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CLIMATE OF THE LAST 500 YEARS: HIGH RESOLUTION ICE CORE RECORDS

E. Mosley-Thompson, L.G. Thompson, J. Dai, M. Davis and P.N. Lin
Byrd Polar Research Center, 108 Scott Hall, 1090 Carmack Road, The Ohio State University, Columbus, OH 43210, U.S.A.

Precipitation accumulating on the Earth's ice sheets and ice caps records a variety of physical and chemical information about the atmosphere and, in some cases, provides unique insight to both the history and the mechanics of the Earth's environmental system. High resolution (well-dated) dust records from both polar ice sheets suggest a linkage between increased atmospheric dust and cooler temperatures over Antarctica, but a similar relationship is not observed in ice cores from either Greenland or China. Net accumulation histories for the last 490 years reveal no discernible global pattern although interesting regional differences and similarities exist. Excess (non-sea salt) sulfate profiles provide

INTRODUCTION

Annual to decadal scale records of paleoenvironmental conditions are available from ice cores drilled in carefully selected polar and non-polar locations. These 'proxy' histories of atmospheric conditions extracted from ice cores include temperature, chemistry, dust content and volcanic emissions. In addition, the history of net snow accumulation may be reconstructed when individual annual layers and/or known time-stratigraphic horizons are identified.

Most natural recording systems are selective as they collect and preserve information from their immediate environment. Likewise, the constituents preserved within ice caps and ice sheets reflect both spatially extensive or global processes as well as local processes. Therefore, ice cores collected for paleoclimatic research must be retrieved from carefully selected sites so the records obtained allow the pertinent questions to be answered. For example, polar ice sheets are particularly valuable for monitoring global atmospheric composition because local sources are minimized; however, little may be learned about processes more dominant in tropical regions (e.g. variability of monsoons and the El Niño-Southern Oscillation (ENSO)). This paper presents a spectrum of ice core proxy records, some reflecting primarily local and/or regional conditions and others representing more global-scale processes.

DATING THE CORE RECORDS

Useful comparison of proxy records requires accurate dating of the stratigraphic sequences. Ice cores are dated using numerous techniques ranging from seasonally varying parameters such as insoluble particulate concentrations (henceforth dust), oxygen isotopic ratios ($\delta^{18}O$), and chemical species (e.g. SO_4^{2-} and NO_3^-), the identification of specific well-dated events, and a variety of modeling approaches (Hammer *et al.*, 1978; Hammer, 1989). To examine records of the last 500 years and make comparisons among them, annual- to decadal-scale resolution is essential. This requires the continuous analysis of the cores (top to bottom) for one or more seasonally varying constituents.

The chemical and physical constituents which vary in concentration throughout the accumulation year differ from one location to another. The character and abundance of chemical species and dust in the overlying atmosphere dictates the type of material available for deposition. The local meteorological regime also controls the availability of atmospheric constituents and their seasonal abundance. Finally, the preservation of an annual signal within the firn depends strongly upon both the annual accumulation rate and temperature range.

The ice core records presented here originate from meteorologically and physiographically diverse sites just as would a global array of meteorological stations. Therefore, the individual histories presented offer different degrees of time resolution and precision and contain a unique local/regional background component upon which larger-scale variability is superimposed. The cores presented here include: two from Antarctica, two from Greenland, one from Peru and one from China (Fig. 1).

South Pole Station (90°S; 2800 m a.s.l.)

A 101 m core drilled in 1974 was cut into 5218 samples for microparticle concentration measurements used to establish a 911 year record (Mosley-Thompson and Thompson, 1982). In addition, the core was cut into 1024 samples for $\delta^{18}O$ analyses made at the University of Copenhagen. As the $\delta^{18}O$ samples were cut to approximate annual increments they did not contribute to the establishment of the time scale which is based solely upon seasonal variations in dust concentrations. The estimated accuracy of the time scale is ± 90 years at 911 BP. For more discussion of the time scale see Mosley-Thompson and Thompson (1982) and Mosley-Thompson (1992).

Siple Station (75° 55'S; 84° 15'W; 1054 m a.s.l.)

Records of the concentrations of dust, $\delta^{18}O$ and SO_4^{2-} for the last 550 years were obtained from a 302 m core drilled in

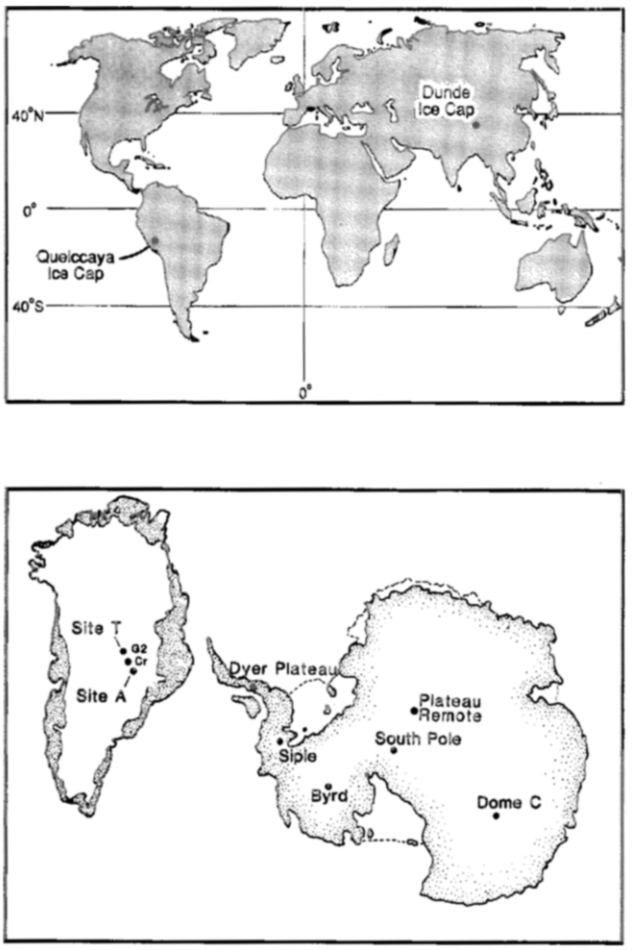

FIG. 1. This map shows both polar and non-polar drilling sites from which ice core proxy records discussed in this paper were obtained.

1985/86. The 302 m core was cut into 5757 samples for dust and $\delta^{18}O$ and 3492 samples for SO_4^{2-}. The small sample size, and hence large number of samples, coupled with the well-preserved seasonality in both $\delta^{18}O$ and SO_4^{2-} (Fig. 2) contributed to the excellent time scale estimated to have an accuracy of ± 5 years at A.D. 1435. The importance of using more than one seasonally varying parameter for dating is illustrated in Fig. 2 where A.D. 1788 is not present in the sulfate record, but is preserved distinctly in the $\delta^{18}O$ record.

Site A, Greenland (70° 38'N; 35° 49'W; 3090 m a.s.l.)

