full summer conditions were probably similar to those prevailing today
- the Weddell gyre intensified
- the Weddell polynya was displaced northward a few degrees.

In another study, Dow (1978) inferred that 18,000 years ago temperatures were 2.2°C colder than today and that the Antarctic Convergence advanced to lower latitudes six times in the last 600,000 years. *Eltanin* cores continue to yield new results, such as detailed dissolution and water-mass patterns in the southeast Indian Ocean for the Pleistocene to Recent (Williams et al, 1985a; 1985b).

Oxygen-isotope analysis of forams have established a trend of steadily declining isotopic oxygen-18 values with superimposed sharp steps and fluctuations through the Cenozoic (Shackleton and Kennett, 1975). The isotopic oxygen-18 values, which reflect both water temperature and ice volume changes, have been interpreted with respect to the glacial history of Antarctica and paleoclimate (Kennett, 1978b). The oxygen-isotope signals, the history of IRD, the record of disconformities, the northward migrations of the biosiliceous province, and the faunal and floral characteristics combine to suggest that, following an early cooling at the Eocene-Oligocene boundary, a major cooling occurred in the late Miocene, a warm period in the early Pliocene, a deterioration in the climate in the middle to late Pliocene, which was particularly marked at about 2.5 million years ago, and repeated fluctuations during the last 2 million years. The latter fluctuations seem to be directly related to northern hemisphere ice volume variations (Corliss, 1982).

Piston cores, taken largely from icebreakers and the *Eltanin*, together with other core material, have yielded much data on modern sediment dynamics within the continental shelf region and on the processes of glacial marine sedimentation. Using this data base, Anderson et al (1983) have proposed a model for polar glacial-marine sedimentation in which differences between the marine ice sheet environment and other types of antarctic coastline are brought out. The model emphasizes the influence of the great depth of the shelf on sedimentation processes and contrasts this with other modern glacially-dominated marine environments. The major role of resedimentation in sediment facies distributions on the shelf and abyssal plains, via submarine canyons, also is evident (Wright et al., 1983).

Marine geophysical surveys of the Ross Sea region established the unusual depth, about 500 meters, of the shelf and the presence of two major sedimentary basins separated by a major gravity high along the 180° meridián (Houtz and Davey, 1973; Hayes and Davey, 1975). These basins were subsequently drilled on Leg 28 of the Deep Sea Drilling Project (Hayes, Frakes, et al., 1975) and yielded important information on the inception of glaciation (see glacial geology section). The westernmost Ross Sea was not surveyed by those *Eltanin* cruises but was the focus of a recent multichannel seismic survey, which defined a major rift basin with as much as 14 kilometers of sedimentary section, possibly Cretaceous or older at the base (Cooper and Davey, 1985). A similar survey off Wilkes Land (Eittreim et al, in press) has shown that margin to be a classic passive margin with well-defined seismic unconformities interpreted in terms of rift-onset, break-up and tectonic subsidence.

The marine geophysical data sets from the deep oceans have established the timing and kinematics of continental separation. Antarctica and Australia rifted apart in the Late Cretaceous but with very slow spreading until the Late Eocene (Cande and Mutter, 1982). The pattern of anomalies associated with the East Pacific Rise show separation of the Campbell Plateau from West Antarctica at about 80 million years and a relatively straight forward spreading history as far east as the continental intersection of the Eltanin Fracture Zone (Weissel et al, 1977). In the southeastern Pacific history is complicated by the presence of migrating triple junctions associated with Cenozoic reorganization of boundaries between the Pacific, Aluk, Antarctic and Farallon Plates (Cande et al, 1982) and ridge crest-trench collision along the Antarctic Peninsula (Weissel et al, 1977). The southernmost South Atlantic is also a complicated region and the Weddell Sea, in which anomalies possibly as old as M29 (more than 65 million years ago) have been identified (LaBrecque and Barker, 1981), is particularly important for understanding the early stages of evolution of Gondwana break-up. Lawver et al, (1985) have recently proposed a model for the evolution of the southernmost Atlantic. This model shows the major role that plate motions and evolving bathymetry have in controlling paleocirculation. Similar controls are evident for the gateway between Antarctica and Australia (Weissel and Hayes, 1972). The history of paleocirculation undoubtedly bears on the history of climate change (Kennett, 1978b).

Terrestrial geophysics

Continental geophysics has been largely confined to West Antarctica and the Transantarctic Mountains. The early oversnow traverses included seismic and gravity surveys. The results from these investigations, together with regional airborne magnetic surveys and subsequent detailed studies, established the basic framework of a 40-kilometer-thick crust under East Antarctica, the abrupt change in crustal thickness along the Transantarctic Mountains front, the thin (25 to 30 kilometer) crust of West Antarctica, the regional magnetic pattern, and the state of isostatic balance (Bentley, 1983; Behrendt et al, 1980).

The radio-echo sounding program, conducted in cooperation with the Scott Polar Research Institute (Cambridge, England) and the Technical University of Denmark, collected ice thickness data and, during two years, magnetic data that have proved to be invaluable in understanding West Antarctica, the Pensacola Mountains region, a wide swath of the continent on the polar plateau side of the Transantarctic Mountains, and Wilkes Land (figure 2). (See Cameron and Bentley, this issue). The establishment of the sub-ice topography has been an important part of the development of ideas about geologic evolution (Dalziel and Elliot, 1982). More recent seismic work has confirmed the shallow depth to the Moho (Rooney et al, in press; Kim et al, 1986) and the rifted nature of the Ross Sea region (Cooper and Davey, 1985).

