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ICE CORE PALEOCLIMATE HISTORIES FROM THE ANTARCTIC PENINSULA: WHERE DO WE GO FROM HERE?

Ellen Mosley-Thompson

Byrd Polar Research Center, Department of Geography, The Ohio State University, Columbus, Ohio

Lonnie G. Thompson

Byrd Polar Research Center, Department of Geological Sciences, The Ohio State University, Columbus, Ohio

It is essential to determine whether the strong 20th century warming in the Antarctic Peninsula (AP) reflects, in part, a response to anthropogenically driven, globally averaged warming or if it is consistent with past climate variability in the region. The necessary time perspective may be reconstructed from chemical and physical properties preserved in the regional ice cover and ocean sediments. Only three multi-century climate histories derived from ice cores in the AP region have been annually dated with good precision (± 2 years per century). The longest record contains only 1200 years and the three histories do not provide a coherent picture of 20th century climate variability. The highest elevation core, Dyer Plateau, reveals a 20th century increase in accumulation and isotopic enrichment (warming) and indicates that the high ice plateau extending southward to the West Antarctic Ice Sheet is strategically situated to capture large-scale climate variability in the region. Such histories are critical to unraveling the role of various forcing mechanisms and discerning the leads and lags in the system. Ocean-atmosphere connections between Antarctica and the tropics have gained considerable attention as Antarctic Intermediate Water (AAIW) links conditions along the Antarctic margin with those in both the tropical Pacific and the North Atlantic. Current knowledge of past climate conditions in the Antarctic Peninsula is limited. High resolution proxy histories from ice cores drilled at carefully selected sites along the AP spine offer tremendous opportunities to examine past climate variability and place regional climate changes within a much broader geographical context.

INTRODUCTION

Chemical constituents and physical properties preserved within the permanent ice cover along the spine of the Antarctic Peninsula (AP) contain a record of climatic and environmental changes over tens to thousands of years. Ice cores drilled at higher accumulation sites that are carefully selected to minimize disturbance of the ice strata by flow at depth will provide land-based proxy records to complement the climate histories emerging from high deposition rate sediment cores along the Peninsula margin [*Domack et al.*, this volume]. An ice core drilling project currently underway on Berkner Island is expected to produce a long history, possibly back into the Last Glacial Stage (LGS). However, at present the longest annually dated ice core-based history for the western side of the Ronne-Filchner Ice Shelf (RFIS) is the Dyer Plateau record that extends back to AD 1504 (all dates henceforth are AD). Here we review the status of ice-core derived climate records in the Peninsula region with emphasis upon those offering multi-century histories, summarize what we have learned from these records, discuss what new insights may be gleaned from the ice, and emphasize the need to extract longer, high resolution ice core-based climate histories.

MODERN CONTEXT

Temperature records for Antarctica are sparse and short with few extending prior to the International Geophysical Year (1957–58). This is particularly true for the continental interior. The longest and most dense network of meteorological records is in the Antarctic Peninsula region where the temperature record at Orcadas (South Orkney Islands) extends to 1903. *King et al.* [this volume] review the surface temperature records in the Peninsula that extend to the late 1940s and the upper air measurements that began in 1956. Their analyses demonstrate marked differences between the temperature trends in the AP and the rest of the continent (East and West Antarctica). *Jones et al.* [1993] also noted that temperature variations in the AP region are poorly correlated with those on the main part of the continent and concluded that extending the Antarctic temperature record by using the longer temperature histories from the Peninsula would be inappropriate. Within the AP region there are strong interannual differences among the station temperatures [*Peel,* 1992*; Limbert,* 1974] that reflect differential responses to forcing by sea ice extent (proximity to open water) and temporal variations in atmospheric and oceanic circulation patterns. Nearly two decades ago *Schwerdtfeger* [1984] highlighted the strong climatological differences between the east and west sides of the Peninsula's mountain range that extends over ~16°of latitude (~80–64°S) and acts as a natural barrier to the circum-Antarctic current, the prevailing westerly winds, and the katabatic barrier winds. With the advent of routine satellite-borne observations, installation of automatic weather stations (AWS), and computer models to synthesize these data, the spatial variability of climate in the Antarctic Peninsula is now better documented [*Simmonds,* this volume].

Near-surface air temperatures have warmed markedly in the AP region [*Marshall et al.,* 2002; *Morris and Vaughan*, this volume]. *King et al.* [this volume] report that over the past 50 years summer air temperatures have risen about ~1.0°C, increasing ~0.2°C per decade. Temperatures in the lower- and mid-troposphere have warmed at a rate that is consistent with Southern Hemisphere trends. However, they note the most striking observation is the marked difference in the strength of the surface warming trend in summer and winter along the west side of the Peninsula. Here winter temperatures near the surface are warming at a rate of 0.1°C annually, making this the region of strongest warming in the Southern Hemisphere [*King et al.,* this volume]. They note that this strong warming is confined to the lower layers of the atmosphere. *Smith et al.* [1999] also observed this seasonal difference and suggested a strong oceanic role in the forcing. Observations reveal that the winter trend of +0.11°C per year at Faraday/Vernadsky Station is among the largest in the Southern Hemisphere. In 2001 the AP (Palmer Land) was one of Earth's three warmest regions [*Hansen et al.*, 2002].

This well-documented warming in the AP is of significant concern in light of the climatological and ecological sensitivity of the region. The warming in the last 50 years has been accompanied by other marked physical and biological changes. These include the distribution and persistence of coastal fast ice and a reduction in the extent and integrity of many of the ice shelves [*Vaughan and Doake,* 1996*; Vaughan et al.,* 2001*; Scambos et al.,* this volume; *Skvarca and De Angelis*, this volume], the persistence of lake ice [*Quayle et al.*, this volume], and changes in the range and size of sea bird populations [*Emslie et al.,* 1998]. The region is fragile from both a physical and biological perspective. A vast volume of land-based ice and floating ice shelves exists very close to the –9°C isotherm, the upper limit for viability of ice shelves [*Morris and Vaughan,* this volume], that appears to be creeping southward. This raises concerns about the potential melting and/or enhanced calving of the land-based ice that could contribute significantly to global sea level rise. The ecological systems in the region are complex and highly dependent on the physical and chemical cycles that will undoubtedly be affected by warming temperatures, reduced ice cover in the near-shore environment and increased fluxes of fresh water to the sea [*Convey,* this volume; *Emslie et al.*, 1998; *Smith et al.*, 1999].

A number of pressing questions emerge: Why are temperatures in the AP increasing so strongly while the rest of the Antarctic continent shows little change? What processes are responsible for the strong warming in winter along the west side of the Peninsula? Is this recent warming anthropogenically forced and if so, how much? Is the recent multi-decadal warming in the AP just one more in a sequence of naturally forced oscillations within the complex, coupled ocean-atmosphere system?