In 1985 a 100 m core was drilled at this site 40 km east of the ice sheet crest as part of the site selection activities in preparation for the Greenland Ice Sheet Drilling Program (GISP II). The core was continuously analyzed by ion chromatography for inorganic anions (Cl^-, SO_4^{2-}, NO_3^-) and by Coulter Counter for dust concentrations and size distributions. Figure 3 illustrates the distinct seasonality in both particulate and NO_3^- concentrations which made possible the detection of each annual layer to A.D. 1735. Note the contrast with Siple Station where SO_4^{2-} and not NO_3^- is deposited with a well-defined seasonal cycle. In addition, the dust concentrations at Siple do not exhibit a distinct seasonality, while in Greenland dust deposition is very seasonal with maximum concentrations in the spring and early summer. Therefore, identical techniques or the same seasonally varying parameters can not be used to date every ice core. The appropriate dating technique must be selected after the characteristics of the drill site have been assessed.

Site T, Central Greenland (72° 35'N; 38° 27'W; ≈ 3200 m a.s.l.)

Near the summit of the Greenland Ice Sheet close to the

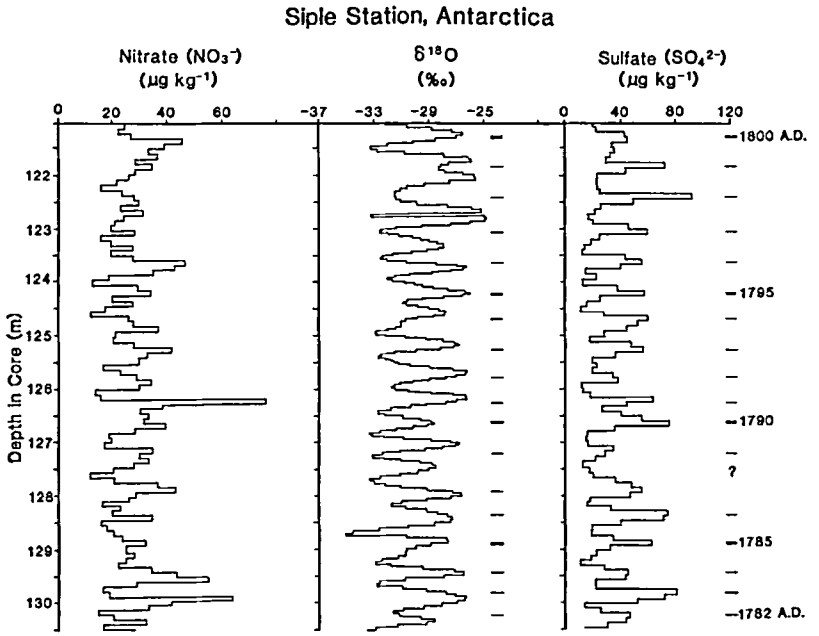

FIG. 2. This 8 m section of an ice core from Siple Station, Antarctica, illustrates the seasonal variations in both $\delta^{18}O$ and SO_4^{2-} by which the core was dated. Seasonal variability in NO_3^- concentration is much less reliable.

GISP II site, two cores (200 m and 84 m) were drilled in 1989. Both cores were analyzed continuously by the Coulter technique for dust concentrations and size distributions and the 84 m core was analyzed continuously by ion chromatography for Cl^-, SO_4^{2-} and NO_3^-. In central Greenland the accumulation is too low (about 220 mm H_2O equivalent) and summer temperatures are too warm for the long-term preservation of the annual $\delta^{18}O$ signal. Johnsen (1977) demonstrated that the seasonal $\delta^{18}O$ signal will be smoothed gradually by diffusion during the firnification process and may not be preserved at depth when accumulation rates fall below ~250 mm H_2O equivalent. For example, at Site T the seasonal signal in $\delta^{18}O$ is unreliable for accurate dating below 150 m. As at Site A seasonal dust and NO_3^- variations provide an excellent means for accurate dating. Figure 4 illustrates well-preserved seasonal variations in insoluble dust measured in four sections along the Site T core.

Quelccaya Ice Cap, Peru (13° 56'S; 70° 50'W; 5670 m a.s.l.)

Ice cores to bedrock were drilled in 1983 on Quelccaya, located in the southern Andes of Peru (Fig. 1). These cores were dated precisely (± 2 years at A.D. 1500) using a combination of seasonally varying dust concentrations and $\delta^{18}O$, visible dust layers deposited each year during the dry season and identification of ash from the A.D. 1600 eruption of Huaynaputina. Numerous paleoenvironmental records for this remote region have been extracted from these cores (Thompson *et al.*, 1984a, b, 1985, 1986, 1988; Thompson, 1992).

Dunde Ice Cap, China (38° 06'N; 96° 25'E; 5325 m a.s.l.)

Dunde is located on the Qinghai-Tibetan Plateau (Fig. 1) between the highest Chinese desert, the Qaidam Basin, to the south and the Gobi Desert to the north. Here cores containing very long (> 10,000 years) records were drilled in 1987 (Thompson *et al.*, 1989). The upper 500 years of the Dunde cores were dated using a combination of seasonal variations in dust and $\delta^{18}O$ in conjunction with the visible dust layers deposited during each dry season (Thompson, 1992).

PARTICULATE CONCENTRATIONS

The concentration of insoluble particulates (dust) within falling snow varies greatly over the Earth. Dust content is orders of magnitude higher on non-polar ice caps and glaciers while the lowest concentrations occur in the polar regions (Mosley-Thompson *et al.*, 1991). In central Greenland (Fig. 4) and in non-polar regions dominated by a monsoonal or seasonal precipitation regime (e.g. Quelccaya) seasonal dust variations are a primary dating tool.

The analyses of two Site T cores (2 and 5) separated by roughly 4 km allow assessment of the natural small-scale spatial and temporal differences that exist in dust content (Fig. 5). On short time scales (years) dust content varies by as much as 50% over distances of a few kilometers. These differences probably arise from both time scale inaccuracies and real differences between the sites as both dust histories contain the same major dust events and trends, except from A.D. 1890 to 1920 when Core 2 concentrations were higher. Lags of one decade between major features probably reflect time scale inaccuracies in Core 5, dated using only dust variations. Core 2 was more precisely dated using a combination of dust, NO_3^- and excess SO_4^{2-}. Figures 3 and 4 illustrate that interannual variability in dust content is quite high; therefore, the assignment of an unusually high or low dust year to one decade or another may alter the decadal average.

