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TEMPORAL VARIABILITY OF MICROPARTICLE PROPERTIES IN POLAR ICE SHEETS

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ABSTRACT

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Four recent ice core studies reveal a consistently recurring temporal correlation between increased microparticle concentrations and lower global temperatures (more negative $^{18}O/^{16}O$ ratios). A continuous 900-year record of particle deposition from the 101-m South Pole core was obtained by analyzing 6218 samples. The concentration of insoluble particles with diameters >0.63 μm increases substantially between A.D. 1450 and 1850, a period of slightly reduced global temperatures encompassing the latest Neoglacial or Little Ice Age. There is evidence suggesting that some of the additional material may be volcanic, although further substantiation is required.

The microparticle analyses of selected sections from three deep cores coupled with the respective $\delta^{18}O$ measurements reveal that in all three cores the last glacial or Late Wisconsin ice contained great quantities of microparticles. The ratio of the average microparticle concentration in Wisconsin sections to that in Holocene sections is 6 for the 905-m Dome C, Antarctica core, 3 for the 2164-m Byrd Station, Antarctica core and 12 for the 1387-m Camp Century, Greenland core. Microparticle increases of this magnitude can not be accounted for merely by a reduction in net accumulation. These data suggest that the global atmosphere was heavily laden with suspended particulates near the end of the last major glaciation

INTRODUCTION

The precise nature of the complex relationship between the particles in the atmosphere and particles within the associated precipitation is poorly understood. Nevertheless, the particles deposited within firn and ice cores offer the best possible record of the past characteristics of the atmospheric particulate mass. Of the world's ice sheets, the remote Antarctic Ice Sheet is the ideal site for investigating the temporal variations in the global background particulate mass (Hogan, 1975) as there are few local sources. Furthermore, the transportation of the atmospheric mass over Antarctica is dominated

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by steady subsidence, inflow of air at upper levels and outflow at low levels rather than by synoptic disturbances (Reiter, 1971). This mode of mass transportation suggests that the upper tropospheric and stratospheric masses are primary sources of the material brought to the ice sheet surface. Therefore, any substantial increase in the concentration of particles within the global stratosphere should be recorded within the Antarctic Ice Sheet.

The size distribution and concentration of insoluble particles within firn and ice cores is determined by the Coulter counter procedure (Thompson, 1977a) which provides 15 intervally scaled size ranges between 0.50 and 16.0 μm diameter. In the atmosphere Aitken particles (radius $\leqslant 0.1$ μm) dominate the total number concentration while the large particles (0.1 μm $<$ radius $\leqslant 1.0$ μm) dominate the total aerosol mass which controls the aerosol optical depth, a sensitive component of the earth—atmosphere radiation balance (Pollack et al., 1976). Particles with diameters $\leqslant 1.0$ μm have a stratospheric residence time on the order of years and thus may be transported great distances (Lamb, 1970; Shaw, 1979). This paper presents the results from the analysis of the microparticles within four cores. These measurements were conducted under class 100 clean room conditions. The temporal variations in microparticle concentration, size distribution and elemental constituents are assessed with respect to known large-scale climatic events.

900-YEAR PARTICLE RECORD FROM SOUTH POLE

In 1974 a 101-m firn core was drilled at Amundsen—Scott South Pole Station. This was the longest Antarctic core to be analyzed continuously for particles by the Coulter counter technique. A total of 6218 samples representing 65 m of water (101 m of firn) were analyzed for total particle concentration and size distribution. The average sample length was 0.01 m water which, coupled with the average annual water accumulation of 0.07 m (Gow, 1965) yields a resolution of seven samples per accumulation year.

The time scale was constructed by using cyclical variations in microparticle concentrations (see Mosley-Thompson, 1980, figure 17). The vertical layer separation (in water equivalent) between these particle peaks was found to be consistent with the current average annual net water accumulation (7 g a^{-1}) suggesting these to be annual features. A complete discussion of these annual particle peaks and the construction of a 911-year net accumulation record are discussed elsewhere (Thompson, 1979; Mosley-Thompson, 1980). The time scale was derived by counting these particle peaks downward in the core from the 1956 time-stratigraphic horizon identified by gross Beta activity levels (W. Dansgaard, pers. comm., 1977).