Progress has been made on the first question. *Thompson and Solomon* [2002] present an analysis of radiosonde temperatures and geopotential heights since 1979 that suggest a long-term trend toward a stronger circumpolar flow that warms the AP and southern tip of South America, but isolates and thus cools eastern Antarctica and the high polar plateau. The question remains whether this trend that is linked to the strength of the Southern Annual Mode is influenced by anthropogenically produced trace gases and/or stratospheric ozone depletion [*Simmonds*, this volume]. Whether the AP warming is anthropogenically forced or part of a longer-term oscillatory feature can only be addressed from the much longer temporal perspective available from proxy (indirect) climate histories preserved in stratified deposits such as marine sediments and ice cores.

This volume contains a number of papers presenting marine-based histories and to complement these, this paper reviews the existing ice core-based climate histories. The discussion below highlights the dearth of multi-century ice-core records in the AP, their temporal limitations, and argues strongly for an immediate and sharply focused effort to recover cores from those sites offering the potential for both long and high temporal resolution records. The discussion in the following sections highlights the need for rigorous development of a modern context for the climatological interpretation of the proxy indicators preserved within the accumulating snow. Implementing an array of AWS that include an acoustic depth gauge and sensors at multiple levels at drilling sites would reveal the timing of snowfall (when the record is produced) and allow calculations of surface fluxes for energy balance considerations. In addition, a geophysical survey is needed to guide site selection and thereby ensure the longest and least disturbed records possible. Currently, it is unknown whether the ice fields along the spine of the AP are gaining or losing mass, but such an evaluation is essential in light of the strong regional warming and the recent loss of extensive areas of shelf ice. If the plateau ice fields are threatened by the current warming, then attaining the paleoclimate histories preserved therein would assume a new level of urgency.

EXISTING ICE CORE HISTORIES FROM THE PENINSULA REGION

In the past two decades scores of shallow depth (< 40 meters) cores have been collected in the Antarctic Peninsula region by researchers from various international institutions. The major efforts have been by British, Argentine and German scientists and no attempt is made here to compile a list of all these cores because most of them are short (in both length and time represented). Further, it would be virtually impossible to use many of the existing cores to compile a ‘representative’ ice core-based climate history because of the differences in their chemical and physical analyses, their temporal resolution and coverage, and the quality of their time scales. In fact, due to the diversity of the climatological regime in the region [*Jones et al.*, 1993; *King et al.*, this volume], a single composite would not be appropriate. The strong climatological differences between the east and west sides of the Peninsula, as well as between the east and west sides of the Weddell Sea sector, argue that such an integration on annual and decadal scales would diminish important details of the regional climate histories. However, a large-scale composite would be quite useful on centennial to millennial scales.

A search of the literature reveals six cores from the AP that extend to earlier centuries. The locations of these core sites are shown in Figure 1. *Peel* [1992, his figure 28.6] synthesizes the results from three sites: James Ross Island (JRI), Site T340, and Dolleman Island (DI). Thus, we review them only briefly and chronologically. The ice core drilled in 1979 on JRI (Fig. 1) extended back to ~1850 and provided the first ice core-based climate study in the AP [*Aristarain et al.*, 1987]. Their comparison of the hydrogen isotopic (deuterium) records with surface air temperatures measured since 1956 at nearby stations (Esperanza and Faraday) suggested that the climate on James Ross Island is influenced by the climate regimes of both the eastern and western sides of the Peninsula, but the western climate regime dominates. Their filtered isotopic record (Fig. 2c), calibrated with AP temperature records (1953–1980), suggests a cooling of ~2°C for the northern part of the Antarctic Peninsula over this 27-year span and a general cooling trend over most of the 20^{th} century. This isotopic record is inconsistent with the known air temperature trends in the AP. Their observation calls into question the use of isotopic records for paleoclimate reconstruction. As discussed later, the isotope-temperature relationship must be critically evaluated as part of future paleoclimatic research endeavors in the AP.

In 1989 a 100-meter core was drilled at Site T340 (~78°60’S; 55°W; Fig. 1) on the RFIS by the German Antarctic Research Program [*Graf et al.*, 1988]. Here accumulation is estimated to be ~155 mm w.e. (water equivalent) and the core was dated using seasonal $\delta^{18}O$ variations preserved throughout most of the core. The

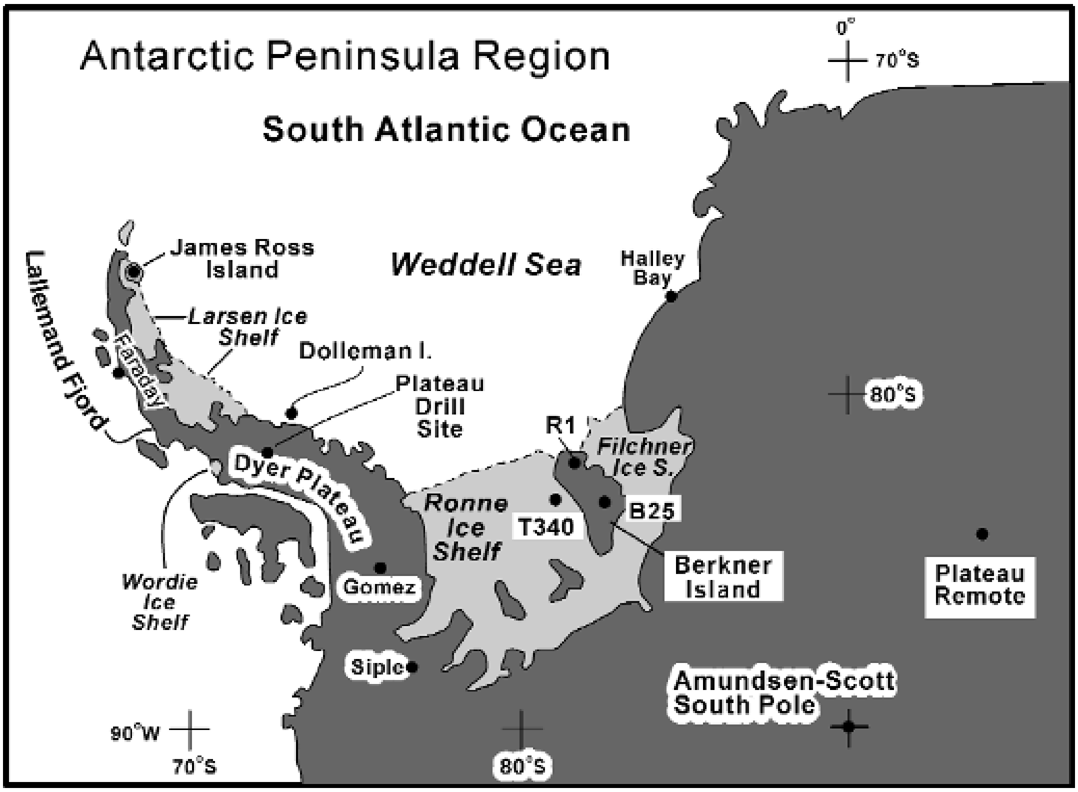

Fig. 1. The locations of the Antarctic Peninsula ice core sites discussed in the text are shown.

quality of the δ¹⁸O signal was compromised by partial melting in the upper 89 meters during storage so that of the 479 annual δ¹⁸O layers identified, about 80 (~16%) were expressed only as small maxima on shoulders of larger peaks. Five meters of core (in the upper part) were not recovered and extrapolation from surrounding sections resulted in the addition of 41 years so that the record extends back to 1460. The northward flow of the ice means that the ice (originally deposited as snow) did not accumulate at a single location, but over time as the ice progressed northward along its flowline. Thus, *Graf et al.* [1988] attempted to correct the δ¹⁸O record downcore (back in time) for increasing continentality. The T340 δ¹⁸O record, smoothed with an unspecified filtering function, suggests a slow cooling from the mid-nineteenth century toward the present and no recent warming, inconsistent with instrumental observations.