It is likely that most of the differences between the two records shown in Fig. 5 are real. Preservation of atmospheric dust in firn depends heavily upon the topography of the

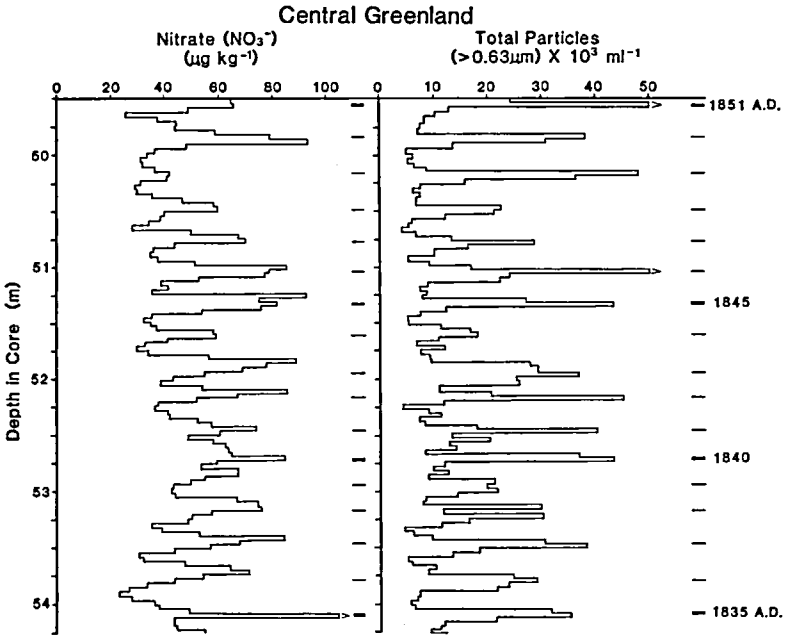

FIG. 3. This 4 m section of Core 5 from Site T, Greenland, illustrates the seasonal variations in NO_3^- and insoluble dust concentrations which were used to date the core.

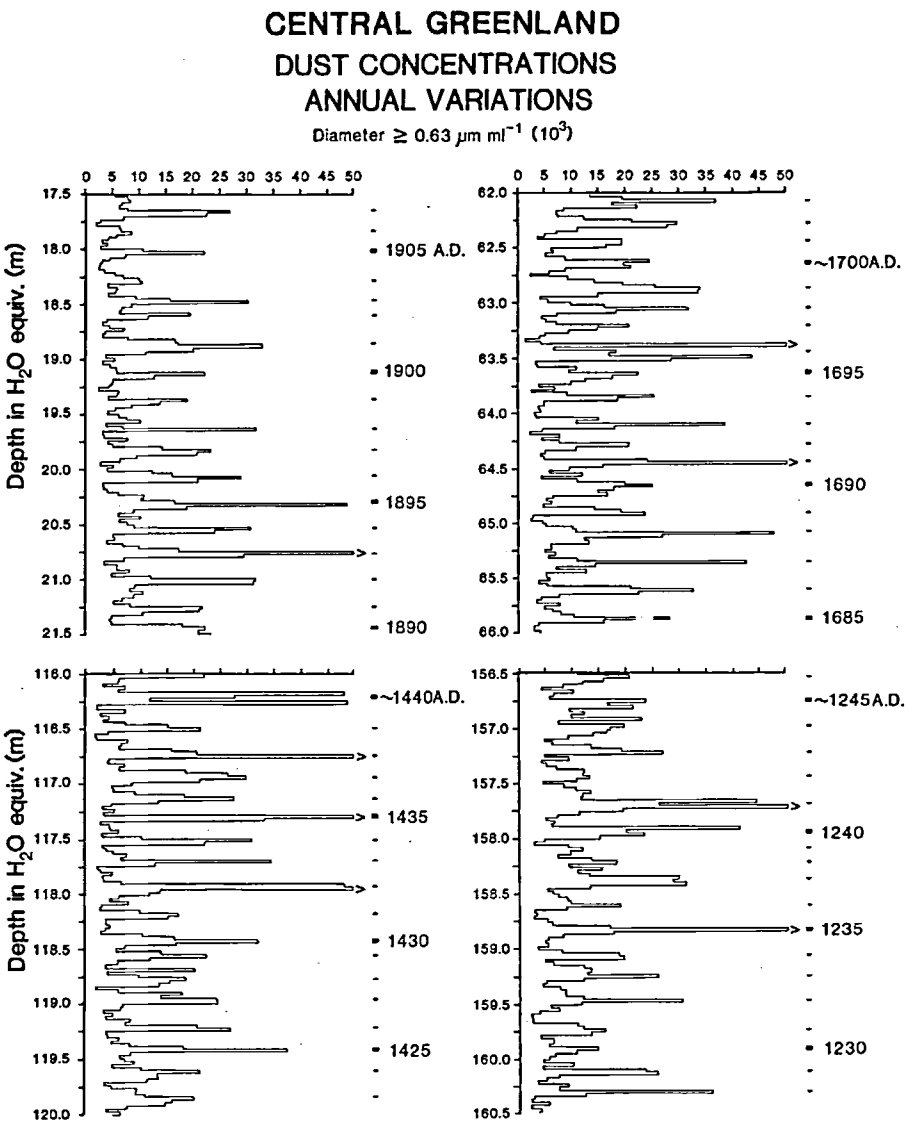

FIG. 4. Dust (diameters ≥ 0.63 μm) concentrations per ml sample in four sections (depths in water equivalent) over the length of Core 5 at Site T, Greenland, illustrate the preservation of the annual cycle in dust deposition. Note that the dust flux is highly variable from one year to another.

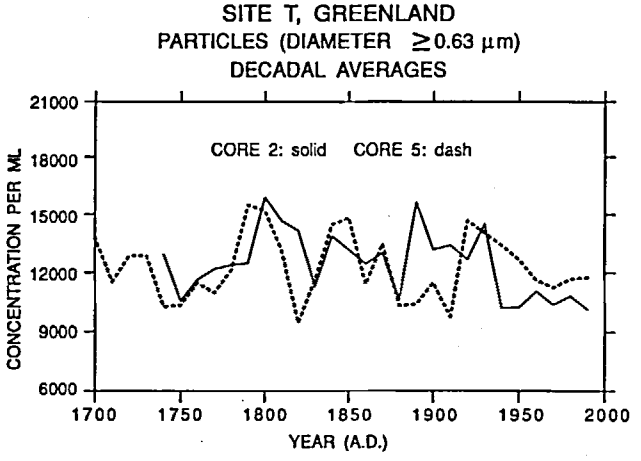

FIG. 5. Decadal averages of dust (diameters ≥ 0.63 μm per ml sample) concentrations are shown for two cores (Core 2 and Core 5) drilled 4 km apart at Site T, Greenland. On short time scales (years) dust content may vary by as much as 50% over distances of a few kilometers.

surface and efficiency of local removal processes as well as proximity to the source region, entrainment capacity of the wind, and the type and amount of the precipitation. Although the sites are only 4 km apart, both lie very near the local ice divide. Ice divides are climatically sensitive regions where different meteorological regimes (and hence local air masses) constantly interact. Therefore, the physical and chemical nature of the accumulating snow at any given time may vary greatly over short distances. However, as discussed below, spatial differences diminish as the averaging interval increases.

Previous dust analyses of cores extending into the Last Glacial Stage (LGS; 12,000 to ≥ 50,000 BP) from both polar regions (Thompson and Mosley-Thompson, 1981, 1987) and the Dunde ice cap, China (Thompson *et al.*, 1989) confirm the dusty nature of the LGS atmosphere. In fact, substantially elevated dust content and depletion of ^{18}O are two key signatures of LGS ice leading scientists to conclude that prolonged periods of colder atmospheric temperatures were associated with elevated dust content. The LGS dustiness

resulted from a combination of factors including: increased desertification in major source regions (e.g. Chinese deserts, South Africa and Australia), increased wind speed, increased areas of exposed continental shelves and, in some cases, reduced net accumulation. Here ice core dust records covering the last five centuries are examined to explore whether shorter and less dramatic cold periods, such as the most recent neoglacial or Little Ice Age (LIA), were characterized by similar increases in atmospheric dust.