The 900-year South Pole record of the concentration of insoluble particles with diameters $\geqslant 0.63$ μm per 500 μl of sample is illustrated in Fig.1. This record encompasses the latest neoglacial or Little Ice Age, ca. A.D. 1450—1850, evident in the central England temperature record (Fig.1) and is

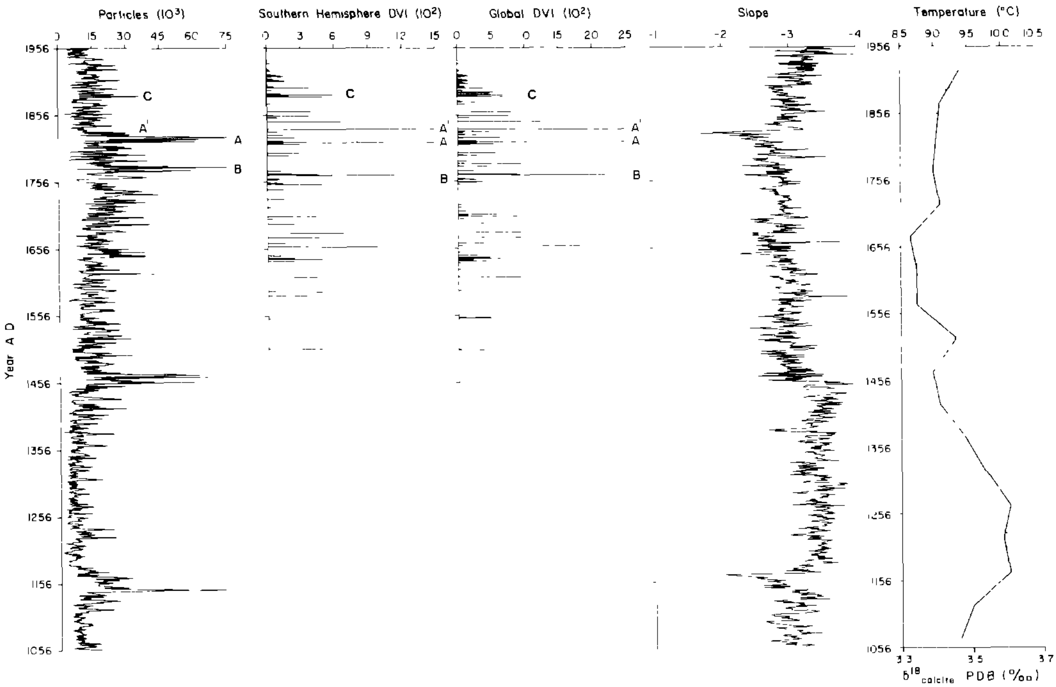

Fig.1. The concentration of particles with diameters $\geqslant 0.63$ μm per 500 μl sample in the South Pole core. The ordinate is the time scale obtained by counting annual particle concentration peaks downward from the 1956 horizon. The unmodified dust veil index (DVI) of Lamb (1970) is plotted for the Southern Hemisphere and the world. The letters suggest potentially correlative features. A designates the eruption of Tambora, Sumbawa in 1815 (DVI = 3000) and A' designates the eruption of Coseguina, Nicaragua in 1835 (DVI = 4000). B designates the eruption of Mayon, Luzon in 1766 (DVI = 2300). C represents the 1883 eruption of Krakatau (DVI = 1000). The slope of the Junge power law size distribution function characterizing the size distribution of each firn sample is presented. 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 spleothem (Wilson et al., 1979).

recorded in the Southern Hemisphere by geophysical processes in New Zealand (Wilson et al., 1979) as well as by alpine glacier advances in New Zealand (Salinger, 1976) and southern Chile (Mercer, 1976). This period of reduced surface temperature is characterized by a nearly twofold increase in total particle concentration (Fig.1). On the other hand, the lowest concentrations occur between A.D. 1200 and 1450.