In 1986 British Antarctic Survey (BAS) scientists recovered three cores, the deepest to 133-m, on Dolleman Island (Fig. 1) where annual accumulation is roughly 420 mm w.e. *Peel et al.* [1988] reconstructed the DI climate (δ¹⁸O) record that extends back to 1795 (Fig. 2b). In 1981 two shorter (30.5 and 83-m) cores were collected by BAS scientists at the Gomez Nunatak (record not shown) where the very high accumulation rate of 880 mm w.e. resulted in a much shorter record extending back only to 1942. In brief, *Peel et al.* [1988] note that from 1938 to 1986, the δ¹⁸O records reflect most of the pronounced interannual variations observed in AP surface temperatures and from 1960 to 1980 the enrichment of δ¹⁸O is consistent with the overall warming in the AP. However, from the middle of the nineteenth century to the 1960s the Dolleman δ¹⁸O history also shows a broad cooling trend toward the present similar to that at T340 and JRI. Thus, from 1902 to 1960 the DI isotopic record does not show an isotopic enrichment (warming) contemporaneous with the warming trend evident in the Orcadas surface temperature record [*Peel et al.*, 1996, their Figure 28.6] and throughout the Peninsula region [*Jones et al.*, 1993].

In 1988 a cooperative glaciological-climatological ice core project was initiated on the Dyer Plateau (70°40’16”S; 64°52’30”W; 2002 masl; Fig. 1) where the mean annual temperature is about -21°C. In 1988–89 the first geophysical observations were made *[Raymond et al., 1996*] and two cores were drilled to 108-m depth at a site 6 km west of the ice divide. In 1989–90 two cores (233.8 m and 235.2 m) were drilled one meter apart at the crest in the ice divide. The 1989 cores were analyzed only to 181-meters because the quality of the core recov-

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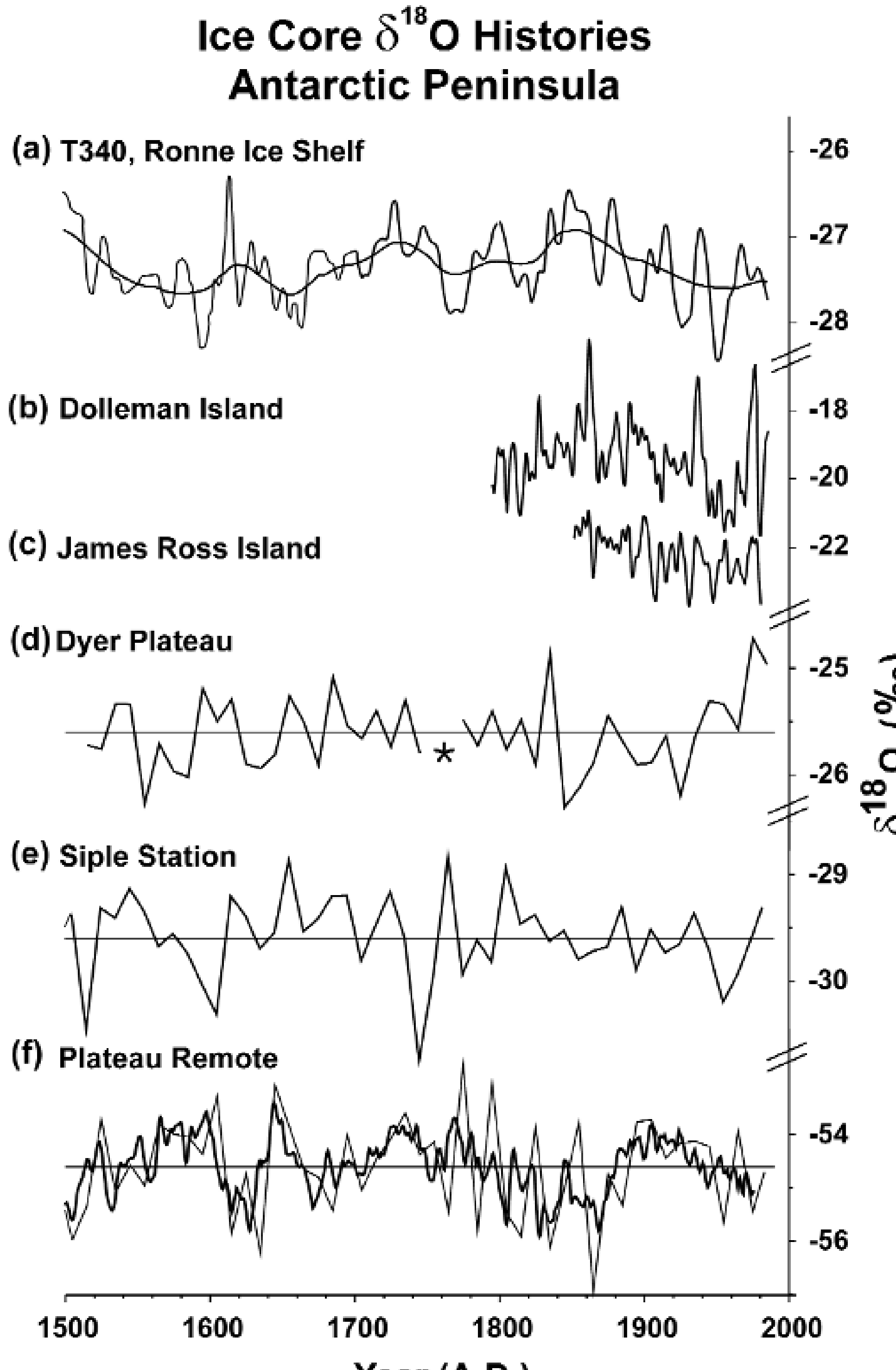
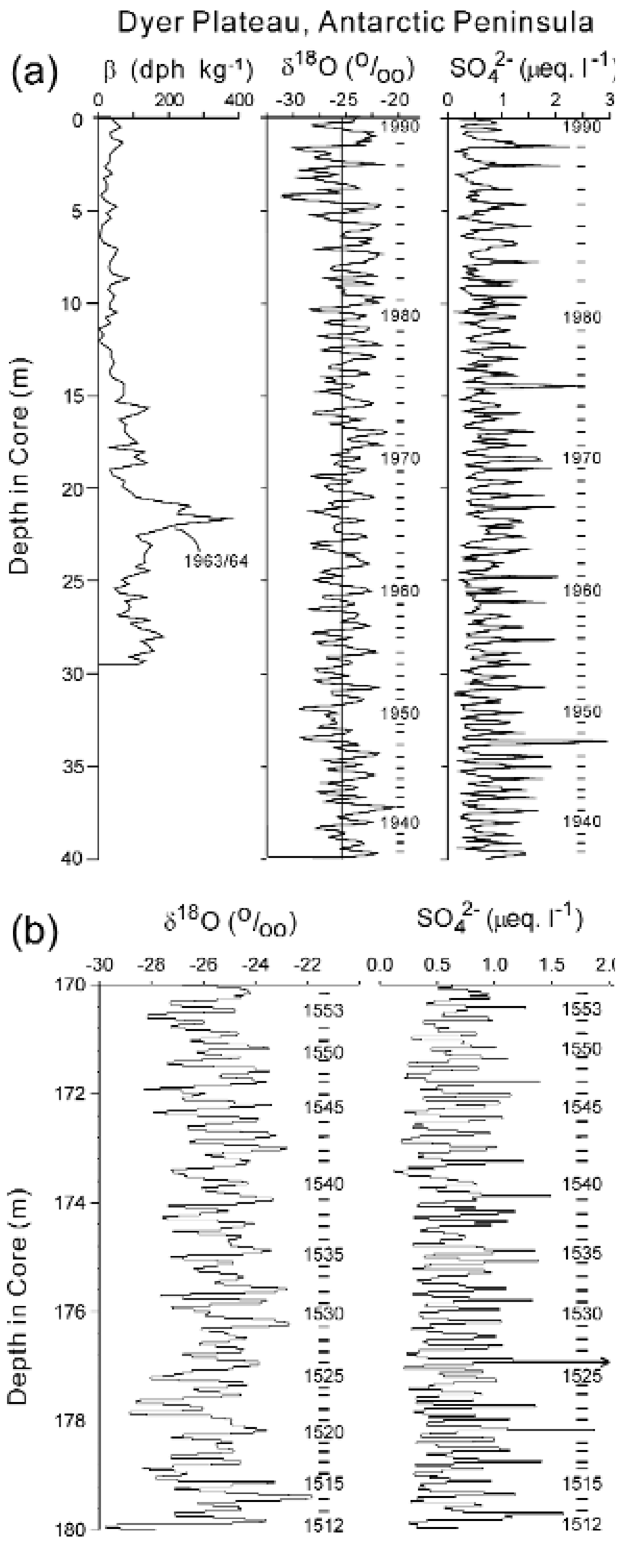