The first Antarctic core to be analyzed continuously over the last millennium was from a South Pole Station. Here, snow deposited during the Little Ice Age (ca. A.D. 1450–1850) had a dust content roughly double that deposited before A.D. 1450 (Fig. 6). In addition, dust content was most consistently above the long-term average from A.D. 1650 to 1850. Interestingly, over this same interval dust content at Siple Station was below the long-term average (Fig. 6). In fact, the South Pole and Siple records of dust (Fig. 6) and $\delta^{18}O$ (Fig. 7) reveal an anti-phase relationship between atmospheric conditions over the high East Antarctic Plateau and the Antarctic Peninsula area. During cold and dusty periods over East Antarctica, conditions are warmer and the atmosphere is less dusty in the Peninsula region. High resolution records from central West Antarctica are as yet unavailable to determine whether the climate in this region is synchronous with that over East Antarctica, the Peninsula region, or whether it is totally different. High resolution records from central West Antarctica should be a high priority for future antarctic drilling plans.

The dust records from Sites T and A in central Greenland and the Dunde ice cap in China (Fig. 6) are substantially different from the antarctic histories. Central Greenland sites experience dusty periods which persist for two or three decades and are dispersed throughout the 490 year record. Over Dunde the alternating periods of increased and decreased dust deposition are of longer duration, but do not exhibit an obvious LIA response. Similarly, the $\delta^{18}O$ histories from Camp Century, Greenland (Johnsen *et al.*, 1970) and Dunde do not reveal any periods (multi-centennial) of persistent warmth or cold (Fig. 7). These northern hemisphere $\delta^{18}O$ histories contrast sharply with those at Quelccaya and South Pole which suggest a prolonged period of cooler conditions from ≈ A.D. 1550 to 1880.

There are strong regional similarities in the two Greenland dust records. Although temporal variability is high over short time intervals (decades), when averaged over longer periods the central Greenland dust concentration averages are remarkably consistent. Average dust concentrations in the shorter Site A record (A.D. 1725–1985) is 13,500 particles (diameter ≥ 0.63 μm) per ml sample, quite similar to the combined average of 13,750 over the same time interval in Cores 2 and 5 from Site T. Figure 6 also reveals some regional similarities in the timing of major dust events. Both histories show that since A.D. 1720 there have been three prominent periods of elevated dust centered on A.D. 1800, 1850 and 1930. The latter is temporally associated with the great North American drought (the dust bowl era) of the 1930s. However, the two earlier dust events do not appear to be linked with major North American or northern hemisphere droughts. Currently no cause and effect relationship has been established between the Greenland dust record and the North American 'dust bowl' event.

To summarize, longer (500 to 1000 year) dust histories from this global array of ice cores core reveal large spatial variability. Regional processes and conditions appear to have dominated atmospheric dustiness over the last 500 to 1000 years. No global-scale increase in dust characterized the LIA as it did the LGS although some regions appear to have similar dust histories. This may be fortuitous or may reflect some degree of upper atmospheric teleconnection. For example, during much of the LIA dust content was elevated over both East Antarctica and the Peruvian Andes in association with cooler conditions in those areas as inferred from $\delta^{18}O$ (Mosley-Thompson, 1992). On the other hand, this temperature–dust relationship is not evident in central Greenland or north central China (Dunde).

NET ACCUMULATION

Net accumulation is not equivalent to precipitation unless all of the snow falling at the sampling site remains there throughout the year and is preserved in the stratigraphic record. This is unlikely to occur as mass may be removed or added to the snow surface at any time by deflation, re-deposition and sublimation. Therefore, the net amount of precipitation which accumulates in any specified time interval is termed the net accumulation (NAC). The detection of annual layers within ice cores makes it possible to extract the annual net accumulation history for the drill site.

Net accumulation in any given year has been shown to be quite variable over small distances because it is strongly controlled by topography (Black and Budd, 1964; Gow and Rowland, 1965; Mosley-Thompson and Thompson, 1982). Both large-scale waves or dunes (wavelength 5 to 30 km) and small-scale randomly scattered sastrugi may influence the spatial distribution of accumulation. Therefore, net accumulation time series often exhibit substantial temporal and spatial variability. This is not unlike the relationship commonly found among a regional array of precipitation records.

Observations at the South Pole (Gow, 1965; Mosley-Thompson and Thompson, 1982) indicate that sastrugi produced by the winter accumulation are slowly leveled by deflation and sublimation processes dominating during summer. In addition, deflation and re-deposition result in a slow filling of the depressions and erosion of the surface highs. Studies at the South Pole suggest that an averaging interval of 10 years may be sufficient to obtain a representative average annual accumulation (Mosley-Thompson *et al.*, 1985).

Precipitation regimes vary in Antarctica. At South Pole the average yearly accumulation is ≈ 0.08 m H_2O equivalent, winter is the accumulation season and much of the precipitation falls as crystals under clear sky conditions. In contrast, Siple Station (Fig. 1) accumulation is ≈ 0.56 m H_2O equivalent, falls more regularly throughout the year and consists primarily of snowflakes associated with passing storm systems. Nevertheless, accumulation at Siple appears

