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Nine Centuries of Microparticle Deposition at the South Pole[1]

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The analysis of microparticles in a 101-m core from Amundsen–Scott South Pole Station, Antarctica has revealed a substantial increase in total particle concentration between approximately 1450 and 1850 A.D., a period encompassing the latest Neoglacial interval or Little Ice Age. It is likely that this reflects a simultaneous increase in the concentration of particulate material in the Antarctic atmosphere. This is important climatologically, for the Antarctic atmosphere may represent the closest approximation to the natural background aerosol. Thus cores from East Antarctica may contain long and detailed records of the natural global background aerosol. Such records are unavailable from any other medium. Additionally, a cyclical variation which appears to be annual has been detected in the South Pole particle record. These features allow construction of a relative time scale for ice cores older than 100 yr from regions of low accumulation (<10 g a^{-1}) where many traditional techniques are not applicable. This is especially significant, as the comparison of climatic data extracted from ice cores with other records of proxy data depends upon the ability to assign an accurate time scale to the ice core. An estimated nine-century record of net annual accumulation at the South Pole has been compiled and the calculated error in the time scale is ± 90 yr.

INTRODUCTION

In 1974 a 101-m firn core was drilled at Amundsen–Scott South Pole Station (Rand, 1975). This is the longest Antarctic core to be analyzed continuously for particles by the Coulter Counter technique which is conducted within a Class 100 clean room and which measures the concentration of insoluble particles with diameters between 0.50 and 16.0 μm (Thompson, 1977). The 6218 samples collected, representing a vertical increment of 65 m of water (101 m of firn), were analyzed for total particle concentration and size distribution (16 channels). The average sample size was 1 g of water which, coupled with the average annual water accumulation ($\bar{A}$) of 7 g (Gow, 1965), yields a resolution of seven samples per accumulation year. This detailed resolution made it possible to detect a cyclical variation in particle concentration which appears to be annual. These variations were employed to construct an estimated time scale for the core, to extract a record of net annual surface accumulation over the last nine centuries, and to examine in detail the temporal fluctuations of the particulate mass (Fig. 1) within the Antarctic Ice Sheet (Mosley-Thompson, 1980; Thompson and Mosley-Thompson, 1981).

Due to the nature of atmospheric processes, the atmosphere provides little information about the circulation, turbidity level, and temperature of past times. Fortunately, polar ice sheets continuously record the chemical and physical constituents within the snow creating a record of these high-frequency, low-amplitude variations and providing a record unavailable from any other source.

The remote Antarctic Ice Sheet is an ideal site for investigating the temporal variations in the global background particulate mass (Hogan, 1975, 1976), as there are few local sources. Additionally, over East Antarctica atmospheric motion is pre-

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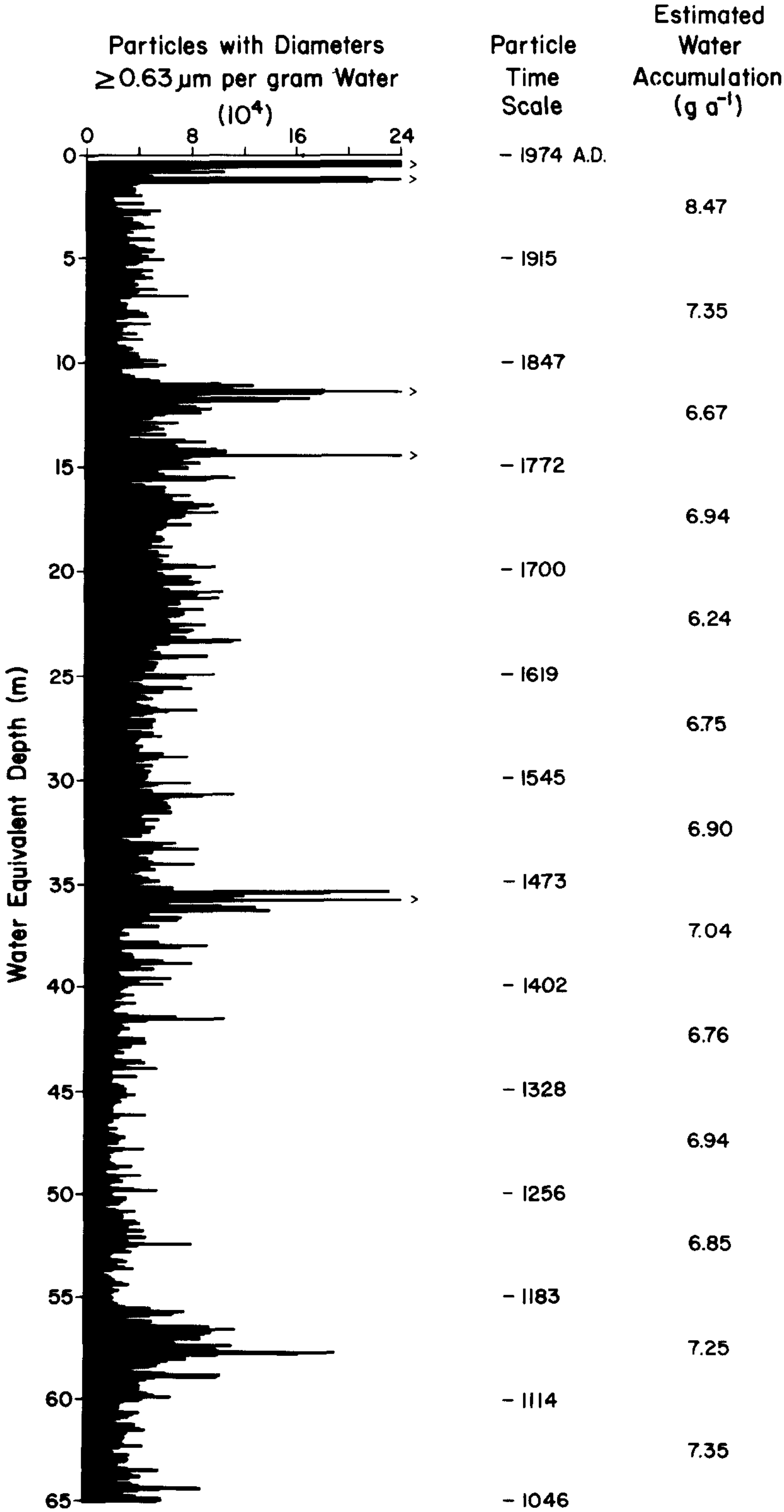