The unmodified dust veil indices (DVI) for the Southern Hemisphere and the world are presented in Fig.1. These estimates have not been modified for latitude with respect to Antarctica and although the estimates are often subjective and open to criticism (Dermendjian, 1973), this record is the most comprehensive chronology available. Hirschboeck (1980) recently compiled a volcanic chronology expanding the original work of Lamb (1970) to include many more eruptions and to emphasize the record of the last 100 years. This new work reveals that during the 1910s volcanoes were fairly active in all latitude bands and in the Southern Hemisphere an intensely active period of volcanism occurred between 1925 and 1945. This period was previously accepted as rather quiescent as reflected by the DVI profiles in Fig.1. However, the microparticle concentrations between 1900 and 1940 exhibit several moderate but broad peaks.

Some of the major features of the particle concentration profile and the DVI estimates correspond reasonably well despite the imprecision and paucity of the DVI estimates (e.g., Hoyt, 1978; Hirschboeck, 1980) and the potential error in the microparticle time scale resulting from missing years in the accumulation record (Mosley-Thompson, 1980). Although major eruptions in the tropics should be recorded in the stratigraphy of the polar ice sheets, events of similar magnitude will not necessarily create equivalent microparticle concentrations. The latitude and season of the eruption as well as the duration of the post-eruptive phase will control dust dispersion and residence time. For example, interhemispheric mass exchange is weaker in January than in July (Reiter, 1969). Examination of Fig.1 indicates the lack of a pronounced particle concentration peak in association with the January 20, 1835 eruption of Coseguina, Nicaragua (13°N, 87°30′W) designated by A' in Fig.1. As Hammer (1977a) noted the DVI estimate for Coseguina was derived primarily from temperature anomalies (Lamb, 1970). 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 in Fig.1) which continued in some degree until 1819. Interestingly, in the Crête, Greenland core, Hammer (1977a) reports a more pronounced specific conductivity for the Tambora eruption than for the Coseguina eruption. The Coseguina DVI estimate appears much too high in light of the stratigraphic records in both polar ice sheets.

Working on several cores from Greenland, Hammer (1977a) has shown that elevated specific electrical conductivites due to the fallout of acids produced by violent volcanic eruptions bear a close resemblance to the Northern Hemisphere volcanic record between A.D. 1770 and 1970, which he modified for latitude with respect to Greenland. On the other hand, particulate measurements by light scattering and Coulter counter techniques exhibit little coherence between Lamb's volcanic indices and the dust peaks between A.D. 1600 and 1951 in southern Greenland (Hammer, 1977b). These results do not contradict the South Pole results. Greenland is under the influence of the westerly flow of tropospheric air laden with continental dust (Hammer, 1977b; Reiter, 1977), while subsidence and surface outflow bring upper tropospheric and stratospheric matter to the surface over central Antarctica (Reiter, 1977). Although many of the pronounced particle concentration peaks in the South Pole core may reflect elevated levels of volcanic activity, such correlations are speculative pending further substantiation of the microparticle record from another South Pole core and positive identification of the material as volcanic in origin.

Fig.1 illustrates the slope of the size distribution for each sample calculated by a least-squares minimization of the power law function (Junge, 1963). The decrease in the absolute value of the slope, which often appears to be associated with an increase in the particle concentration, reflects an increase in the proportion of larger particles (diameter >1.0 μm) within the sample. Junge (1963) reports the size distribution slope for average atmospheric aerosol masses is ≈ -3. The aerosol measurements of Shaw (1975) during two austral summers at the South Pole indicate that the aerosols are distributed in size with a Junge power law slope of -3.2 (± 0.3). For insoluble particles in the 1950—1956 South Pole strata, the slope is -3.35 and for the 1910—1950 strata it is -3.2. This similarity between the size distribution slopes of the atmospheric aerosol mass and the insoluble particles from the snow is interesting and requires further investigation. The relationships between particles (and gases) in the atmosphere and in the precipitation are complex and poorly quantified (Junge, 1977). Thus, inferences about atmospheric conditions or composition from snow constituents must be made with caution.