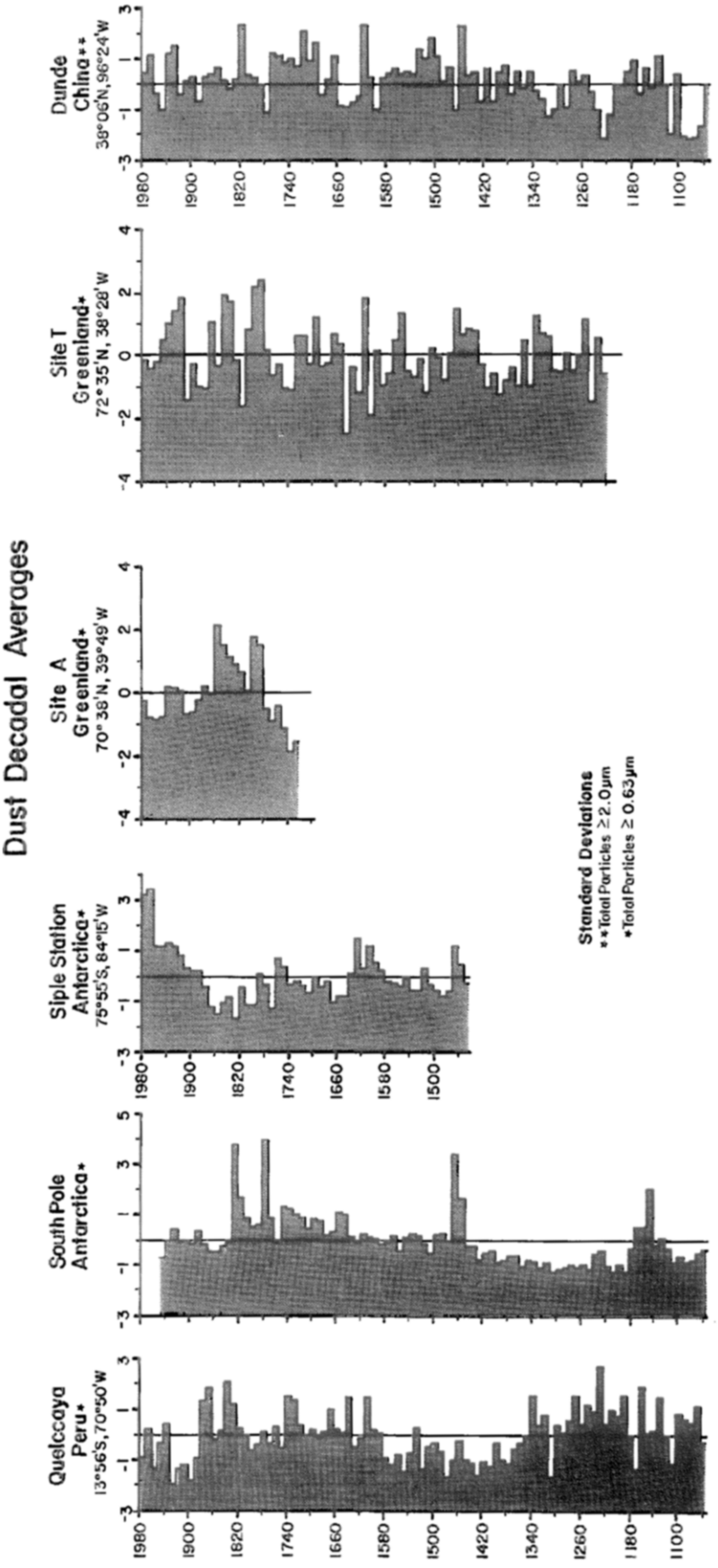

FIG. 6. Decadal averages of dust concentrations are illustrated for six cores: two from Greenland, two from Antarctica, one from Peru and one from China. Concentrations are expressed as standardized deviations from each time series mean. Total particles refers to those with diameters ≥ 0.63 μm for all cores except Dunde, China (diameters ≥ 2.0 μm).

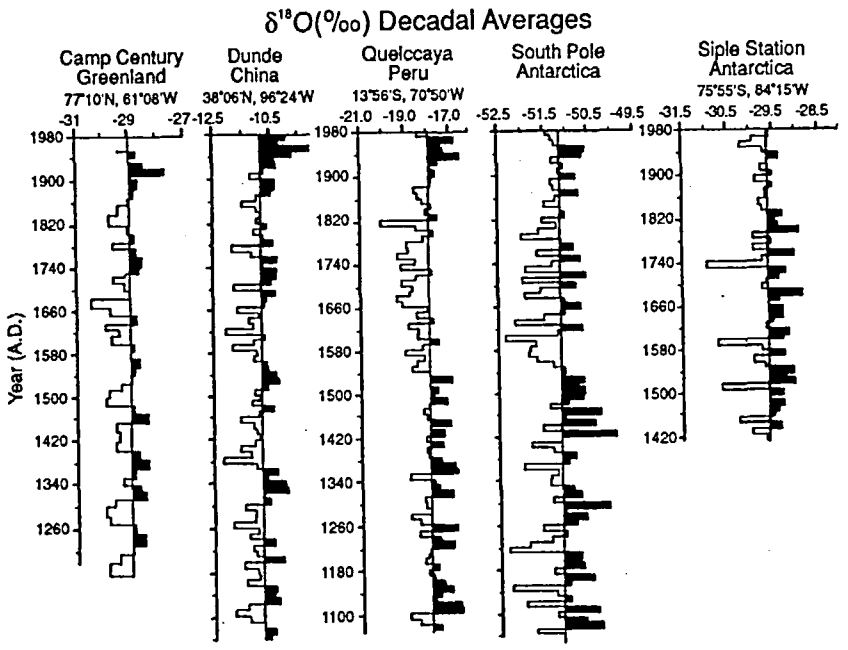

FIG. 7. Decadal averages of the $\delta^{18}O$ records are shown for a north–south transect from Camp Century, Greenland, to the South Pole, Antarctica. The shaded areas represent isotopically less negative, or warmer, periods and the unshaded areas represent isotopically more negative, or cooler, periods relative to the respective means of the individual records.

also to be remarkably constant from site to site, particularly when averaged over a 10 year interval. This was demonstrated using a known time-stratigraphic marker horizon. While drilling a core at Siple Station, Neftel *et al.* (1985) reported a distinct meltlayer 7 m below the 1983 surface which had formed in the summer of 1976. This same meltlayer was present in 8 of 10 cores drilled in 1985 at Siple. The meltlayer depth varied only slightly in the eight cores between 10.46 and 10.63 m below the 1985 surface.

Figure 8 illustrates the decadal averages of net annual accumulation from two cores drilled 4 km apart at Site T, Greenland. As discussed previously, dating is more precise in Core 2 as insoluble dust, NO_3^- and excess SO_4^{-2} were used while only insoluble dust was used to date Core 5. Nevertheless, with a few exceptions the estimated net decadal accumulations do not differ by more than 10%. Note

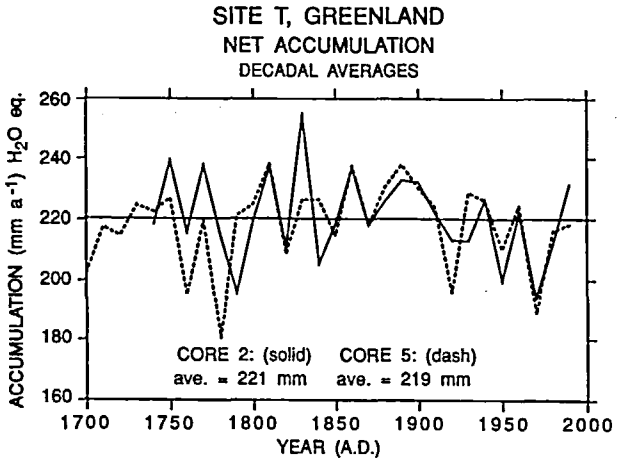

FIG. 8. Decadal averages of net accumulation at Site T, Greenland, extracted from Cores 2 and 5 located 4 km apart.

that discrepancies increase for the older (deeper) portions of these cores where slight errors in dating (probably in Core 5) may result in identical years falling into different decadal averages. Despite these minor decadal differences the average accumulation at these two sites is nearly identical (Core 5: 219 mm and Core 2: 221 mm of H_2O equivalent) over the last two centuries.