Terrestrial geology

Geological investigations have been conducted not only over much of the Transantarctic Mountains and West Antarctica but also in the Scotia Arc region. The Scotia Arc has long been of interest because it seems to form part of a link between South America and the geologically similar Antarctic Peninsula. Investigations in this region, that encompasses the northern Antarctic Peninsula and the Andes as far north as 50°S, have contributed not only to understanding the regional geology but also to more fundamental problems of orogenesis (mountain-formation processes) and marginal basin evolution. Studies of the structurally deformed metamorphic basement in the South Shetland Islands and South Orkney Islands (Dalziel, 1984), along with investigations in South Georgia and the Andes, have demonstrated the presence of a late Paleozoic-early Mesozoic active plate margin, which forms part of the Gondwana plate margin. Superimposed on that margin in the southern Andes and South Georgia is a younger plate margin that involved the creation of a marginal basin followed by its destruction with accompanying intense local deformation, including basement reactivation, and uplift. The history of this marginal basin and subsequent orogenesis has contributed to the broader understanding of Andean-type plate boundaries (Dalziel, 1981; 1985).

West Antarctica has been the focus of much research since it was realized that the Phanerozoic fold belts are associated with a relatively thin crust (20 to 30 kilometers thick) as compared with the 40-kilometer-thick crust of the east antarctic craton. The scattered outcrops of the rather inaccessible coastal regions of West Antarctica have been mapped (Sporli and Craddock, 1981) and the geologic history established.

Ellsworth Land and the southernmost Antarctic Peninsula also have been mapped and studied in detail. Geologists have shown that these regions are part of the Mesozoic volcanic arc and back arc terranes that can be identified throughout much of the Antarctic Peninsula (Rowley et al, 1983). The most intriguing areas—the Ellsworth Mountains, the isolated nunataks that are scattered to the south and southwest, and the Thurston Island region—have yielded information critical for understanding the evolution of West Antarctica. The upper part of the Ellsworth Mountains sequence shows clear affinities with the Beacon rocks of the Transantarctic Mountains, including glacial beds and *Glossopteris*-bearing sandstones and shales (Craddock et al, 1965). The geology of the pre-glacial beds in the Ellsworth Mountains shows similarities with sequences in the Pensacola Mountains. However, the most striking aspects of the Ellsworth Mountains are the great thickness of the Paleozoic strata, their deformation in what seems to be a single episode in the Early Mesozoic, and the orientation of the structures NNW to SSE (nearly at right angles to the structural trends in the Pensacola Mountains and the projected trends on the Pacific margin of the continent).

Starting with Schopf (1969), geologists have proposed models that suggest that West Antarctica is made up of a number of discrete crustal blocks, some of which may be allochthonous (rock transported by tectonic processes over great distances from its original site of deposition). Preliminary paleomagnetic data on the Cambrian rocks showed that the Ellsworth Mountains may have rotated 90° counterclockwise (Watts and Bramall, 1981), but recent geological and geophysical work, conducted in cooperation with the British Antarctic Survey, is providing much new data. The Ellsworth Mountains and most of the nunataks in the Ellsworth-Thiel Ridge now are regarded as part of a single structural domain, the southern limit of which runs adjacent to the Transantarctic Mountains (Storey and Dalziel, in press). The Ellsworth crustal block is now better defined, but new paleomagnetic data suggest a 20° to 30° clockwise rotation with respect to East Antarctica (Grunow et al, in press) and raises about the previously inferred original position between the Cape Fold Belt and East Antarctica. These results (Dalziel et al, in press), plus those coming from Thurston Island, will help constrain models of the tectonic evolution of West Antarctica. These models, which can be tested in the coming decade, will bear on the reconstruction of the Pacific margin of Gondwana, the fragmentation and dispersal of that plate margin, and the paleobiogeographic and paleo-oceanographic development around Antarctica.

Investigations in the Transantarctic Mountains have established that the Beacon sequence is fundamentally similar to the other Gondwana sequences but particularly to that of South Africa. The Victoria Group of the Beacon Supergroup includes glacial deposits, a black shale unit, *Glossopteris*-bearing coal, Triassic vertebrate-bearing beds that pass upward into *Dicroidium* and coal-bearing strata, and a capping sequence of Jurassic basalts and comagmatic diabase sills intrusive into the Beacon rocks. With continuing study, geologists have been able to develop models for the evolution of the Beacon depositional basins and the relations to the sequences on adjacent Gondwana landmasses (Elliot, 1975; Collinson et al, in press).

Paleontology

Beacon rocks have yielded some highly significant paleontologic finds. Reptile, mammal-like reptile, and amphibian fossils recovered from the Lower Triassic Fremouw Formation were crucial in the paleontologic demonstration of the reality of continental drift and sea-floor spreading (Barrett et al, 1968; Elliot et al, 1970; Kitching et al, 1972). The composition and diversity of the early Triassic faunas not only demonstrate close taxonomic parallels with the Lystrosaurus zone of South Africa but now make paleoecological studies worthwhile (Hammer and Cosgriff, 1981).

Paleobotanical discoveries have been equally impressive. Initial recovery of abundant leaf impressions of the *Glossopteris* and *Dicroidium* floras have been followed by the discovery of silicified peat deposits associated with both floras. The Permian (*Glossopteris*) locality is one of only two known for that time period. The other locality, which is in Australia, lacks the exquisite preservation, diversity of components, and abundances of material that are present in Antarctica at Skaar Ridge, Mt. Augusta, near the head of the Beardmore Glacier (Schopf, 1982).

The deposit of Triassic age (*Dicroidium*) is unique because no other similar deposit exists anywhere in the world. These silicified peats are comparable to the Carboniferous coal balls of northern Europe and the Mid-West. Like them, the deposits permit such studies as the anatomy of plants, their histology, the occurrence of fungal attack, and the associated fruiting bodies (Stubblefield and Taylor, in press). These peat deposits are yielding data of fundamental importance in paleobotany.