Fig. 2. The isotopic records from six of the cores discussed in the text are shown: (a) The record from T340 on the Ronne Ice Shelf is from *Graf et al.* [1988]; (b) The Dolleman Island record is from *Peel* [1992]; (c) The James Ross Island core is from *Aristarain et al.* [1986]; (d) The decadal averages of $\delta^{18}O$ from the Dyer Plateau are from Thompson *et al.* [1994]; (e) The decadal averages of $\delta^{18}O$ from the Siple Station record are from *Mosley-Thompson* [1992]; and (f) The decadal averages of $\delta^{18}O$, along with the 20-year un-weighted running mean (darker line) are from *Mosley-Thompson* [1996].

ered below that depth was very poor. The upper 181 meters provided an annually dated record extending back to 1505 [*Thompson et al.*, 1994]. Figure 3(a) shows $\delta^{18}O$ and sulfate (SO_4^{2-}) concentrations for each sample in the upper 40-m of the core to illustrate the seasonal variations used to date the cores. The beta radioactivity profile reveals the 1963–64 time-stratigraphic marker associated with thermonuclear testing [*Crozaz*, 1969] that confirms the annual character of chemical signals used for dating. Figure 3(b) shows $\delta^{18}O$ and sulfate (SO_4^{2-}) concentrations for each sample in the lowest 10 meters of the 181-m core to confirm that the seasonal features are still excellently preserved. The time scale was reconfirmed by the identification of the major known volcanic events in the last 500 years [Fig. 4 in *Dai et al.*, 1995].

In 1995 a joint BAS-AWI (Alfred Wegner Institute) project recovered two cores (151 and 181-m), one from each of the two main domes of Berkner Island (Fig. 1). *Mulvaney et al.* [2002] present the chemical and isotopic records that extend back ~700 years for the R1 core (northern dome) and ~1200 years for the B25 core (southern dome). At present these are the longest, best dated cores in the AP region and the borehole temperatures suggest a warming of 0.5 to 1.0 °C in the recent past. The shape of borehole temperature records can be modeled to extract past temperature changes if past accumulation rates, the ice flow pattern, and geothermal heat flux are known or can be approximated [*Dahl-Jensen et al.*, 1998]. The Berkner cores were analyzed in very high temporal resolution and dated using seasonal variations in electrical conductivity (ECM) supplemented by chemical records in parts of the core where ECM was vague. The ECM signal does identify some of the largest known volcanic events (e.g., Tambora), but *Mulvaney et al.* [2002] report that in general the ECM does not give as clear a volcanic history as sites higher on the polar plateau because the volcanic signal is masked by the large seasonal ECM signal. The relationship between the isotopically inferred temperatures and those calculated from sea level temperatures using the dry adiabatic lapse rate suggest that Berkner Island experiences a persistent surface inversion. Their 1200-year $\delta^{18}O$ history oscillates around a fairly stable mean, lacks much variability, and does not record a 20th century warming. The discrepancy between the $\delta^{18}O$-inferred temperature history and that from borehole measurements warrants future investigation. The chemical signals retain their annual character to the bottom of the core which bodes well for their preservation deeper in the ice dome. Currently a project is underway to recover an ice core to bedrock from the southern dome where ice is ~1000 m thick,



accumulation is high (~1300 mm w.e.), the underlying bedrock is flat, the winds are low, and basal temperatures are expected to be about –12°C. *Mulvaney et al.* [2002] conclude that this is an excellent site from which to capture the long-term climate history of the region, possibly extending back to the Last Glacial Maximum (LGM) and resolving whether Berkner Island ice cap emerged from the overlying West Antarctic Ice Sheet to become an independent dome or whether the ice dome was deposited *in situ*.