The extraction of net accumulation histories from ice cores often requires estimating the effects of thinning due to densification, compression and flow. For records discussed here different approaches were applied depending primarily upon the depth of each core with respect to the thickness of its ice sheet or ice cap. For reference, the ratios of core length to ice sheet depth are: Site T, Greenland: 200/3000 m; Siple Station, Antarctica: 302/2000 m; South Pole: 100/2800 m; Plateau Remote, Antarctica: 200/3500 m; Quelccaya ice cap, Peru: 164/164 m; Dunde ice cap and China: 140/140 m. Thus, the polar cores (Greenland and Antarctica) are relatively shallow in comparison to the total thickness of the ice sheets. This allows a simple approach to be adopted. The ice sheets are assumed to be in steady state with a constant accumulation rate equivalent to the current value and the ice flow is assumed to be two dimensional. These assumptions allow the original layer thickness $L(t)$ at time (t) to be estimated using

$$L(t) = L_0 e^{(-bT/H)}$$

where L_0 is the measured (current) layer thickness in the core expressed in ice equivalent, b is the current accumulation rate in ice equivalent, H is the thickness of the ice sheet at the drill site and T is the age of the specific layer. Original annual layer thicknesses upon which the decadal averages of net accumulation are based (Figs 8 and 9) were reconstructed in this fashion for the polar cores. This simple approach is not

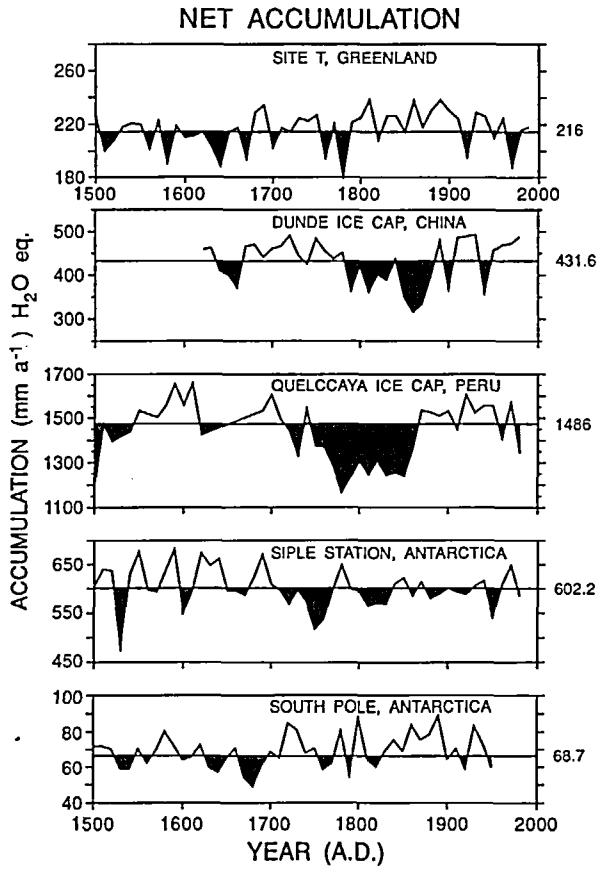

FIG. 9. Decadal averages of net accumulation are shown for five sites from Site T, Greenland, to the South Pole, Antarctica, since A.D. 1500. Shading reflects net accumulation below the respective long term averages for each core.

applicable to the Quelccaya and Dunde cores which extended to bedrock. The time scale construction and annual layer thickness estimates for these cores have been discussed elsewhere (Quelccaya: Thompson *et al.*, 1985; Dunde: Thompson *et al.*, 1989, 1990).

Figure 8 suggests that net accumulation (NAC) at Site T was frequently above the long-term average in the nineteenth century, but decreased steadily from A.D. 1890 to ≈ 1960. In the last two decades NAC has shown an increasing trend although the decadal averages are barely above the long-term mean. Viewed from the perspective of the last three centuries the increase over the last two decades is small with much sharper increases, e.g. A.D. 1780 to 1810, previously recorded.

Recent satellite altimetry has indicated a possible thickening of the Greenland ice sheet (Zwally, 1989; Zwally *et al.*, 1989) from 1978 to 1986. The recent thickening is attributed to an hypothesized precipitation rate increase speculated to be above the long term average and possibly attributable to warmer conditions in the polar regions. These results, speculations and conclusions are controversial (Douglas *et al.*, 1990; Zwally *et al.*, 1990). The NAC histories reconstructed from the two Site T cores do show an increase (positive trend) in the last two decades, but when compared to the longer record (Fig. 8), NAC for the last two decades is near or below the long term mean.

Core 5 provides a longer NAC history (Fig. 9) which reveals that accumulation in central Greenland region was consistently above the long-term mean (LTM) from 1780 to 1900 and consistently below the LTM from 1500 to 1680. Again the increasing NAC trend of the last two decades is insignificant from a 490 year perspective. Large polar ice sheets respond rather slowly to environmental changes (their actual response times are poorly quantified). The postulated recent thickening of the central and southern portions of the Greenland ice sheet, if real, could be a response to the extended period of above average accumulation from A.D. 1780 to 1900. Nevertheless, these proxy records of NAC do not support a recent accumulation increase above the LTM in central Greenland.

Figure 9 compares the decadal averages of NAC for three polar sites and two non-polar sites. NAC varies by two orders of magnitude from 68.7 mm at South Pole to 1486 mm on the Quelccaya ice cap, Peru. Not surprisingly, a globally consistent NAC pattern over the last five centuries does not emerge; however, several interesting relationships are evident.

NAC in central Greenland and at the South Pole was predominantly below the long-term mean prior to A.D. 1700 and more frequently above the long-term mean from A.D. 1700 onward. At both polar sites, A.D. 1600 to 1700 was characterized by NAC consistently below the LTM. These similarities could be fortuitous as there are no obvious mechanisms linking these two polar sites. To complicate matters, NAC at Siple and the South Pole exhibits an anti-phase relationship similar to the dust concentrations discussed earlier. Prior to 1700 NAC was above average at Siple and below average at the South Pole, but since 1700 this relationship has reversed. This anti-phase relationship between Siple and the South Pole extends to the $\delta^{18}O$ histories (Fig. 7) and has been noted in surface temperature observations from A.D. 1945–1984 (Jones *et al.*, 1986). Such spatial differences are thought to result from minor shifts in preferred locations for large-scale circulation features. Rogers (1983) demonstrated a statistically significant relationship between intensification of zonal westerlies and cooling at the South Pole and warming in the Peninsula region.

Focusing upon the two non-polar ice core histories, Dunde and Quelccaya, there are some similarities in the NAC trends, but a definite time lag between the records with Quelccaya leading Dunde by two or three decades. In general, NAC has been increasing at these two sites since ≈ 1880, but was consistently below the LTM during most of the late eighteenth and nineteenth centuries. It is easier to envision a possible teleconnection between the Andes of Peru and the Tibetan highlands of China via the El Niño-Southern Oscillation (ENSO) which dominates the climate regime of the Pacific Basin.

In summary, decadal-scale NAC histories (Fig. 9) do not suggest any discernible global patterns on multi-decadal to century time scales. This is not surprising as precipitation is one of the most variable meteorological parameters. Bradley *et al.* (1987) used northern hemisphere precipitation records since A.D. 1860 to examine temporal and spatial trends. They found that regional differences were quite large as might be expected. Similarly, the NAC histories from a

global array of ice cores also reveal large regional differences over the last 500 years.