MICROPARTICLE VARIATIONS OVER MILLENIAL TIME INTERVALS

Selected sections of three deep cores have been analyzed for microparticle concentration and size distribution. The particle concentrations in the 900-m Dome C, Antarctica core, the 2164-m Byrd Station, Antarctica core and the 1387-m Camp Century, Greenland core have been coupled with the corresponding $\delta^{18}O$ measurements conducted by Lorius et al. (1979), Epstein et al. (1970) and Dansgaard et al. (1971), respectively. A comparison and discussion of the microparticle analyses of these three cores are presented below.

900-m Dome C, East Antarctica ice core

The particle analyses of 5367 samples representing 51 nearly continuous and unfractured sections (averaging 0.76 m in length) of the French 900-m Dome C core comprise the most detailed microparticle record from any deep core. The average sample size of 0.0067 m ice when coupled with the average annual accumulation of 0.035 m ice (Petit et al., 1979) yields a resolution of 5.5 samples per accumulation year. Fig.2 presents the average concentration of particles with diameters >0.63 μm per 500 μl samples for each core section analyzed and the $\delta^{18}O$ measurements (Lorius et al., 1979).

The particle concentrations (Fig.2) reach a peak just prior to the end of the last glacial or Late Wisconsin glaciation ($\approx$500 m in core). The transition into the post-glacial or Holocene strata is marked by an abrupt five-fold

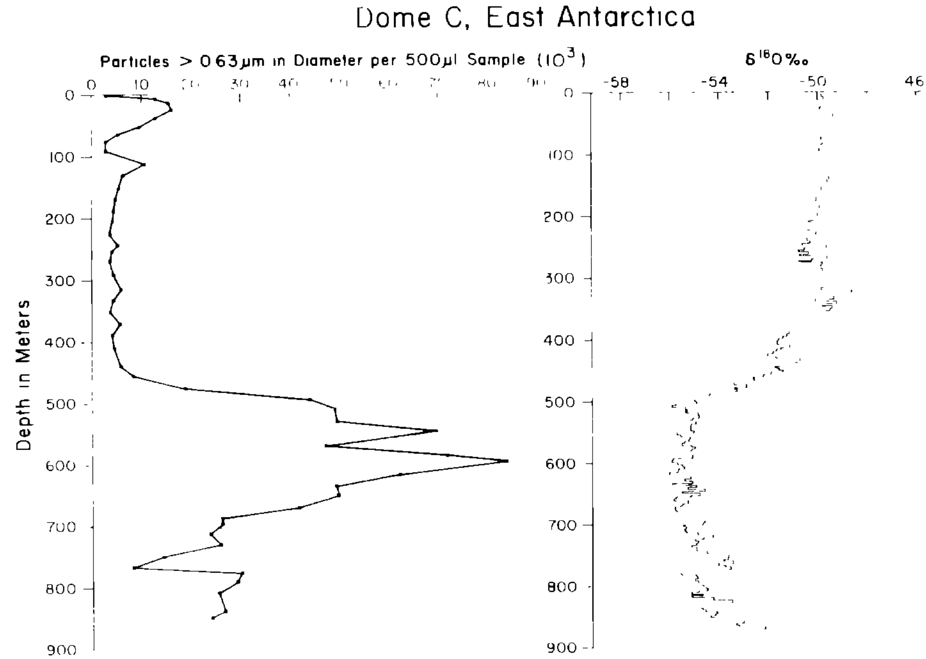

Fig.2. The average concentration of particles with diameters ⩾0.63 μm per 500 μl sample for each of the 51 sections of the Dome C, Antarctica core. The corresponding $\delta^{18}O$ measurements provided by Lorius et al. (1979) are plotted on the right. The particle concentration reaches a peak just prior to the end of the last glacial stage (Late Wisconsin). The transition from Wisconsin to Holocene ice is abrupt with concentrations decreasing by 80% in less than 38 m of ice representing less than 1000 years.