Although $\delta^{18}O$ is widely used as a temperature proxy, interpretations necessarily suffer from the limitations of isotope thermometry. The $\delta^{18}O$ relationship is influenced by multiple processes that include (1) air temperature at the time of condensation; (2) condensation and evaporation that occur within the airmass along its route from the source (ocean) to the deposition site (ice sheet); (3) local glaciological conditions as snow is converted to firn and then to ice; (4) the elevation of the deposition site; and (5) seasonality in the precipitation regime (a signal is only produced when snow is falling). The seasonality of precipitation is particularly critical when comparing meteorological observations averaged throughout the calendar year to an ice core $\delta^{18}O$ record that may be strongly biased to a specific season.

Peel and Clausen [1982] conducted an extensive investigation of the temperature-isotope relationship using 10-meter temperatures and $\delta^{18}O$ analyses of 10-meter cores at 25 sites located on or in close proximity to the Peninsula (for sites see their Figure 1). They report a systematic δ-T relationship throughout the AP that they were able to describe by a model in which an air mass in equilibrium with SMOW (standard mean ocean water) at 10°C (i.e., a mixing ratio of 7.8 g of water per kg of air) cools isobarically as it moves poleward, reaching the coast at ~ –4°C. Subsequent cooling by adiabatic uplift results in further isotopic depletion. Their investigation, designed to identify potential drill sites, led them to conclude that the best sites would be on the ice rises along the east coast (such as Dolleman Island) and along the spine of the Peninsula at sites south of 73°S.

A more recent comparison of the existing temperature and isotopic records in the Peninsula region [*Jones et al.*, 1993] highlights the lack of a consistent picture of climate variability in the AP as pieced together from the available ice core records, observations made at permanent stations, and records taken by early expeditions [*Jones et al.*, 1990]. In general, the $\delta^{18}O$ records (interpreted as a proxy for temperature and subject to the limitations discussed above) are at odds with the limited meteorological observations over the last century. While the AP has experienced a century-long warming, the ice core evidence is mixed. The James Ross record suggests that the warmest temperatures occurred in the mid-nineteenth century with subsequent cooling. This broad scale trend is also evident in the cores from Dolleman Island and T340, although the isotopic trend on DI reversed in 1960 to become more consistent with observed air temperatures.

These core records suggest an increase in net annual accumulation (more precipitation would likely reflect warmer air temperatures [*Jones et al.*, 1993]) throughout the 20th century and this observation is also at odds with the isotopic records. This discussion highlights the perplexing nature of the ice core evidence of climate variability in the Peninsula. Clearly, more progress must be made in understanding the linkages among the various climate regimes in the Peninsula, the relationship of the Peninsula climate to that of the rest of the Antarctic Continent, and the utility of ice cores from the Peninsula to provide representative multi-millennial histories of climate variability in the region. Certainly expecting five cores, from widely diverse climatological settings, to provide a coherent picture for a region with complex meteorological and oceanographic forcing is not realistic. In the concluding section of this paper we return to this point along with recommendations for future research.

As with any ice cores, those from the AP reflect local, regional and larger-scale processes, but regional and larger-scale processes are of greater climatological interest. Excluding the Gomez core that extends back only to 1942, the Dyer Plateau cores provide the only paleohistory from the ice plateau that blankets the spine of the Peninsula. To expand our spatial perspective on climate variability along the axis of the Peninsula, two other ice core histories are included in this discussion. A 302-meter core was drilled in 1985 in West Antarctica, at the base of the Peninsula at Siple Station (75°55'S; 84°15'Wl; 1054 msal; Fig. 1). The Siple core provides a 550-year proxy climate history [*Mosley-Thompson et al.*, 1991; *Mosley-Thompson*, 1992] that covers nearly the same time interval as the Dyer cores. To expand the spatial view even further, we have included the most

Fig. 3a,b. The seasonal variations in $\delta^{18}O$ and sulfate concentration used to date the entire DP core are shown in (a) for the upper 40 meters. The major beta radioactivity peak in 1963/64 confirms the seasonality of the chemical signals. (b) The excellent preservation of the annual variations in $\delta^{18}O$ and sulfate concentrations is shown for the lowest 10-m (170 to 180 m) of the 181-m core.

recent 500 years of a 4000-year record from a 200-meter core drilled in 1986 at Plateau Remote (84°S; 43°E; 3330 masl; Fig. 1) in East Antarctica [*Mosley-Thompson*, 1996].

Figure 2 illustrates all the existing multi-century records from the Peninsula region, except the new 1200-year history from Berkner Island [*Mulvaney et al.*, 2002]. The top three records, T340, DI and JRI are reproduced as they were originally presented and were smoothed using different filters as discussed in their respective references. The Dyer and Siple records are shown as simple decadal averages. The PR $\delta^{18}O$ record is plotted as decadal averages with a 20-year un-weighted running mean (darker line in Fig. 2f). Unlike the DP and SS cores in which each annual value was the average of 6 to 10 samples, the low accumulation (~40 mm w.e.) at PR resulted in only one or two samples per year such that a single sample might reflect only winter or summer precipitation or even parts of two different years when accumulation was unusually low. The decadal averages of annual accumulation and dust flux for the DP, SS, and PR cores are shown in Figure 4a and 4b, respectively.

The $\delta^{18}O$ record from DP (Fig. 2d) varies consistently around the long-term mean (1505–1989) until ~1840 after which conditions apparently cooled until 1920. From 1920 to 1940 the average $\delta^{18}O$ became progressively more enriched and since 1940 the decadal averages have remained above the long-term mean. Thus, unlike the JRI, DI and T340 records, the DP site recorded much of the 20th century warming evident in the meteorological records. Moving southward to Siple Station, the $\delta^{18}O$ record shows little variation about the mean (1500–1986) and no 20th century warming. At the PR site on the East Antarctic Plateau $\delta^{18}O$ is more variable, in part reflecting the low resolution sampling interval discussed above. The Plateau Remote (PR) record contains some longer-term (~century scale) oscillations with a brief (~3 decades), but strong cooling in the early 17th century. Conditions remain at or above the long-term mean from 1660 to 1780 after which a gradual cooling trend persists until 1870 after which conditions warm rapidly, peaking at the turn of the 20th century. Since that time the $\delta^{18}O$ record indicates a cooling trend to the present. The PR $\delta^{18}O$ record, like those from South Pole, does not show 20th century ^{18}O enrichment (warming) [*Mosley-Thompson*, unpublished data]. Similarly, the recently published isotopic record from Berkner Island [*Mulvaney et al.,* 2002] also does not show a 20th century warming. Thus, with the exception of the Dyer Plateau and Dolleman Island records, the ice core isotope histo-