SULFATE CONCENTRATIONS

Sulfate concentrations vary seasonally in antarctic snow with a late spring/summer maximum and a winter minimum which allows accurate ice core dating. There are two likely explanations for the late spring/summer sulfate maximum: enhanced stratosphere to troposphere air exchange when the stratospheric vortex over Antarctica weakens and the photocatalyzed conversion of reduced sulfate species to sulfate during the austral day (summer). Sulfate concentrations measured in the snow reflect a combination of sea salt and non-sea salt aerosols. The major sources of excess sulfate (e.g. non-sea salt aerosol) include biogenic marine emissions of organic sulfurous compounds and volcanic injection of sulfur species (Delmas *et al.*, 1982). Excess sulfate $(SO_4^{2-})_{ex}$ is estimated from the measured total sulfate $(SO_4^{2-})_{tot}$ by removing the sea salt component as follows:

$$(SO_4^{2-})_{ex} = (SO_4^{2-})_{tot} - R\,(Cl^-)$$

where Cl^- is the total chlorine concentration and R (0.103 in equivalent/l) is the ratio of sulfate to chlorine in bulk sea water. Sea salt sulfate is overestimated using total chloride (as chloride may have other sources) and therefore, the excess sulfate is underestimated, but the error is calculated to be less than 1%. The sulfate data presented here are expressed as excess sulfate (EXS).

Explosive volcanic eruptions often inject large amounts of ash and gaseous aerosols into the upper troposphere and stratosphere. The larger ash particles (tephra) generally settle out within a few months, but the volcanic gases along with the finest ash may remain 6 to 18 months in the stratosphere. This material will be spread hemispherically, and in some cases, globally (Cadle *et al.*, 1976).

Sulfur dioxide (SO_2) is oxidized to sulfuric acid (H_2SO_4) or sulfate (SO_4^{2-}) by reactions with the hydroxyl radical and other oxidants (Cadle, 1980; Hammill *et al.*, 1977). When concentrated in the stratosphere, these aerosols increase the optical depth and thereby reduce the receipt of solar radiation at the Earth's surface. Although the nature of climatic impacts from volcanic eruptions are still debated, there is a consensus that the most explosive eruptions temporarily increase the temperature of the stratosphere (Labitzke and McCormick, 1992) and reduce both land and ocean surface temperatures (Bradley, 1988; Mass and Portman, 1989). The recent eruption of Mount Pinatubo (Philippines) provides an excellent example of the substantial, albeit short-term, effects that very explosive eruptions with a high sulfur gas content may produce. By June 1992 the atmospheric cooling attributed to Pinatubo had temporarily overwhelmed the current long-term global warming trend and the short-term warming trend in the Pacific driven by ENSO (McDonald, 1992) as predicted by the GISS climate model (Hansen *et al.*, 1992). Inadequate volcanic and surface temperature data bases extending beyond several centuries hinder attempts to assess quantitatively the climatic impacts of explosive volcanism.

Explosive volcanism is one of the many environmental records preserved in ice cores. The volcanic record from Greenland ice core is well documented for the last 1000 years. Using acidity measurements in Greenland ice cores, Hammer (1977) demonstrated that concentrations of sulfuric acid in snow are significantly elevated by the deposition of volcanic aerosols. Although acidity provides a fairly reliable and quickly accessible record, the volcanic sulfate content of snow is more precisely determined by ion chromatography whereby each sample is prepared and analyzed under Class 100 Clean Room conditions. Continuous acidity and SO_4^{2-} analyses of shallow and intermediate depth cores have provided proxy volcanic histories which augment and extend the historical records of globally significant volcanic events (Hammer, 1980, 1984; Delmas *et al.*, 1985; Legrand and Delmas, 1987; Langway *et al.*, 1988; Dai *et al.*, 1991). In general, proxy volcanic records cores from Antarctica are less well developed and more poorly dated due to the low annual accumulation at most drill sites (South Pole, Dome C, Vostok). The high accumulation at Siple Station made annual layer identification, and hence accurate dating, possible. Well-dated cores from both polar regions offer a unique opportunity to isolate the most explosive tropical and subtropical volcanic eruptions.

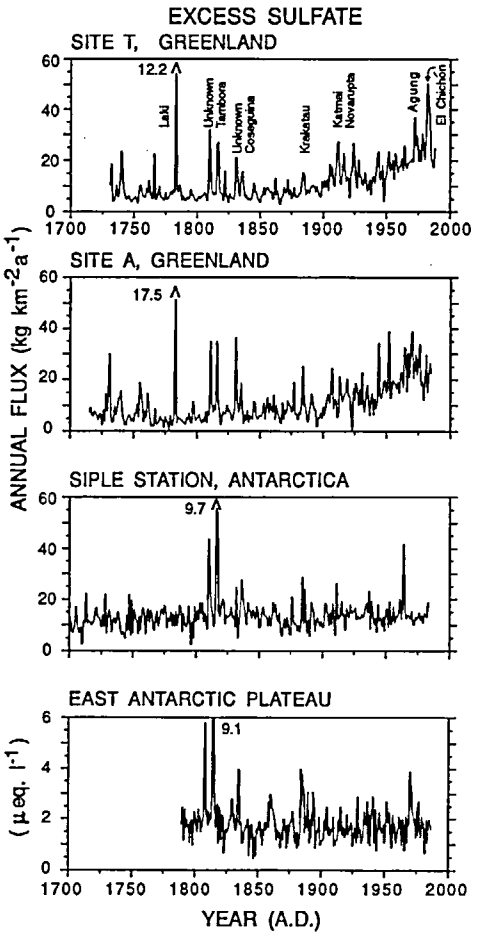

FIG. 10. Annual fluxes of excess sulfate (kg $km^{-2}a^{-1}$) for the last 250 years are illustrated for two sites in Greenland and for Siple Station in Antarctica. The sulfate concentration (μequivalent per liter) is shown for the Plateau Remote site on the East Antarctic Plateau where annual accumulation could not be determined due to the very low (0.04 m H_2O equivalent) net accumulation rate.

This was demonstrated by the identification in the Siple core (Dai *et al.*, 1991) of a previously unknown tropical eruption in A.D. 1809 (Fig. 10) which injected roughly half the sulfate of Tambora (Indonesia; 8°S) into the atmosphere. A more detailed sulfate analysis of the two Greenland cores revealed a contemporaneous sulfate event at both sites (Fig. 10). Obviously the sulfuric acid from the A.D. 1809 eruption was injected into the tropical stratosphere, transported into both hemispheres and ultimately deposited in the snow on both polar ice sheets. Such contemporaneous EXS peaks in both polar regions probably reflect the same near-equatorial volcanic eruption with high sulfur gas content and a column height well into the stratosphere. Langway *et al.* (1988) reported a previously unknown large eruption in A.D. 1259 based upon contemporaneous acidity peaks in cores from Antarctica and Greenland. More recently, Palais *et al.* (1990) convincing matched contemporaneous fine ash (tephra) layers in both polar ice sheets on the basis of major element analyses. These results lend support to the qualitative approach of matching contemporaneous sulfate events, but this approach will not confirm a common source.