FIG. 1. Concentration of particles with diameters ≥ 0.63 μm/g of sample (1000 μl) in the 101-m South Pole core. To incorporate all 6218 samples into a figure representing the entire core, the equally weighted six-sample averages are presented. Depth is in meters of water equivalent. The time scale is derived by counting "annual" concentration peaks downward in the core from the 1956 time-stratigraphic horizon. The estimated net annual surface accumulation in grams of water equivalent for each 5-m (water) section is presented on the right.

dominantly one of subsidence and surface outflow (Reiter, 1971) suggesting that the upper tropospheric and stratospheric masses are the primary sources of near-surface material. Therefore any substantial increase in the concentration of particles within the global stratosphere should be recorded within the Antarctic Ice Sheet. This research examines the variation in concentration and size distribution of the particles deposited within the Antarctic snow over the last nine centuries.

SAMPLE PREPARATION AND ANALYSIS

The physical dissimilarity of firn and ice cores demands separate methods for sample cutting and cleaning as outlined by Thompson (1977). Due to its porosity, firn [like that] in the 101-m core is more easily contaminated and requires special handling. The size of the individual firn samples analyzed depends upon several factors. The lower limit is established by the Coulter Counter requirement for a minimum of 5 ml of liquid, while a subjective limitation derives from the desire for six to eight samples from a core length representing the average annual accumulation.

Beginning with a sample size of 18 mm at the top, the cutting was conducted in the cold storage facility and individual firn pieces were placed in labeled, air-tight containers. After transportation to the Class 100 clean room, precleaned scrapers and tongs were used to remove 2 to 5 mm from each side of the sample to ensure that the analyzed material was never in contact with the drill or the shipping container, only with the precleaned equipment. The clean-room water is reagent-grade deionized and filtered water provided by a Millipore Milli-Q3 and Milli-Q2 system. These procedures and equipment provide the best available conditions for reducing contamination of both ice and firn samples.

To ensure further the validity of these data, the lowest size range, 0.5 to 0.63 μm, is eliminated for interpretative purposes. External electronic noise may introduce a signal that can be interpreted as a particle and added to the lowest channel. To eliminate this possibility, all diagrams and interpretations are based upon the concentration of particles with diameters $\geqslant 0.63$ μm/g of liquid sample ($C_{0.63}$).

The upper few meters of the 101-m core were disturbed and contaminated by post-International Geophysical Year activities at the station. This was evident in $C_{0.63}$ which averaged $\approx 10^6$ at the top of the core and slowly decreased to 1.8×10^4 at a depth of 4 m.

The top of the core was 0.62 m below the 1974 surface and the 1954–1955 level was located by gross β activity (W. Dansgaard, personal communication, 1977). The particle concentration peak just above this horizon was assigned to 1956 and was assumed to be the first undisturbed and uncontaminated horizon. The counting of particle concentration peaks proceeded downward from this time-stratigraphic reference point.

DATING THE CORE

An accurate time scale is essential for interpreting past atmospheric conditions from ice-core data and for comparison with other records. Dating of strata older than 100 yr is a particular problem on the central Antarctic Plateau where accumulation rates are low (<10 g a^{-1}) (Bull, 1971) and where the deepest cores and, hence, the longest paleoclimatic records will be obtained. Annual variations in oxygen-isotopic ratios, tritium, and microparticle concentrations have been employed successfully for dating cores in regions of high annual accumulation such as Greenland (Hammer *et al.*, 1978), the Antarctic Peninsula (Thompson, 1977), and the Quelccaya Ice Cap in Peru (Thompson *et al.*, 1979). Where accumulation is low (<0.26 m a^{-1} ice) isotopic variations are attenuated with depth (Dansgaard *et al.*, 1973). Because microparticle variations are not attenuated with depth, this method offers great potential for ice-core dating in regions of low accumulation.