Besides contributions to the study of the Gondwana flora and fauna, significant paleontological work has been done in other areas of the continent. Of the studies on the Cambrian faunas, the most interesting is probably the current work on the faunas from the Heritage Group in the Ellsworth Mountains. This fauna may be the most diverse fauna of that age anywhere; furthermore, preservation is very good with many fossils preserved as shells rather than casts or molds. The fauna includes the only conodonts from the antarctic continent proper and has the youngest known Archeocyathids. A wide variety of trilobites are present and some primitive echinoderms, but most important are the 20 species of molluscs that include monoplacophorans, rostroconchs, cephalopod-like fossils and gastropods. The fauna is unique for the variety of primitive molluscs (Webers, 1972; Webers et al, in press). Collections from the Devonian strata in the Ohio Range and the Ellsworth Mountains have extended the Malvino-kaffric faunal province into West Antarctica.

The investigation of the geology and paleontology of Seymour Island off the northern Antarctic Peninsula also has provided significant data. Seymour Island has possibly the best upper most Cretaceous-Lower Tertiary marine sequence in the Southern Hemisphere. The late Cretaceous molluscan fauna, particularly the ammonites, has considerable biogeographic importance as well as significance for Cretaceous-Tertiary boundary problems (Macellari, 1986). The Cretaceous-Tertiary boundary now is being located through paleontological studies of the associated faunas.

The late Eocene-early Oligocene invertebrate faunas are exceptionally well preserved, diverse, and abundant. A distinctive austral faunal province referred to as the Weddellian Province (Zinsmeister, 1979; 1982) has been observed, and these fossils also have yielded data bearing on heterochroneity (Zinsmeister and Feldmann, 1984). A small number of marsupial fossil remains, the only terrestrial fossil mammals known from Antarctica, have been found in the Upper Eocene beds (Woodburne and Zinsmeister, 1982, 1984). These fossils are significant in the paleobiogeography of marsupials. They demonstrate that a land connection existed between the southern tip of South America and the Antarctic Peninsula during the latest Cretaceous and earliest Tertiary periods and that Antarctica acted as a dispersal corridor for marisupials between South America and Australia before Gondwana broke up (Zinsmeister, 1984).

On the other side of the continent, micropaleontologic work on core material from the ice-free valleys of southern Victoria Land and from McMurdo Sound (core samples in the latter case were provided by the New Zealand Antarctic Research Program) has yielded data on the timing of glacial events.

Mapping

From these geological and paleontological studies, as well as many others not mentioned in this paper, geological maps of the continent have been compiled. The 1:1,000,000 sheets of the principal outcrop areas produced by the American Geographical Society (AGS) (Bushnell and Craddock, 1969) with support from the National Science Foundation (NSF) and the AGS 1:5,000,000 map of the whole continent (Craddock, 1972) include data collected not only by the U.S. program but also by programs of other nations. More recently, NSF has funded the U.S. Geological Survey to publish quadrangle maps of parts of the Transantarctic Mountains and West Antarctica. Mapping by Dalziel and co-workers has been incorporated in a tectonic map of the Scotia Sea region (Anon, 1985). The antarctic sheets being compiled under the Circum Pacific Map (Craddock, in press) also include much data gathered by U.S. scientists.

Glacial geology

Since the IGY, earth scientists have made major advances in understanding the glacial history of Antarctica and, consequently, in understanding the history of climatic change in the Cenozoic. The data comes primarily from five sources—the study of piston cores from the deep ocean (obtained largely during cruises of *Eltanin*), more recent continental drilling in the ice-free valleys of southern Victoria Land, marine cores drilled from McMurdo Sound, the Deep Sea Drilling Project Legs 28 and 35, and studies of the terrestrial record of glaciation.

The deep-ocean cores have provided much data from ice-rafted debris, disconformities, sediment type, and the contained fossils on the changes in the behavior of water masses and the position of the Polar Front. These changes most likely are related to variations in the volume of the ice sheets on Antarctica. The deep-sea record has yielded data primarily on the changes during Pliocene to Recent time; however, much important information on pre-Pliocene events has been obtained from the Maurice Ewing Bank (51°S 43°W) (Ciesielski et al, 1982).

Investigations in southern Victoria Land and the McMurdo Sound region have included both the Dry Valley Drilling Project coring and the geologic mapping of glacial deposits and features (Stuiver et al, 1981; Denton et al, 1984). The results of these studies clearly show that the ice-free valleys of southern Victoria Land have been largely deglaciated for more than 4 million years, are uplifted fjords, and contain a record of glacial events going back to the Late Miocene. It is also evident that there have been glacial advances from the Ross Sea side as well as from the polar plateau. Detailed mapping has built a chronology of glacial fluctuations and also points to overriding of the Transantarctic

Mountains by the east antarctic ice sheet. Higher relative ice levels have been demonstrated also for the Ellsworth Mountains and inferred for the region of the Marie Byrd Land volcanoes. Ice volume increases, however, are difficult to determine because of the lack of information on the age of the glacial features and the uplift of the mountains.

Along with the moraines associated with present glacial drainage there are tills which have a less obvious relationship. Many of these till deposits are included in the Sirius Formation which occurs at elevations up to 2,700 meters and in settings that are unrelated to present drainage. These tills have yielded marine microfossil floras and faunas (Webb et al, 1984). During the 1985-1986 austral summer, wood fragments and other plant debris, including pollen and spores, also were recovered (P.N. Webb and R. A. Askin, personal communication, 1986). The marine microfossils, contained in mud clasts as well as being dispersed in the tills, are dominated by Pliocene taxa and suggest open marine waters, which Webb and others argue were located over East Antarctica during the Pliocene and possibly at several intervals of time earlier in the Cenozoic. This suggest much greater changes in ice volume than previously thought. The plant debris infers temperatures warm enough at 85°S and 1,800 meters elevation (assuming no uplift) to support a sparse vegetation, possibly of tundra type (R.A. Askin, personal communication, 1986). The scale of these variations had not been indicated in the commonly accepted proxy record of antarctic glaciation based on the oxygen isotope record from the oceans.