Ice core EXS records from both polar regions provide a history of global-scale volcanism, along with crude estimates of the associated global atmospheric sulfur burden. Unfortunately, in the absence of historical records, it is unlikely that specific volcanic sources will be easily identified. Figure 10 presents the annual flux of excess sulfate for three cores (Sites T and A in Greenland and Siple Station in Antarctica) from A.D. 1700 to the present. In addition, the EXS concentrations (μequivalent l^{-1}) are shown for the Plateau Remote site on the East Antarctic Plateau. Here the annual accumulation is too low to discern annual increments and thus annual fluxes could not be calculated. The time scale was estimated by assuming a constant accumulation rate of (0.04 m H_2O equivalent) and no loss of complete annual units (years) by deflation. Therefore, some of the major EXS peaks in the Plateau Remote core are slightly offset (< 10 years) from those in the three better dated records.

Figure 10 reveals those eruptions whose effects were global in scale and those whose effects were regionally restricted. As might be expected, the 1783 eruption of Laki (Iceland; 64°N) produced a time-stratigraphic marker well known in Arctic ice sheets and glaciers, but the sulfuric acid was restricted to the high northern latitudes and had no global effect. Similarly the high latitude eruptions of Katmai and Novarupta (1912) affected only the northern hemisphere.

On the other hand, the closely spaced couplet consisting of the A.D. 1809 (unknown) and A.D. 1815 (Tambora) eruptions provides a clear interhemispheric marker horizon. Comparison of the annual fluxes in Greenland and Antarctica (Fig. 10) demonstrates that both eruptions contributed more sulfate to Antarctica snow than Greenland snow suggesting that more sulfate was injected into the southern hemisphere than the northern hemisphere atmosphere (Dai *et al.*, 1991). The second couplet consisting of another unknown eruption (≈ A.D. 1828) and Coseguina (A.D. 1835; Nicaragua; 13°N) also provides an interhemispheric marker horizon. However, unlike the previous couplet, the SO_4^{2-} deposition from these eruptions was greater in the Greenland ice sheet. The A.D. 1883 eruption of Krakatau (Indonesia; 6°S) is recorded in both polar ice sheets, but more prominently in Antarctica as is the 1963 Agung (Bali; 8°S) eruption. The 1982 eruption of El Chichón (Mexico; 17°N) is absent at the two antarctic sites, but is present at Site T in Greenland. Interestingly, at Site A El Chichón sulfate is not clearly above the background concentrations. Based upon a comparison of H_2SO_4 deposition from Tambora at 11 sites in Greenland, Clausen and Hammer (1988) demonstrated that the input to the ice sheet from even this large eruption was quite variable from site to site (H_2SO_4 range: 129 to 13 kg km^{-2}). This variability reflects the dependence of deposition on both atmospheric and surface processes of which accumulation rate may be quite important.

The prominence in Greenland ice cores of more recent eruptions is diminished by the upward trend in EXS background levels (Fig. 11) due to the addition of anthropogenic sulfate to the atmosphere. The primary source of this sulfate is coal combustion for power generation and gasoline consumption by automobiles (Wigley, 1992). To better examine background concentrations of EXS, decadal averages are examined (Fig. 11) and reveal a steady rise in EXS deposition in Greenland since A.D. 1870. Equally obvious is the lack of a contemporaneous anthropogenic increase in background EXS over Antarctica. These data confirm that (1) sulfur by-products from southern hemisphere combustion are substantially lower than those in the northern hemisphere and (2) northern hemisphere sulfate pollution has yet to perturb the antarctic atmosphere. It is likely that most northern hemisphere aerosol effluents are restricted to that hemisphere.

CONCLUSIONS

High resolution (annual- to decadal-scale) ice core proxy

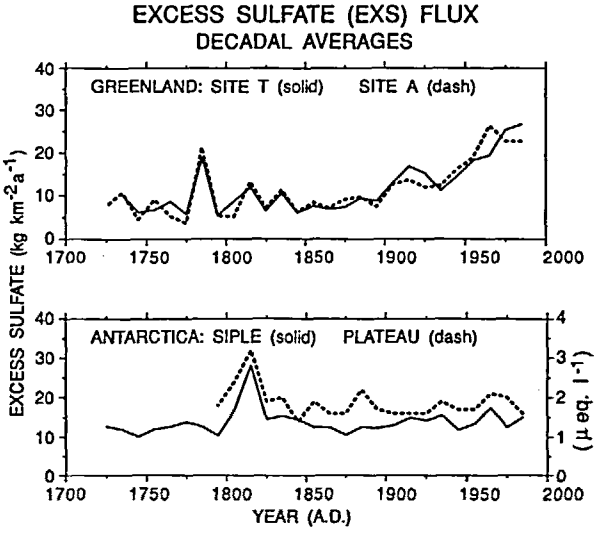

FIG. 11. Decadal averages of excess sulfate are compared for two northern hemisphere and two southern hemisphere ice core records. The steadily increasing concentrations since A.D. 1880 in the northern hemisphere contrasts sharply with the lack of an increase in anthropogenically produced sulfate in the antarctic atmosphere.

records of dust content, $\delta^{18}O$, net accumulation and excess sulfate from six different sites were presented. Comparison of these histories provides a global perspective and reveals that large spatial differences have characterized the latter half of this millennium. Atmospheric dustiness appears to have been dominated by regional processes and conditions as no global-scale increase in dust characterizes the LIA as it did the LGS. Although the antarctic and peruvian records suggest a relationship between cooler atmospheric temperatures and elevated atmospheric dust content, no similar relationship is found in the northern hemisphere core records. Histories of net accumulation, like long-term precipitation records, do not show any discernible global patterns on decadal to century time scales. Regional NAC trends are evident in central Greenland, but no persistent long-term, large-scale hemispheric or global trends are revealed.

When high resolution excess sulfate records from both polar regions are integrated they provide a history of global-scale volcanism. These records also allow crude estimates of the associated global atmospheric sulfur burden and provide a unique opportunity to extend the Earth's volcanic history beyond the period of documentation. These longer proxy volcanic records are necessary if the climatic impacts of explosive volcanism are to be quantitatively assessed. An interhemispheric comparison of the excess sulfate background concentrations confirms that anthropogenic sulfur by-products from southern hemisphere industrialization are substantially lower than those in the northern hemisphere. In addition, the northern hemisphere increase in background excess sulfate since A.D. 1880 has not yet begun to perturb the antarctic atmosphere suggesting that most northern hemisphere aerosol effluents are restricted to that hemisphere.

Documenting regional environmental variability will become more important as scientists strive to forecast the range of future climate changes under a potentially warmer Earth scenario. Ice core records provide a multi-faceted history of changes, both regional and global, and frequently in very high resolution. Ultimately, the integration of a broad spectrum of proxy records, including those from ice cores, will challenge our constructs of how the Earth operates as a system, provide greater insight into the mechanics of the Earth System, and provide a valuable time perspective for understanding and possibly predicting future environmental changes.

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