The counting of successive concentration peaks, a procedure described in detail elsewhere (Mosley-Thompson, 1980), yielded an age of 1046 A.D. for the bottom of the core (Fig. 1). The counting of microparticle peaks is sometimes subjective, although every attempt is made to adhere to an objective approach. Ideally, to be considered annual a microparticle concentration peak should have an adjacent supporting peak and be separated from the preceding and following major peaks by a background level consisting of at least two adjacent samples with low concentrations. Common interpretation problems can be demonstrated using Figure 2 which illustrates $C_{0.63}$ in individual samples (not averaged) from a 2-m section of the core. This section would be located at about 7 m in Figure 1 which illustrates a six-sample average plotted in water equivalent depth.

The two features designated by a question mark are not included in the counting procedure. The feature between 1883 and 1884 does not have two adjacent background samples below it and thus it is considered part of the strata deposited between 1883 and 1884. The second feature so designated has two adjacent background samples on either side, but consists of only one modest particle peak and therefore it is not counted. The prominent peak designated as 1879 ? is accompanied by two adjacent background concentrations on each side. Although it is not supported by an adjacent concentration peak, but by the next sample up, this peak is counted (with reservation as denoted by ?) as it is similar in magnitude to the other well-defined peaks in the core section (Fig. 2). Unfortunately, it is virtually impossible to eliminate all subjectivity from stratigraphic interpretations (e.g., Giovinetto, 1960).

Independent support for the counting procedure comes from the 1977 French pit excavated 3 km from Amundsen–Scott Station. In this pit the 1925 layer was identified at a depth of 8.98–9.10 m after adjustment to the 1974 surface (K. Harrower, personal communication, 1978). By counting the particle peaks downward from the 1954–1955 surface in the 101-m core, the 1925 layer is assigned at 9.4 m, a difference of 0.3 to 0.42 m firn (density ≅ 500 kg m^{-3}; Giovinetto, 1960, p. 79) or approximately 3 years' accumulation. This is an excellent correspondence for two sites separated by 3 km.

As with any firn-stratigraphic study there

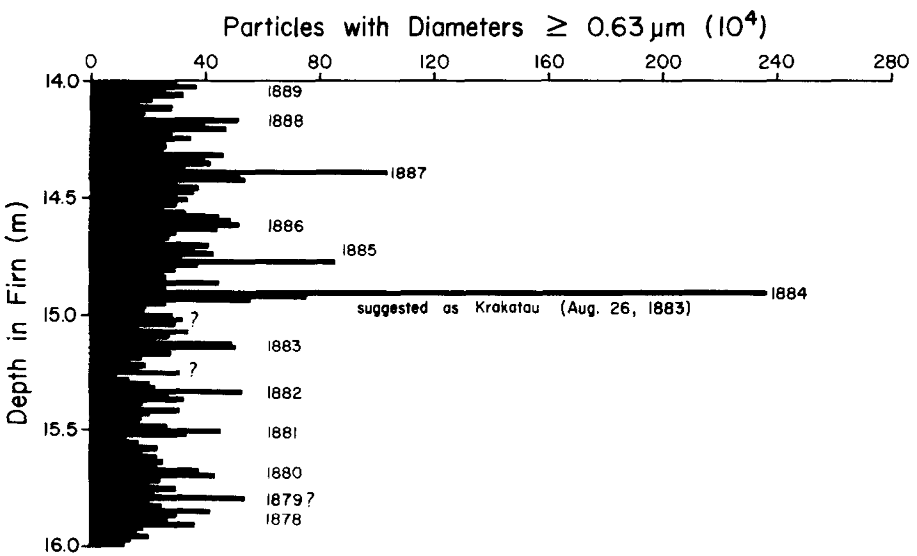


FIG. 2. Concentration of particles with diameters ≥0.63 μm/g sample in a 2-m section of the South Pole core. Data are from individual samples (not averaged) plotted by actual depth. These dates were obtained by counting presumed annual peaks downward in the core from the 1956 horizon. (?) indicates a peak with a questionable interpretation as discussed in text.

are two major sources of error which must be considered. When more than one particle concentration peak is contained within 1 yr accumulation, an overestimation of age in subsequent layers results. When all or part of an entire year's accumulation along with the associated particulate material is removed by wind erosion or is never deposited at the sampling site (Gow, 1965), an underestimation of the age in subsequent layers results. South Pole snow accumulation measurements at 42 stakes for 3 yr (1958–1961) indicate that 1 in 20 (5%) may be missing in a particular stratigraphic section (Giovinetto, 1963). Recent estimates indicate that 1 in 10 yr is more realistic (J. R. Petit, personal communication, 1978). These estimates indicate that as many as 90 yr may be missing from the 101-m core. Additional detailed pit studies could help quantify these estimates.

NET ANNUAL ACCUMULATION

Figure 3 illustrates the record of net surface accumulation (A_n) smoothed to attenuate high frequencies that may reflect noise or mask the lower frequencies which are of more interest when the record is examined for secular trends. The time series was filtered by the selective removal of periods less than 10 yrs, an arbitrary step accomplished by applying an appropriate filter to individual frequencies after a Fourier transformation of the original data sequence. This is preferable to an equally weighted running mean (Holloway, 1958) which may exhibit a negative response function at some frequencies (e.g., a maximum becomes a minimum), thereby resulting in distortion of spectrum.