The absolute dating of glacial events and features, however, remains a major hurdle. Studies of the terrestrial record in West Antarctica have shown the antiquity of glaciation, although the nature and extent of the ice cover remain uncertain. Subglacially-erupted hyaloclastites of Marie Byrd Land volcanoes indicate an age of at least 27 million years (LeMasurier and Rex, 1983). A similar age for early glaciations is provided by results obtained from the Ross Sea during Leg 28 of the Deep Sea Drilling Project (Hayes, Frakes, et al., 1975). At Site 270, glacial sediments indicate that tidewater glaciers calved into the Ross Sea embayment approximately 25 million years ago. Recent paleontological and paleomagnetic data obtained by U.S. scientists from the cores recovered by the New Zealand Antarctic Research Program from McMurdo Sound suggest glacial sedimentation by about 30 million years ago and seven expansions of terrestrial ice into this region (P.N. Webb, personal communication, 1986). On the other hand, the oldest glacial striae, found in the Jones Mountains, can only be dated at about 7 million years or older based on radiometric age determinations of the overlying basaltic rocks (Rutford et al, 1971).

Meteorite studies

Since 1976 U.S. scientists have searched the blue ice areas* along the Transantarctic Mountains for meteorites. During the first 3 years the U.S. Antarctic Program collaborated with the Japanese Institute of Polar Research in these searches. U.S. investigators have found more than 2,000 fragments.

By ice sheet transport and direct fall, meteorites are concentrated in certain areas of blue ice where ablation is the dominant surface process (Whillans and Cassidy, 1983). The meteorite finds give a new perspective because of petrological and geochemical differences in the antarctic and non-antarctic populations, but the causes and extent of these differences are unclear and debated (Lipschutz and Cassidy, in press). Accepting these differences, the antarctic populations provide not only quantitative estimates of the proportions of different types of meteorites but also estimates of the influx rate because the terrestrial ages can be determined from the decay of cosmogenic nuclides. The oldest age determined so far is 1 million years. This age has important implications for the long-term existence of the east antarctic ice sheet.

The meteorites, despite their age which for the Allan Hills averages 0.3 million years, have suffered very little weathering and are as valuable as modern falls. Apart from these aspects, finds are being made of rare and unusual meteorites, and nearly every season produces another discovery. A lunar sample was recovered in 1981 and is believed to have originated from part of the lunar highlands not sampled by the Apollo or the U.S.S.R. Luna programs. New samples of another unusual group of meteorites, the SNC meteorites, have been found and include one shergottite that contains noble gases and nitrogen with isotopic compositions suggesting derivation from Mars.

Outside the research accomplishments but of major service to the international community on the part of the U.S. scientists are the Symposium on Antarctic Geology and Geophysics held in Madison, Wisconsin, in 1977 and, although less directly concerned with Antarctica, the Sixth Gondwana Symposium held in Columbus, Ohio, in 1985, and the associated publications of the proceedings.

*Blue ice areas occur where glacial movement is stagnated by solid earth ridges. The wind continually ablates less-dense surface layers and exposes the very dense layer, which appears to be a very dense blue.

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Glaciology

Antarctic glaciology has advanced dramatically since the International Geophysical Year (IGY). Perhaps the most striking technological advance was the development of radar sounding of ice thickness, particularly from the air. Its importance to glaciology is comparable to the importance to oceanography of the development of the sonic echo sounder that replaced the lead line. During the IGY an individual sounding of the ice sheet by seismic shooting took 2 or 3 hours and was followed a day later by another sounding several kilometers away. Radar sounding, in contrast, takes less than 50 microseconds for an individual measurement and yields a continuous profile of ice thickness at aircraft flying speed.

In January 1958, Amory H. Waite of the U.S. Signal Corps conducted the first successful radar sounding of an ice sheet on ice up to 600 meters thick near Wilkes Station, East Antarctica. Following his lead, researchers at the Scott Polar Research Institute in England, the University of Wisconsin in the United States, and the Technical University of Denmark developed this technique further. By the middle 1960's, scientists routinely used radar sounding on the surface and from the air to map the subglacial topography and to study ice characteristics.