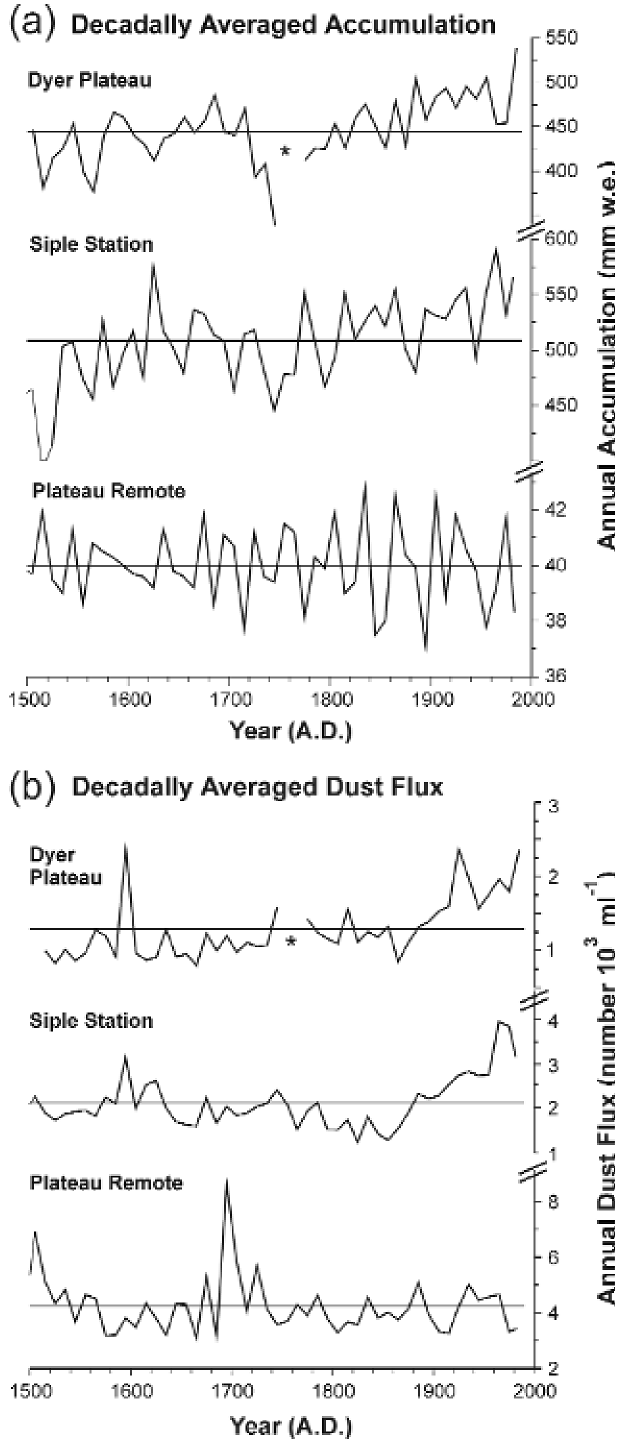


Fig. 4a,b. The decadal averages of net annual accumulation are shown in (a) and the annual dust flux is shown in (b) for the Dyer Plateau core [*Thompson et al.*, 1994], the Siple Station core [*Mosley-Thompson*, 1992], and the Plateau Remote core [*Mosley-Thompson*, 1996].

ries in the AP do not record a 20th century warming. Unlike the Dyer Plateau where warming begins around 1920, the warming on DI begins four decades later in the 1960s. In light of the precision with which these core are dated (Fig. 3a, b), dating differences cannot account for this offset.

Peel [1992] noted that the Dolleman Island cores show a 20th century increase in accumulation that is counterintuitive if conditions are not warming. Figure 4a illustrates the decadal averages of the 500-year records of net annual accumulation from DP, SS, and PR. The PR accumulation record should be viewed cautiously given the dating limitations as noted above. Since 1900 accumulation has been consistently above the long-term mean at Dyer and at Siple it has been above the mean in all decades but one. Both accumulation records were corrected for compression with depth [*Thompson et al.*, 1994; *Mosley-Thompson et al.*, 1993, respectively], although the effect is small in the upper layers of the ice plateau. The accumulation increase at DP is also consistent with geophysical measurements that suggest a gradual increase in accumulation over the last 200 years from 460 mm ice equivalent to 540 mm ice equivalent [*Raymond et al.*, 1996]. The PR site shows no trend in accumulation.

To summarize, there is strong evidence for a regional increase in 20th century accumulation (i.e., Dolleman, Dyer, Siple), but proxy-based ($\delta^{18}O$) evidence of warming over the entire 20th century is evident only in the Dyer Plateau records. Clearly, meteorological evidence from the Antarctic Peninsula confirms the 20th century warming in both the near surface and mid-troposphere. So why have most of the ice core records failed to capture this larger-scale atmospheric signal? *Jones et al.* [1993], *Peel* [1992], *Peel and Clausen* [1982] and *Peel et al.* [1996] have addressed this issue. *Jones et al.* [1993] note that correlations (r) between temperature and both $\delta^{18}O$ and δD are on the order of –0.5 (R^2 = 0.25), leaving 75% of the variance unexplained. Other factors influencing $\delta^{18}O$ include temporal changes in moisture sources for the different sites, proximity to the sea ice edge and hence the differential influence of sea ice cover, seasonal differences in delivery of snowfall to the site, and glaciological controls on the preservation of the $\delta^{18}O$signal after snow deposition. The few ice cores in hand, coupled with potential dating errors and the lack of analysis of both $\delta^{18}O$ and δD for the same samples, limits resolution of these differences. *Peel et al.* [1996] suggest that the isotopic signals at sites strongly exposed to the weather systems in the Weddell Sea may not be good recorders of regional air temperature trends. For example, the $\delta^{18}O$ records suggesting mid-19th century warmth (Fig. 2a, b, c) may reflect the strong influence of changes in sea ice cover. *Peel et al.* [1996] note that these cores contain elevated concentrations of methane sulfonate (MSA^-) and reduced deuterium excess, d=δD-8($\delta^{18}O$), suggesting proximity of the sites to the ice edge (open water) or the influence of intermittent polyna. They conclude, and we agree, that cores from the higher altitude sites along the ice-covered spine of the AP are more likely to record the regional temperature variations than the lower elevation sites that are more strongly influenced by changes in the local sea ice distribution and persistent surface inversions.