Based upon the microparticle time scale derived above, the average net surface accumulation rate ($\bar{A}_n$) at the South Pole for the period 1046–1956 is 6.96 g a^{-1} (σ = 2.2 g a^{-1}), very close to the estimated rate of 7 g a^{-1} (Gow, 1965). For comparison, Table 1 presents $\bar{A}_n$ estimates obtained at the South Pole using other snow-strata parameters and the microparticle-concentration peaks. Of these parameters, only microparticles and pit studies are applicable for dating strata older than 100 yr in East Antarctica. An increase in A_n since 1965 has been identified using both microparticle and gross β-activity measurements.

The A_n record exhibits no detectable trend over the entire interval (Fig. 3) but contains several periods of consistently higher or lower accumulation. The highest rates characterize the intervals between 1867–1896 (8.03 g a^{-1}) and 1057–1086 (7.93 g a^{-1}) while the lowest rate is 5.47 g a^{-1} for 1657–1686, possibly the period of coldest mean temperatures during the last millennium in both hemispheres (Lamb, 1965; GARP, 1975; Wilson *et al.*, 1979). These records are based upon proxy data and must be viewed with caution as they lack adequate geographical substantiation and quantification.

The net surface-accumulation record encompasses the latest Neoglacial interval and thus, is of particular interest as few climatic records from the south polar regions span this period. This Neoglacial period is recorded in the Southern Hemisphere by $\delta^{18}O$ variations in speleothems in New Zealand (Wilson *et al.*, 1979) as well as by alpine glacier advances in New Zealand (Salinger, 1976) and southern Chile (Mercer, 1976).

The only other record available for comparison is a 198-yr record of A_n obtained from a 26.23 m snow mine about 5 km from the South Pole (Giovinetto, 1960). Figure 4 presents the 10-yr average[2] of $\bar{A}_n$ for the snow-mine data $(\bar{A}_n)_{mine}$ and for the microparticle data $(\bar{A}_n)_{core}$. The 198-yr mean values are 6.57 g a^{-1} (σ = 2.54 g a^{-1}) and 7.13 g a^{-1} (σ = 2.46 g a^{-1}), respectively. Over 198 yr this difference represents 1.1 m of water or about 16 yr at the present rate of accumulation.

The discrepancy in mean values could be real or could reflect either (1) interpretative errors in one or both of the records or (2)

[2] This is an equally weighted 10-yr average derived from the original data (Giovinetto, 1960).