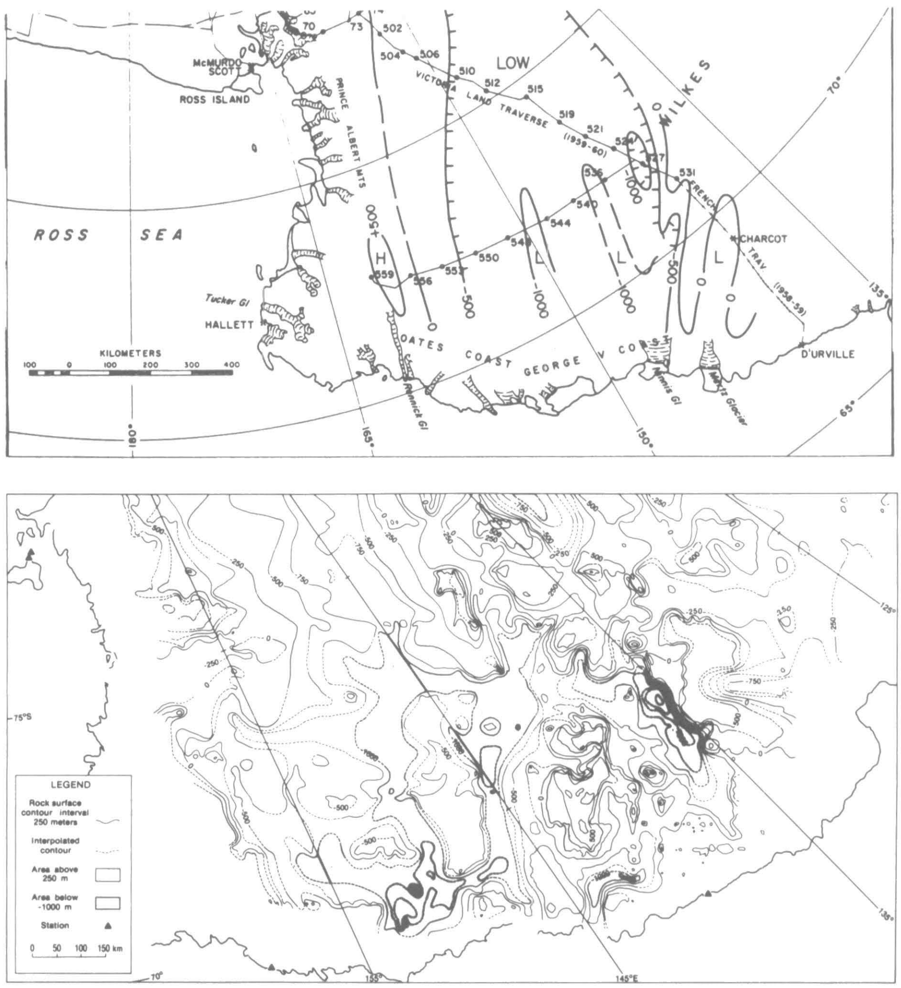
Between 1967 and 1979 a cooperative American-British-Danish radar sounding program from U.S. ski-equipped Hercules (LC-130) airplanes was conducted over 50 percent of Antarctica. An example of how radar sounding improved knowledge of the subglacial topography of the continent is shown in figure 1. The two maps in this figure show the subglacial topography of eastern Wilkes Land based on two different data sets—one from IGY measurements and the other from the radar flight program.

Radar sounding yields much more information than simply the ice thickness (Bogorodsky, et al., 1985). Of particular interest are the many internal layers in ice sheets of Antarctica and Greenland. These internal layers are associated with small density changes, presumably depositional or diagenetic, and with changes in electrical conductivity related to volcanic ash fallout. The internal reflections provide isochrons* within the ice sheet that can be invaluable in studying how ice flow varies in time and space. Changes in the character of the basal echo have proved useful in delineating what appear to be lakes beneath the ice sheet where the ice is thick enough for its bed to be at the melting point. Characteristic signals from features within the ice, such as bottom crevasses on ice shelves, can be identified on successive flight tracks and, consequently, provide precise ice movement paths. Crevassing near the surface is a particular feature of the giant ice streams that glaciologists now know transport most of the ice from the antarctic interior; these ice streams produce a striking difference in the radargram that has been recorded over them and that makes it possible to identify ice streams even when the crevasses are buried and invisible (figure 2).

The advent of radar sounding has not, however, diminished the usefulness of seismic sounding. On floating ice shelves, whose importance to the dynamic balance

*"Isochrons" are lines connecting points of equal age.

Figure 1. Two maps of subglacial topography in Wilkes Land, East Antarctica. The upper map is from seismic and gravity soundings on oversnow traverses during the IGY (Crary, 1963). The lower is from airborne radar sounding (Steed and Drewry, 1982).



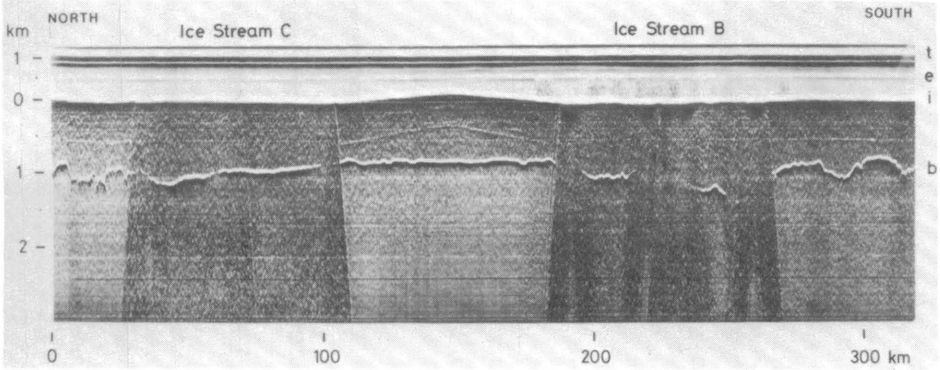


Figure 2. Radargram showing a profile across two West Antarctic ice streams. The ice-bottom reflection is at about 1 kilometer. Note the scattered returns from near-surface crevasses that extend from top to bottom of the record under the ice streams. (From Rose, 1979).