Limited data suggest that on millennial time scales the climate in the Antarctic Peninsula may be more tightly coupled to that on the East Antarctic Plateau. The $\delta^{18}O$ record from the Plateau Remote core extends back 4000 years with nearly annual resolution (Fig. 5d). As discussed in more detail by *Mosley-Thompson* [1996] the long-term isotopic trend shows a cooling over the last four millennia with three broad oscillations of roughly 1200 years. The 4000-year record is much too short to determine whether the oscillations are periodic. The PR $\delta^{18}O$ record suggests warmer conditions from 4000 to 2500 ka, broadly contemporaneous with more open water in Lallemand Fjord (Fig. 1) inferred from elevated total organic carbon (TOC) in ocean sediments (Fig. 5c) [*Shevenell et al.*, 1996], with a mid-neoglacial cooling (~2.5 ka BP) on South Georgia Island (Fig. 5b) [*Clapperton et al.*, 1989], and with warmer conditions inferred from more depleted $\delta^{18}O$ in foraminiferal tests in the high resolution sediment record from the Bermuda Rise [Fig. 5a; *Keigwin*, 1996]. Twelve high to medium resolution sediment cores recently collected on the west side of the AP provide more details about the Holocene climate [*Domack et al.*, this volume]. Their records reflect warmer conditions dominating from the Early to the Middle Holocene with the onset of neoglacial cooling at ~ 3.2 ka. The PR $\delta^{18}O$ record (Fig. 5d) is broadly consistent (within dating uncertainties) with their marine record. The average $\delta^{18}O$ from 3.8 to 2.5 ka BP is –52.11‰ and from 2.5 ka BP to AD 1986 it is –54.12‰, nearly 2‰ more depleted (cooler). *Domack et al.* [this volume] report their cores contain a Medieval Warm Period (1.15 ka to 0.7 ka), a Little Ice Age signal (0.7 ka to ~0.15 ka) and 200-year oscillations in the regional climate/oceanographic conditions. At present there are no high-resolution ice core histories from the Antarctic Peninsula longer than 1200 years so that land-based evi-

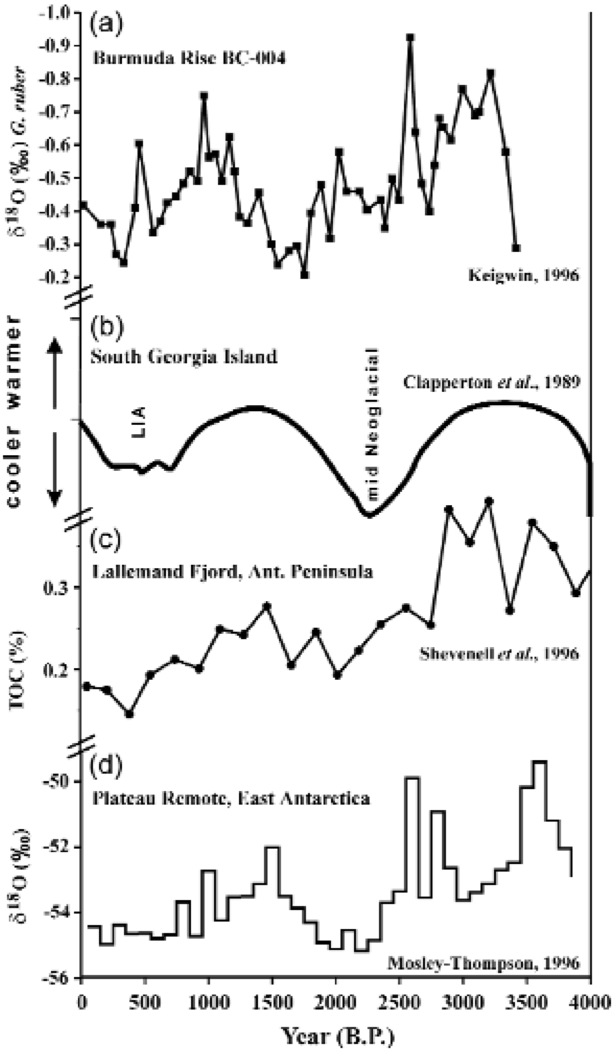


Fig. 5. Four different proxy records covering nearly the last four millennia are shown. These are (a) the isotopic abundance in G. Ruber tests in a high resolution sediment core from the Bermuda Rise [Keigwin, 1996]; (b) the climate history on South Georgia Island inferred from glacial geologic evidence [Clapperton et al., 1989]; (c) total organic carbon from a sediment core in the Lallemand Fjord indicates warmer conditions (more open water and higher TOC) and cooler conditions (more ice cover and lower TOC) [Shevenell et al., 1996]; and (d) the 100-year averages of δ^{18}O from an ice core at the Plateau Remote site (see Fig. 1) in East Antarctica [Mosley-Thompson, 1996].

dence to support these oceanographic records does not exist. The 4000-year δ^{18}O record from Plateau Remote (Fig. 4d) provides a tantalizing hint of teleconnections from the East Antarctic Plateau through the Peninsula region and up through the Atlantic Basin as suggested by its similarity to the high resolution δ^{18}O record from the Bermuda Rise (BR). This linkage is not as speculative as it might appear upon first consideration.

A potential mechanism linking Antarctic proxy histories and those from lower latitudes (e.g., the BR record) is provided by the Antarctic Circumpolar Current (ACC) that constitutes the primary moisture source for snow that accumulates on the Antarctic ice fields. The ACC is a combination of recirculated waters from Pacific Ocean, Indian Ocean and modified North Atlantic Deep Water [*Shevenell and Kennett,* 2002]. *Keigwin* [1996] reports that changes in the production of North Atlantic Deep Water and in sea surface temperatures account for one-third and two-thirds, respectively, of the variability in the δ^{18}O content of *G. Ruber* at the BR site. *Hodell et al.* [2001] illustrate (their Fig. 5b) the similarity of their diatom δ^{18}O record from a piston core at ~53°S with Keigwin's δ^{18}O record from BR. In fact, the near synchroneity of a large mid-Holocene climate change, ~5–6 ka, in both the South and North Atlantic regions [*Hodell et al.*, 2001], as well as in the tropics [*Thompson et al.*, 2002], support the hypothesis [*McIntyre and Molfino*, 1996] that such large-scale changes are initiated in the tropics and transmitted poleward by changes in surface winds that control the poleward advection of warm surface waters. The dynamics of these mechanisms by which climate changes may be propagated over long distances require further investigation as more similarities are reported among polar and low latitude proxy histories. Longer, higher resolution ice cores from the spine of the AP are needed to link climate changes in the AP with those at more distance sites.

CONCLUSION: WHERE DO WE GO FROM HERE?

At present, the number of multi-century ice core records from the AP–Weddell Sea region that are dated with good precision (± 2 years per century) is three: Dolleman Island, Dyer Plateau, and Berkner Island (in press). Dolleman and Dyer were drilled more than a decade ago and show similar accumulation histories, but different isotopic trends. The Berkner Island δ^{18}O record does not show 20th century warming or an increase in accumulation [*Mulvaney et al.*, 2002]. If the 20th century warming in the Peninsula, currently one of the strongest signals on the planet, is to be placed within a longer-term perspective, more well-dated ice cores extending further back in time must be drilled from sites that are sensitive to large-scale regional climate variations. The cores must be analyzed in the greatest possible temporal resolution for numerous chemical and physical constituents, but most particularly for both $\delta^{18}O$ and δD [*Jones et al.,* 1993].