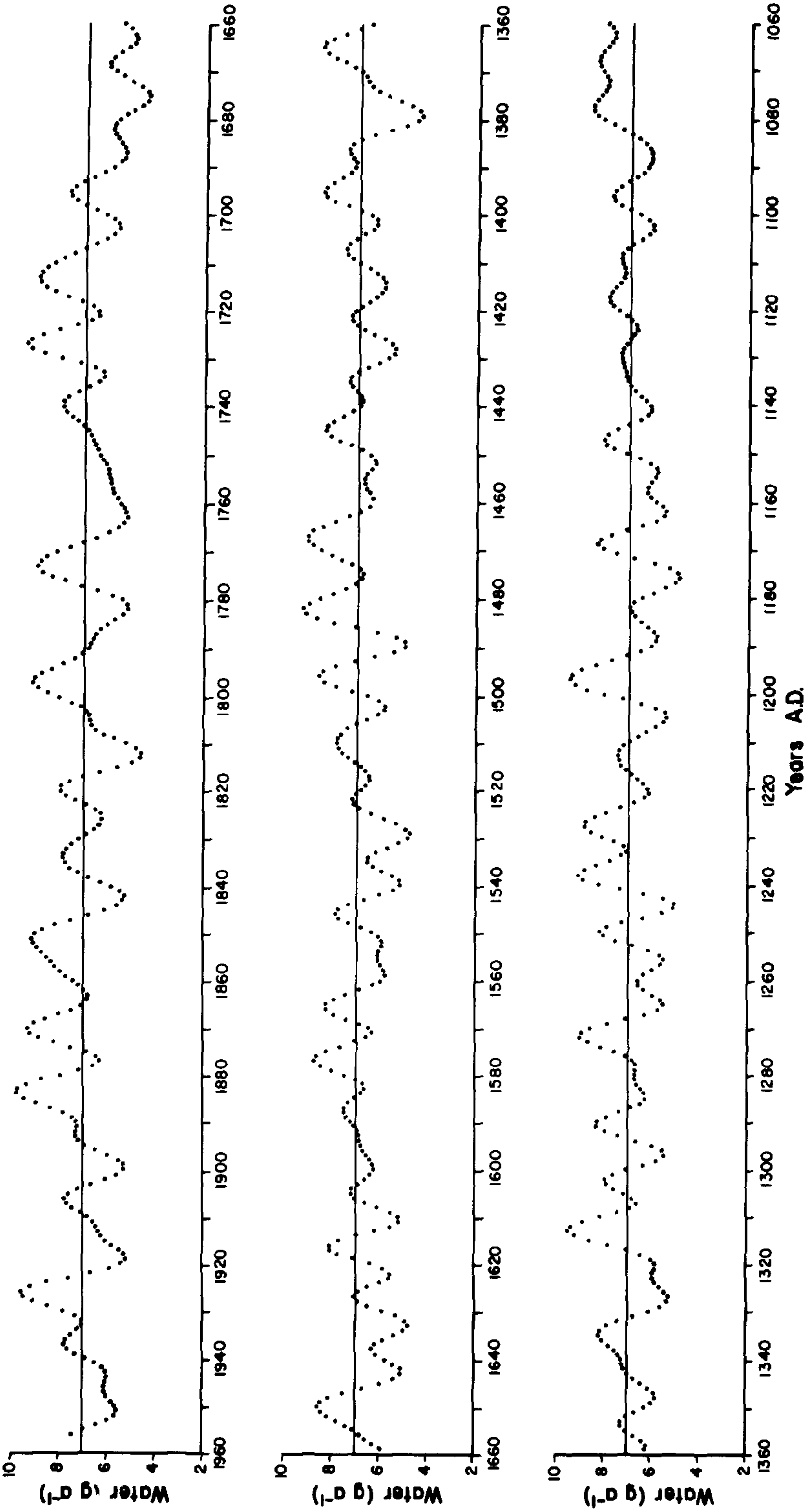


FIG. 3. The ca. 911-yr *time series of annual net surface accumulation filtered to remove periods less than 10 yr. These original data were obtained from* the vertical layer separation between annual peaks in particle concentration. The solid line represents accumulation rate of 7 g a^{-1} at the South Pole (Gow, 1965).

TABLE 1. ANNUAL NET SURFACE ACCUMULATION (WATER EQUIVALENT) IN THE VICINITY OF AMUNDSEN–SCOTT STATION AS DETERMINED BY VARIOUS PROCEDURES

Method	Time interval	Net accumulation ($g\ a^{-1}$)	Source
Gross β	1974–1955	8.54	Lambert *et al.* (1977)
Microparticles	1974–1955	8.74	This paper
$\delta^{18}O$	1963–1958	7.0	Epstein *et al.* (1965)
Stratigraphy	1965–1955	7.5	Picciotto et al. (1971)
^{210}Pb	1963–1850	6.1 ± 1	Crozaz *et al.* (1964)
Stratigraphy	1957–1760	6.6	Giovinetto and Schwerdtfeger (1966)
Stratigraphy	1957–1952	7.0	Gow (1965)
Microparticles	1957–1760	7.16	This paper
Microparticles	1956–1046	6.96	This paper

the differences in the density (ρ) values applied for conversion to water equivalent. Close examination of the ρ values for both records (Mosley-Thompson, 1980) indicates that the difference in the mean values is not related to ρ variations.

The microparticle record (core) does not exhibit the decrease between 1770 and 1850 reported in the stratigraphic record. Interestingly, a similar decrease is found between 1590 and 1770 (Fig. 4) in the core. Between 1900 and 1950 the A_n estimates vary in phase, with the snow-mine estimates exceeding the core estimates. From 1850 to 1900 there appears to be little correspondence between the estimates, but below 1850 the estimates are again in phase, with the core values exceeding the snow-mine values. The apparent synchrony between these two records is puzzling. Although missing accumulation years could account partially for the discrepancy in the two records, topographic control of deflation and deposition (Black and Budd, 1964; Gow and Rowland, 1965) may be partly responsible.

Large-scale surface undulations (wavelength (λ) between 3 and 40 km) are observed on the polar plateau. Nye (1959) attributed these to bedrock topography; however, such fixed waves would tend to self-destruct due to the filling in of troughs by drifting. Black and Budd (1964) suggest that accumulation is closely related to slope so that superimposed upon the standing waves are waves ($\lambda \approx 5-15$ km) which exhibit a net-accumulation maximum slightly downwind from the bottom of the trough and a minimum slightly downwind from the crest. This perpetuates the waves which move upslope into the wind at approximately 25 m a^{-1}. In addition, the ice at the South Pole moves downslope several meters per year. For a hypothetical example, a wave with λ = 15 km would require 600 yr to pass completely over a given site. In 80 yr the wave would move 2 km upslope so that a 100-yr period of reduced or enhanced accumulation could be incorporated into the depositional record.

The effect of ice-sheet topography upon net accumulation is not well understood, but these two records suggest that it may be one mechanism controlling the local variation in net balance. We suggest that these records reflect the homogeneity of meteorological conditions controlling the net-accumulation trend superimposed upon different topographic regimes (Gow and Rowland, 1965; Mosley-Thompson, 1980) producing the out-of-phase 50-yr interval (1850–1900 A.D.) and the slight departure between the mean values (Fig. 4A).

Local variability in net accumulation due to topographic control must be assessed and extracted from those records so that the variability in A_n attributable to meteorological processes can be assessed and records of regional net accumulation can be compiled. Regional records containing