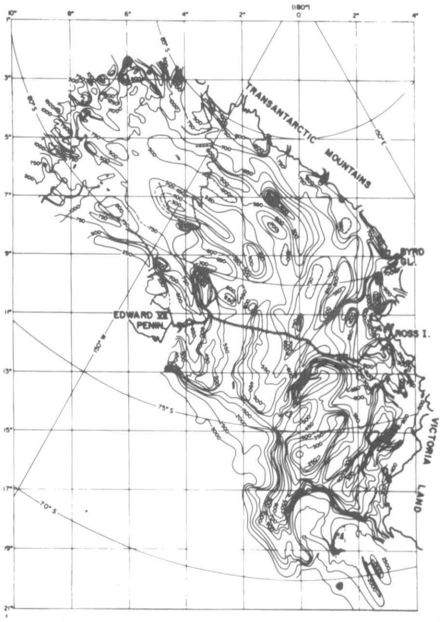


Figure 3. Map of the subglacial and submarine topography in the entire Ross Embayment. The contour interval changes from 50 meters under the Ross Sea and Ross Ice Shelf to 250 meters under the west antarctic inland ice. (From Bentley and Jezek, 1981).

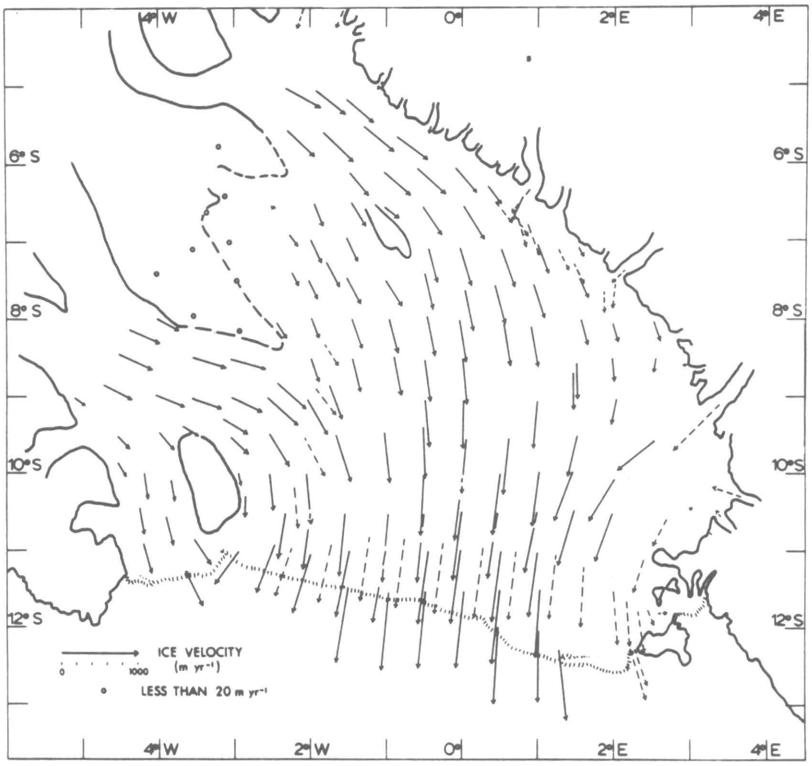
of the ice sheet becomes ever more apparent, seismic sounding can be combined with radar sounding to give both ice thickness and water depth below the ice (radar waves do not penetrate water). In the mid-1970's, as part of the Ross Ice Shelf project (RISP) (one of several detailed surveys of selected areas supported by the United States), a 5-year project called the Ross Ice Shelf Geophysical and Glaciological Survey (RIGGS) was conducted. This program, which used Twin Otter airplanes, included among its many measurements (Bentley, 1984) seismic soundings of the water depth; these soundings were then combined with oceanic soundings in the open Ross Sea and radar soundings of the inland ice of West Antarctica. These data yielded a subglacial morphology map (figure 3) that shows no indication in the subglacial morphology of the outer edge of the ice shelf or of the boundary between the grounded and floating ice. This fact dramatizes the impermanence of the glacial boundaries.

At one RISP site (J-9), oceanographers and biologists used first a flame-jet drill and then a hot water drill to gain access to the ocean beneath the ice shelf. Nearby at the same site, Soviet glaciologists obtained an ice core by using antifreeze-thermal drilling through the shelf (Zotikov, et al., 1980). This core included 6 meters of sea ice that had frozen to the shelf bottom. Although it had previously been proposed that basal freezing occurs beneath parts of the ice shelf, this was the first time that sea ice was observed on the base of the Ross Ice Shelf.

Another technological revolution in glaciology resulted from the development of Doppler-satellite positioning. During the IGY, the velocity of ice movement could only be measured close to rock outcrops, which are few in Antarctica. Satellite techniques now have made possible accurate positioning to a few meters in just a few hours. Measurements repeated at the same spot on the ice after a suitable time period (a few months to a few years, depending on the speed of ice movement), yield precise velocities. One of the accomplishments of RIGGS was the production in this way of a velocity-vector map of the ice shelf (figure 4).

Because glaciologists are now able to map ice thickness and ice movement in detail, they can test some rather dramatic theories about the dynamic behavior of the ice sheet, particularly that of West Antarctica. Many theories on ice sheet growth, surging, and similar behavior exist, but not until Weertman (1976) wrote about "glaciology's grand unsolved problem" did the glaciological community focus its attention on the west antarctic ice sheet. Stimulated by writings of T.J. Hughes, Weertman challenged glaciologists to confront the physics of this marine ice sheet, whose base over much of its area was 0.5 to 1 kilometer below sea level. How does it remain in existence? Is it growing or shrinking at this time? Could it disintegrate in hundreds of years?

Figure 4. Map of ice velocity vectors on the Ross Ice Shelf. Values from RIGGS measurements are depicted by solid arrows; dashed arrows are from earlier measurements. (From Thomas et al, 1984).



Weertman also asked why the ice streams that drain most of the interior west antarctic ice into the Ross and other ice shelves move so fast. The latter question is a key to the stability of the ice sheet, and preliminary results of recent investigations relating to it are now being published. Glaciologists suggested that a thin water layer beneath ice streams was responsible for their swift motion. However, seismic sounding (Blankenship et al, in press) has shown that beneath one ice stream a subglacial till layer that is several meters thick is a likely mechanism for the fast "sliding." Another intriguing aspect of ice-stream behavior is that ice stream C on the Siple Coast, which clearly was once one of the major ice streams, has stopped its rapid motion, perhaps within the last few centuries.