Data from existing cores suggest that the best sites for capturing large-scale climate variability will be on the ice fields that blanket the spine of the AP. Here the higher annual accumulation and strong seasonal variations in a number of chemical constituents, coupled with known volcanic horizons, will allow very accurate dating back thousands of years. Importantly, these records will also provide the critical link between the histories from existing Antarctic cores (Byrd Station, Dome C, Taylor Dome, and Siple Dome) as well as those emerging from more recent cores (Dome Fuji, EPICA-Dome C, EPICA-Droning Maude Land, and Law Dome) and the low latitude ice core histories from the Andes of South America (Sajama and Huascarán) and Kilimanjaro in Africa. At present the climate trends in the Peninsula appear decoupled from those in the Antarctic interior, but only contemporaneous ice core-based climate histories can reveal whether this relationship has persisted over thousands of years or is a late Holocene phenomenon. Moreover, the 20th century warming trend observed in the AP is clearly recorded in the tropical and subtropical ice core records collected around the Pacific Basin [*Thompson*, 2000; *Thompson et al.*, 2003].

The ocean-atmosphere connections between Antarctica and the Tropics are gaining considerable attention. Antarctic Intermediate Water (AAIW) provides an intimate link between conditions along the Antarctic margin and those in both the tropical Pacific and the North Atlantic. Thus, understanding the history of tropical and north Atlantic climate variability also requires knowledge of the conditions along the Antarctic coastal margin where the AAIW forms. *Pierrehumbert* [2000] notes that wind-driven upwelling in the Southern Ocean around Antarctica affects both the volume of AAIW that spreads northward and the depth of the tropical thermocline. Thus, a small shift in the circum-Antarctic wind stress pattern has the potential to modulate the climatic behavior of the tropical Pacific. Further, the rejection of brine by sea ice formation is critical to the formation of the dense water that gives rise to the Antarctic Bottom Water. Thus, *Pierrehumbert* [2000] concludes that the changes along the Antarctic ice margin are likely to be felt in the tropics and from there these effects will ripple to the rest of the planet. However, the hemispheric linkages are complex and issues of leads and lags abound *[Steig and Alley, in press*]. Millennial scale climate variability is well preserved in the inland cores from Vostok, Byrd Station, and the new EPICA core at Dome C but the major cold events are not in phase with those in the Greenland cores (*Blunier et al.*, 1998) leading to the suggestion of a bi-polar seesaw [*Broecker*, 1998]. However, methane concentrations from the Law Dome ice core [*Morgan et al.*, 2002] place the initiation of the Antarctic Cold Reversal before the Bölling transition (~14.5 ka BP in GRIP). These results support other evidence [*Steig et al.*, 1998; *Jouzel et al.*, 2001] that argue against a bi-polar seesaw. For example, Taylor Dome has a deglaciation pattern similar to that in Greenland [*Steig et al.*, 1998; 2000], but concerns remain about the timing of the deglaciation in that core [*Mulvaney et al.*, 2000]. To further complicate matters, the Siple Dome climate history (also from the Ross Embayment) looks more like those from East Antarctica (Dome C and Vostok). Thus, the timing of both the deglaciation and the major warm/cold events between the hemispheres, or even within Antarctica, has yet to be unraveled. New high resolution ice core records from carefully selected sites on the ice field extending along the spine of the Antarctic Peninsula, coupled with the long core currently being drilled on Berkner Island, will contribute new insight to the leads and lags in the global ocean-atmosphere system.

It is time to consider seriously a project to acquire a suite of cores along the spine of the Peninsula. To ensure long and interpretable records, the program must include site selection using radar profiles of the basal topography and internal reflection layers. South of the 1989/90 DP drill site toward Siple Station the ice field becomes thicker and wider, thus decreasing the percent of the ice core that will be disturbed by basal conditions and complex flow. As mentioned previously, the contemporary relationships among annual and seasonal air temperatures, the timing of precipitation, and the isotopic composition of the accumulated and preserved snowfall must be quantitatively evaluated. *In situ* monitoring at selected drill sites by installation of an AWS with an acoustic depth gauge system, coupled with pit sampling and isotopic modeling efforts [e.g., *Werner and Heimann*, 2002] must be included if the chemical signals in the ice cores are to be correctly interpreted [*Jouzel*, 1999]. The ice cores could be recovered using Ohio State's suite of portable, light-weight electro-mechanical and thermal-alcohol drills that recovered good to excellent quality core to a depth of 460 meters on the Bona-Churchill col in southeastern Alaska in 2002. The depth capability of these drills can be extended to 1000 meters with modest modification. The complete drill system [*Zagorodnov et al.*, 2002] including the camp and personnel can be moved from site to site by two twin otters as long as the fuel, ethanol, and core boxes are positioned by other flights.

The key questions that must be addressed with new cores from the ice field along the spine of the Antarctic Peninsula include:

1) Is the apparent decoupling of the climate in the Peninsula and on the polar plateau a 20th century phenomenon (possibly anthropogenic) or does this relationship persist over many millennia?
2) New sediment cores indicate warmer conditions in the Mid to Early Holocene in the AP, but what is the land-based evidence for Early Holocene warmth and how does it compare to the 20th century warming?
3) Can the ice core chemistry shed light on the history of the disintegration of ice shelves in the region? Sediment coring is planned to reconstruct the history of ice shelf growth and decay, but contemporaneous ice core proxy records will be needed to explore the climate forcing. Is the current diminishment of the ice shelves climatically driven, glaciologically driven or both? Long histories from new cores will be essential to unravel the controlling processes.
4) What is the history of local, regional and global volcanism recorded in these cores? This requires comparing excess sulfate histories from AP cores to similar histories from other parts of Antarctica as well as from Greenland.
5) Does the ice field along the spine of the Peninsula contain glacial stage ice? If so, what is the nature and timing of the deglaciation and how does it compare with the transition as recorded in the Ross Sea Sector, Greenland, or South America? This is critical for unraveling the leads and lags in the climate system as it transitions from glacial to interglacial conditions and from stadial to interstadial.
6) Was a large dust event at 4.2 ka BP globally distributed? At present there is great interest in this event that appears to have blanketed much of the tropics during a three century long drought that may have been responsible for societal disruptions in the Middle East [i.e., the beginning of the First Dark Age]. The timing of this dust event is at issue. However, the dust concentrations in the Dyer Plateau core are very low so that if this dust is present it should be easy to detect. As this dust event is prominent in the Andean ice fields of Peru it is reasonable to expect that it might be recorded in ice fields of the AP. If so, carefully sited cores could provide a firm date for this dust event that may have disrupted the course of human history [*Thompson et al.*, 2002].

As the U.S. and its scientific partners formulate their long-range research plans for the Antarctic, it is clear that the ice fields along the spine of the Antarctic Peninsula and the proxy records preserved therein should figure heavily into the program.

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Ellen Mosley-Thompson, Byrd Polar Research Center, 108 Scott Hall, 1090 Carmack Road, The Ohio State University, Columbus, OH 43210; thompson.4@osu.edu; Lonnie G. Thompson, Byrd Polar Research Center, 108 Scott Hall, 1090 Carmack Road, The Ohio State University, Columbus, OH 43210; thompson.3@osu.edu.