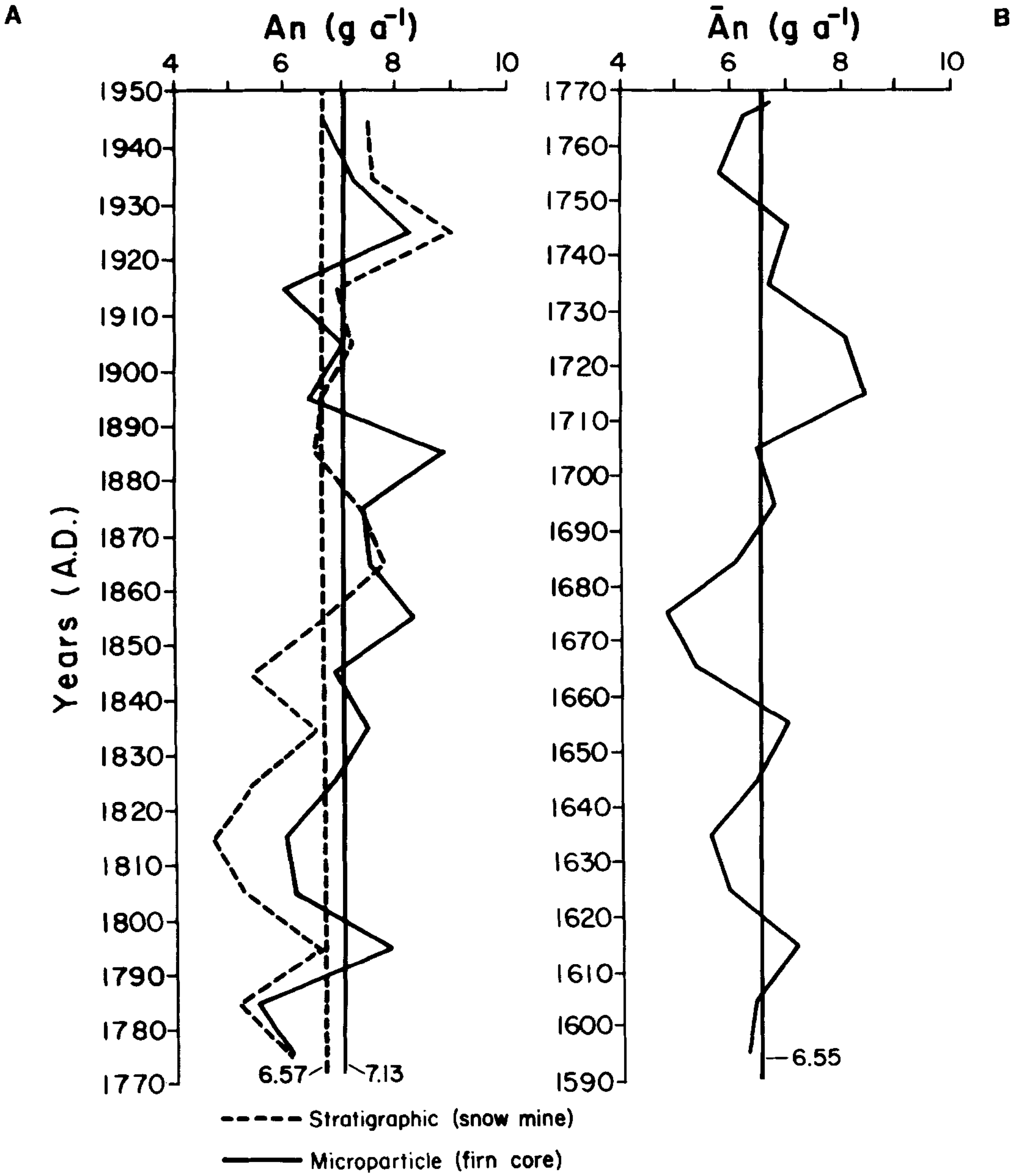


FIG. 4. Profile A: The 10-yr equally weighted averages of net annual surface accumulation (A_n) from the microparticle variations (firn core) and stratigraphy (snow mine) for the interval ca. 1770–1950 A.D. Profile B: The 10-yr averages of A_n from the firn core representing the interval ca. 1590–1770 A.D. The vertical lines represent the average ($\bar{A}_n$) over the respective time intervals.

many centuries of net accumulation on the Antarctic Ice Sheet would fill a critical gap in Southern Hemisphere proxy-data records and would be valuable for incorporation into ongoing paleoclimatic reconstruction of the global climate.

TEMPORAL VARIATIONS IN PARTICLE CONCENTRATIONS

Figure 5 illustrates the record of the concentration of insoluble particles with diameters ≥ 0.63 μm/g of sample. The period

1450–1850 A.D. which encompasses the latest Neoglacial interval or Little Ice Age, is characterized by a substantial increase in particle concentration. The lowest particle concentrations occur between 1200 and 1450 A.D.; since 1850 particle concentrations have slowly declined.

Two potential sources of this additional material include (1) an increase in the concentration of particles within the stratosphere and upper troposphere over Antarctica which may or may not be a hemispheric or global phenomenon, possibly attributable to volcanic activity, and (2) an increase in the lower tropospheric entrainment of material from local sources such as the Transantarctic Mountains and Dry Valleys or from the Southern Hemisphere desert regions.