To understand ice-sheet behavior the rate of snow accumulation on the surface of the ice sheet must be known. Because that rate can differ from year to year, an average over several years is desirable. During the IGY, scientists determined accumulation rates by studying the stratigraphic features in the walls of snow pits and in ice cores. The idea was to identify annual layers by the cyclic variations in density, grain size and type, hardness, and other characteristics. The success of this method depended heavily on the skill and experience of the observers and was subject to serious errors in the cold, low-precipitation interior regions of Antarctica. An important development for mass balance studies, therefore, was the discovery that discrete radioactive-fallout horizons, stemming from atmospheric hydrogen-bomb tests, occur all over the ice sheets. The most distinctive marks occur during the austral summers of 1954-1955 and 1964-1965. These horizons are easily identified in ice cores and provide excellent means of determining mean accumulation rates over a decade or more (depending on when the core was collected).

Measurements of accumulation rates by this means were included in the program of RIGGS; the resulting map (Clausen, et al., 1979) is the only one of the Antarctic that provides accurate values covering the surface of a large region. Many such measurements have also been made along traverses on the high interior plateau of East Antarctica; these measurements led to a drastic lowering of estimates of mean accumulation rates relative to those made from IGY and post-IGY pit studies.

The great strides that have been made in measuring snow accumulation rates, ice thicknesses, and velocities have greatly improved the ability of glaciologists to determine the net mass balance of the ice sheet, i.e., the difference between mass input in the form of snowfall and mass output in the form of melting and calving of icebergs. Although definitive conclusions cannot yet be drawn about the ice sheets as a whole, analyses gradually have accumulated on individual drainage basins within the ice sheet. Together, they strongly suggest that the amount of ice in the Antarctic is not decreasing and may be growing slowly. A recent workshop study on the effect of glaciers and ice sheets on sea level (Polar Research Board, 1985) concluded that at present the best estimate of average net growth of the ice sheet amounts to 20 millimeters (plus or minus 20 millimeters) of ice per year or an equivalent to a sea-level lowering of 0.6 millimeters (plus or minus 0.6 millimeters) per year.

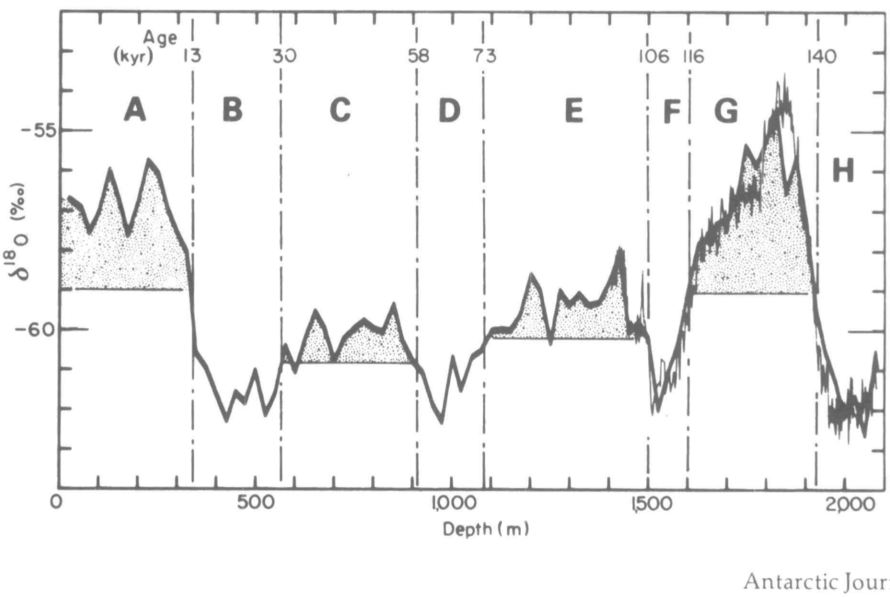
Another impressive leap forward in our understanding of polar ice sheets came from deep ice-core drilling from 1966 to 1968. During those 3 years the ice sheets in Greenland and Antarctica were cored through to bedrock; consequently, more ice core than the world had ever had before was available for immediate and archival study. The U.S. Army Cold Regions Research and Engineering Laboratories (CRREL) fielded engineering and scientific teams that recovered 1,375 meters of core from Camp Century, Greenland, in 1966 and 2 years later (in 1968) recovered 2,164 meters of core at Byrd Station in West Antarctica. This was one of the major engineering and logistics accomplishments of the U.S. glaciological program, considering the remote sites for the drilling, the hostile environment, and the difficulty of drilling in ice.

No aspect of polar glaciology has produced more spectacular results than the analyses of these deep ice cores and those that have been retrieved since the 1960's. There are now five deep core holes that penetrate at least into ice that fell on the surface of the ice sheet during the last ice age. We will consider three parameters in particular—the oxygen-isotope ratios, total gas content, and carbon-dioxide levels. Oxygen-isotope ratios (oxygen-18 to oxygen-16), which depend on the ambient temperature at the time of precipitation, show strikingly the climatic transition from the last ice age to the present interglacial. One core penetrated both the last glacial epoch and the last interglacial and into the top of the ice deposited in the previous glacial epoch. The record in that core, from the Soviet station Vostok in central East Antarctica, shows that the present Holocene period was preceded by a long glacial period marked by two relatively warm interstades** (figure 5). The well-marked last interglacial was significantly warmer than the Holocene, and the end of the previous glacial was similar to the last glacial maximum.

Oxygen-isotope changes may be interpreted in terms of paleotemperature, but the cause of past temperature changes is not only climatic. If the surface elevation of the ice sheet on which the snow fell changed with time, the temperature would have changed accordingly, even without climatic change. The amount of total gas trapped as gas bubbles in the ice depends upon the atmospheric pressure at the time the bubbles were formed by the compaction of porous snow and, therefore, upon the elevation. By measuring both the oxygen-isotope ratio and the total gas content, scientists can separate the two effects. The data suggest that the ice surface of central West Antarctica was no higher than it is today and perhaps even 100 or 200 meters lower during the last glacial period (Raynaud and Whillans, 1982).

**"Interstade" refers to a warmer substage of a glacial stage.

Figure 5. Oxygen-18 versus depth in an ice core from Vostok, in central East Antarctica. An approximate age scale is given at the top of the figure. More negative values of isotopic oxygen-18 mean colder temperatures. (From Lorius et al, 1985).



Weather at U.S. stations

Feature	February 1986				March 1986				April 1986			
	McMurdo	Palmer	Siple	South Pole	McMurdo	Palmer	Siple	South Pole	McMurdo	Palmer	Siple	South Pole
Average temperature (°C)	- 6.6	3.9	-18.2	-36.1	-16.5	3.3	-21.6	-52.0	-20.3	- 0.4	-25.5	-58.2
Temperature maximum (°C) (date)	1.5 (3)	9.0 (5)	- 7.9 (24)	-25.5 (23)	- 2.6 (1)	7.3 (20)	- 6.0 (2)	-35.4 (4)	- 5.8 (30)	6.5 (25)	-14.2 (4)	-40.7 (14)
Temperature minimum (°C) (date)	-16.3 (25)	- 1.2 (8)	-34.7 (9)	-46.8 (28)	-31.4 (30)	- 2.6 (9)	-32.4 (25)	-69.5 (27)	-39.9 (15)	- 5.5 (11)	-40.7 (20)	-65.4 (29)
Average station pressure (mb)	994.4	984.0	870.6	694.6	993.8	986.7	870.7	685.1	983.0	987.2	863.2	681.7
Pressure maximum (mb) (date)	1003.5 (22)	1009.1 (27)	880.0 (25)	704.5 (24)	1007.5 (17)	1017.2 (25)	885.0 (4)	702.2 (17)	993.4 (18)	1006.9 (13)	873.3 (25)	693.9 (7)
Pressure minimum (mb) (date)	981.3 (1)	964.2 (17)	864.8 (14)	683.7 (2)	965.8 (31)	952.1 (30)	858.5 (23)	667.9 (30)	967.9 (1)	964.0 (8)	844.5 (1)	669.5 (15)
Snowfall (mm)	7.6	2.5	0.0	TRACE	3.8	1.8	0.0	TRACE	17.0	12.5	0.0	TRACE
Prevailing wind direction	095°	360°	175°	010°	090°	120°	184°	360°	070°	030°	190°	360°
Average wind (m/sec)	7.0	8.6	9.6	9.4	5.1	6.8	10.6	20.2	5.7	7.5	8.8	9.0
Fastest wind (m/sec) (date)	21.9 160° (25)	26.8 080° (3)	23.0 180° (21)	31.1 023° (20)	25.9 200° (25)	31.9 360° (27)	30.0 180° (12)	39.2 360° (30)	29.1 150° (30)	27.8 060° (28)	28.3 350° (5)	32.2 338° (4& 11)
Average sky cover	5.7	7/10	8/10	0.6	6.7	8/10	9/10	0.4	6.8	8/10	6/10	0.5
Number clear days	8.0	12.8	2.5	7.0	5.0	5.5	2.0	8.0	4.0	6.9	7.0	10.0
Number partly cloudy days	14.0	2.7	4.5	10.0	11.0	5.6	0.2	9.0	5.0	6.4	3.2	13.0
Number cloudy days	6.0	11.5	14.0	11.0	15.0	20.0	13.7	14.0	21.0	16.7	16.0	7.0
Number days with visibility less than 0.4 km.	0.0	---	7.0	0.4	1.4	---	9.0	3.8	1.5	---	3.7	1.0

Prepared from information received by teletype from the stations. Locations: McMurdo 77°51′S 166°40′E, Palmer 64°46′S 64°3′W, Siple 75°55′S 83°55′W, Amundsen-Scott South Pole 90°S. Elevations: McMurdo sea level, Palmer sea level, Siple 1054 meters, Amundsen-Scott South Pole 2835 meters. For prior data and daily logs, contact National Climate Center, Asheville, North Carolina 28801.

Measurement of the carbon-dioxide concentration in the gas bubbles and comparison with the oxygen-isotope record have shown that carbon-dioxide changes are associated with climatic changes. Levels in recent but pre-industrial times were some 40 percent higher than they were during the last glacial epoch. Naturally, it would be of great interest to know whether a cause and effect relationship was apparent between the changes in the amount of ice and the variation in the levels of atmospheric carbon dioxide. Intriguingly, detailed studies, accurate to a few 100 years in relative time, have been unable to distinguish any time lead of one variation over the other (Stauffer et al, 1984). Although this result does not reveal which change (if either) causes the other, it does show that response times in the carbon-dioxide-climate system are very short.

A quantum leap in our understanding of the antarctic ice sheet has occurred since the IGY. As technology provides new tools and physics provides new techniques, more data will be available to improve our understanding of the dynamics of the ice and its historical development. With satellite altimetry, mapping of the surface topography can be conducted with such precision as to measure fluctuations in ice sheet volume, and further deep ice-core drilling could well provide a climatic record for more than a million years.

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