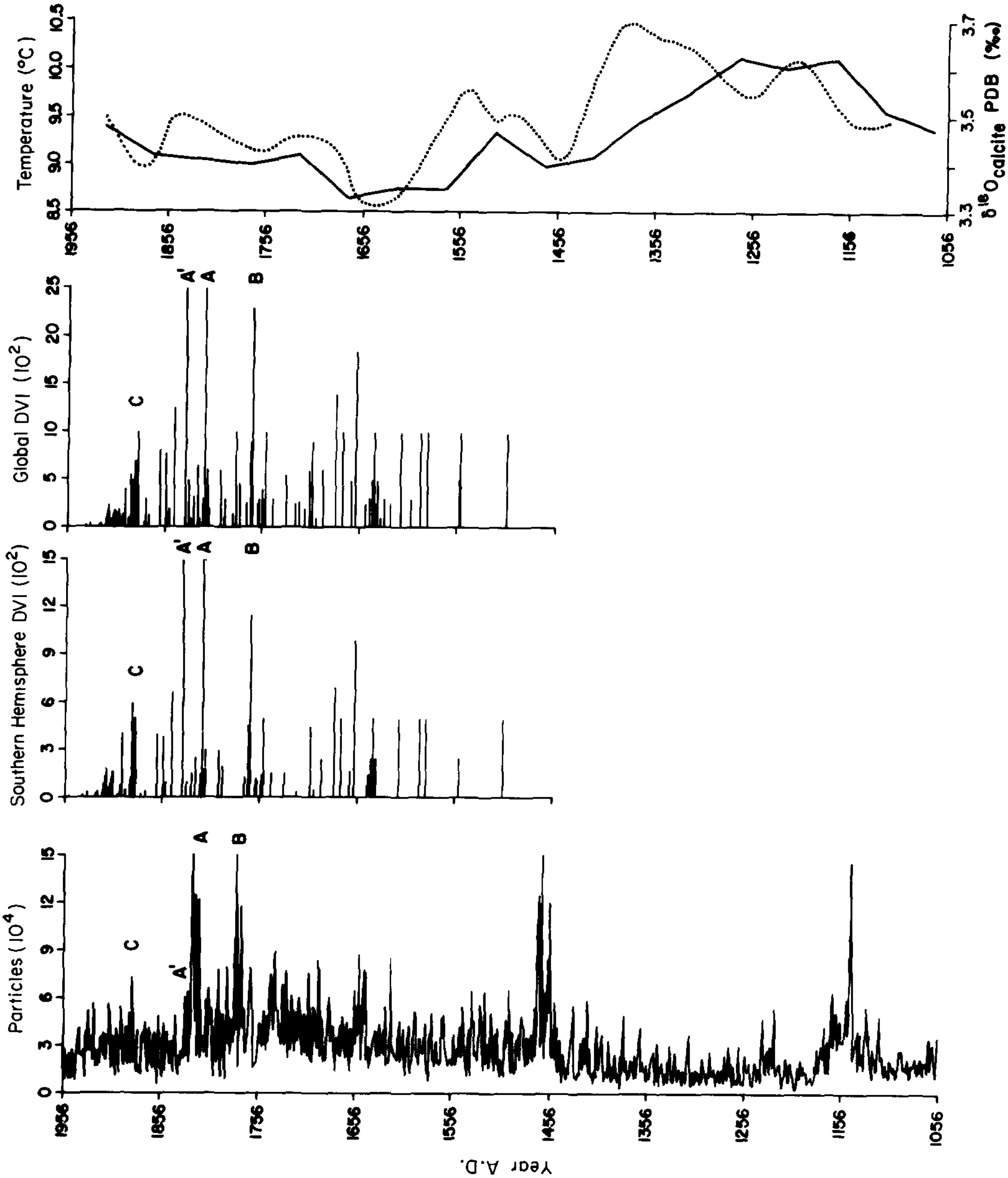
An increase in the frequency and/or intensity of volcanic activity is a particularly viable mechanism for injecting material directly into the stratosphere where it is rapidly transported poleward (Mossop, 1964; Dyer and Hicks, 1968), remaining there for several years (Lamb, 1970). For example, the 1963 eruption of Mt. Agung (6°30′S,115°30′E) was recorded in the radiation measurements at the South Pole (Viebrock and Flowers, 1968). Close inspection of the radiation data by Dermendjian (1973) led him to suggest that the Mt. Agung dust was transported to the South Pole "essentially unmodified from the source region." Undoubtedly, other more-explosive tropical eruptions would increase the concentration of particles in the Antarctic stratosphere.

Lamb (1970) has suggested that the examination of annual layers within ice sheets may produce an improved volcanic chronology as well as indicate the number of years over which deposition continues after a major eruption. The South Pole microparticle data demonstrate that this is quite likely, although much additional core work and better substantiation are required. For example, Figure 2 illustrates that posteruptive background concentrations remained slightly higher for at least 3 yr after the 1883 eruption of Krakatau.

Lamb (1970) derived a volcanic dust veil index (DVI) on the basis of observed climatic anomalies attributed to volcanic activity. As most early observations were made in Europe and Asia the derived chronology represents primarily the climatic effects produced in the Northern Hemisphere by volcanic events north of approximately 30°S. Although major volcanic events in tropical latitudes should be recorded in the stratigraphy of the Antarctic Ice Sheet (and Greenland as well), events of seemingly similar magnitudes will not necessarily produce identical signals in the microparticle record. Dust dispersion and atmospheric residence time are controlled, in part, by the size distribution and concentration of the injected material, the latitude and season of the eruption, and the duration and magnitude of posteruptive phases. For example, interhemispheric mass exchange is weaker in January than in July (Reiter, 1969).

For example, in Figure 5 no pronounced particle concentration is associated with the January 20, 1835 eruption of Coseguina, Nicaragua (13°N,87½°W) designated by A′. On the other hand, a large concentration of microparticles in the South Pole core is temporally correlated with the June 7–12, 1815 eruption of Tambora, Sumbawa (8°S,118°E), designated by A. Interestingly, Hammer (1977) reports a more pronounced specific conductivity for the Tambora eruption than for the Coseguina eruption in the Crête, Greenland core. The Coseguina DVI estimate appears much to high in light of the stratigraphic records in both polar ice sheets. Thompson and Mosley-Thompson (1981) present a more-detailed discussion of the microparticle record.

Persistent activity between 1750 and 1770 A.D. (designated by B in Fig. 5) may be recorded in the particle profile, although the largest eruption, Mayon Luzon (13°30′N,123°30′E, DVI_{world} = 2300) appears to be recorded at 1776 in the core


Temperature (°C)
δ18O calcite PDB (‰)
Global DVI (10²)
Southern Hemisphere DVI (10²)
Particles (10⁴)
A'
A
B
C
Year A.D.
1956
1856
1756
1656
1556
1456
1356
1256
1156
1056

rather than 1767. If it is assumed that these features are temporally correlative, the microparticle time scale is missing 10 yr between 1767 and 1974, an error of 5% or 1 in 20 yr which is similar to the number of missing years inferred by Giovinetto (1963) from accumulation-stake measurements.

After the Coulter counter analysis, the insoluble particles are retained upon 0.45-μm Millipore filter papers. The particles from the strata representing the interval 1824 ± 13 yr (Fig. 5) were examined by scanning electron microscope and X-ray energy dispersive analysis and found to consist mainly of volcanic shards that are andesitic in composition (E. King, personal communication, 1980).

Hirschboeck (1980) recently compiled a volcanic chronology expanding the original work of Lamb to include many more eruptions and emphasizing the record of the last 100 years. This new work reveals that during the 1910s volcanoes were fairly active in all latitudes and between 1925 and 1945 volcanoes in the Southern Hemisphere were very active. This period was previously accepted as rather quiescent as reflected by the DVI estimates in Figure 5. Microparticle concentrations between 1900 and 1940 exhibit several broad, moderate peaks, but the greatest background concentrations increase gradually from 1450 to reach a maximum between 1740 and 1850. Despite the potential error in the microparticle time scale and the paucity of the known volcanic record, we suggest that the major volcanic events south of 30°N are recorded in the Antarctic Ice Sheet. If this can be substantiated by obtaining a similar and more-detailed record from another South Pole core and by positive identification of the material as volcanic, then the microparticle record in the East Antarctic plateau may provide a valuable tool for completing and extending the Southern Hemisphere volcanic chronology.

CONCLUSIONS

The microparticle record from the 101-m South Pole core reveals a substantial and prolonged increase in the particle concentrations within the core strata representing the estimated period 1450–1860 A.D. On the basis of all the above evidence, it is suggested that the central Antarctic snow strata may be continuously recording the fluctuations in the concentration and size distribution of insoluble particles in the Antarctic atmosphere. If as Hogan (1975) suggests, the Antarctic aerosols represent the natural background aerosols, the microparticles within the snow strata may provide a source of information about the insoluble portion of the background aerosol over many millennia. However, as Junge (1977) points out, the relationship between the particles in the atmosphere and the particles within the resulting precipitation is neither direct nor simple and is poorly understood. Certainly the potentially lengthy records available from East Antarctica justify additional investigation and quantification of this relationship.

At locations where the annual variations in microparticle concentrations are preserved within the firn and ice, detailed microparticle analysis can provide a relative time scale for ice cores where low accumu-

FIG. 5. The concentration of particles with diameters $\geq$0.63 μm/g of sample in the South Pole core. The ordinate is the estimated time scale obtained by counting annual concentration peaks. The unmodified dust veil index (DVI) of Lamb (1970) is plotted for the Southern Hemisphere and the world. The letters suggest potentially correlative features as follows: (A) the eruption of Tambora in 1815 (DVI = 3000) and (A′) the eruption of Coseguina, Nicaragua in 1835 (DVI = 4000). (B) the 1750–1770 time interval containing the eruption of Mayon, Luzon in 1766 (DVI = 2300). (C) the 1883 eruption of Krakatau (DVI = 1000). Plotted on the right is the central England temperature curve (solid line) (Lamb, 1965) often employed to represent the global trend (GARP, 1975). Although such interhemispheric comparisons may produce erroneous conclusions (Reiter, 1977), additional support for this comes from $\delta^{18}O$ record (dotted line) from a New Zealand speleothem (Wilson *et al.*, 1979).

lation precludes many traditional techniques. Until absolute dating of layers older than 100 yr (^{210}Pb) is accomplished, relative time scales must suffice. Additionally, this detailed microparticle analysis provides the first record of annual net-surface accumulation longer than 200 yr.

The first step toward accurate interpretation of climatic variations from proxy data should focus upon the detailed investigation of the last 1000 yr. The abundance of historical and instrumental data provides an opportunity to develop fully the interpretative method which then can be applied to elucidate the longer core records. Therefore, it is essential to analyze additional 100-m cores from East Antarctica for microparticles as well as other ice core constituents.

The longest ice cores, and hence the longest records, will be obtained in East Antarctica. Consequently, detailed microparticle analysis of continuous cores, when coupled with other analytical data, should contribute to the production of a more precise, composite record of climatic variations over the last 250,000 yr.

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