decrease in particle concentration within just 38 m of ice representing a time interval of about 1000 years. The particle concentrations in the Holocene strata are very uniform except in the upper 100 m of the core where concentration increases are similar to those found between A.D. 1450 and 1850 in the South Pole 100-m core. The largest increases in particle concentration are temporally correlated with the most negative $\delta^{18}O$ measurements (coldest temperatures).

The detail in which each of the 51 sections were analyzed is illustrated in Figs.3, 4 and 5 which present a chronological sequence of particle concentrations from the Holocene, through the transition and into the last glaciation. Not only are the particle concentrations much less in the Holocene sections but the intersample variations (peak to valley ratios) are quite small (Fig.3). Both the total concentration of particles and the intersample variations increase in the transition zone (Fig.4, left profile). In the lower sections of the core (Fig.5) the intersample variations are quite large and the particle axis was extended to accommodate the five-fold increase in concentration.

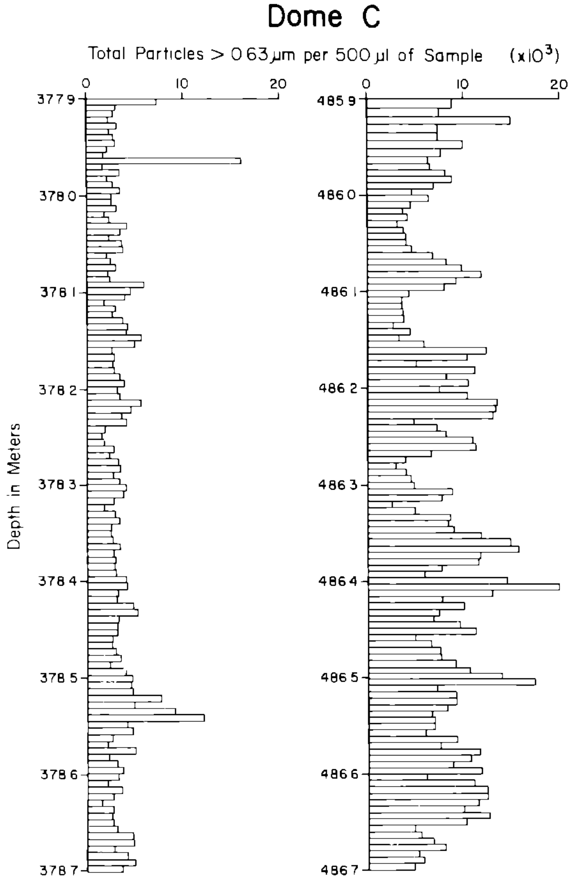

Fig.3. The concentration of particles with diameters $\geqslant 0.63$ μm per 500 μl sample in two sections of the Dome C core. The section at 377.9 m comes from the Holocene portion of the core and the section at 485.9 m represents the end of the transition into the Holocene.

The Byrd Station, Antarctica and Camp Century, Greenland deep cores

The microparticle analysis of selected sections from both the Byrd Station, Antarctica and Camp Century, Greenland deep ice cores have been reported elsewhere (Thompson et al., 1975;Thompson, 1977a, b). Table I summarizes the salient features of this microparticle work for comparison with the Dome C core data. The average concentration of particles with diameters >0.6 μm per 500 μl sample ($\bar{C}$) was averaged for all sections analyzed in each of these cores (Table I). $\bar{C}$ for the Camp Century core is 7.8 times that in the Byrd core and 5.7 times that in the Dome C core. This large concentration within the Camp Century core reflects the extensive particulate source areas in the Northern Hemisphere.

All three cores exhibit substantial increases in particle concentration in association with the more negative $\delta^{18}O$ values which represent the last

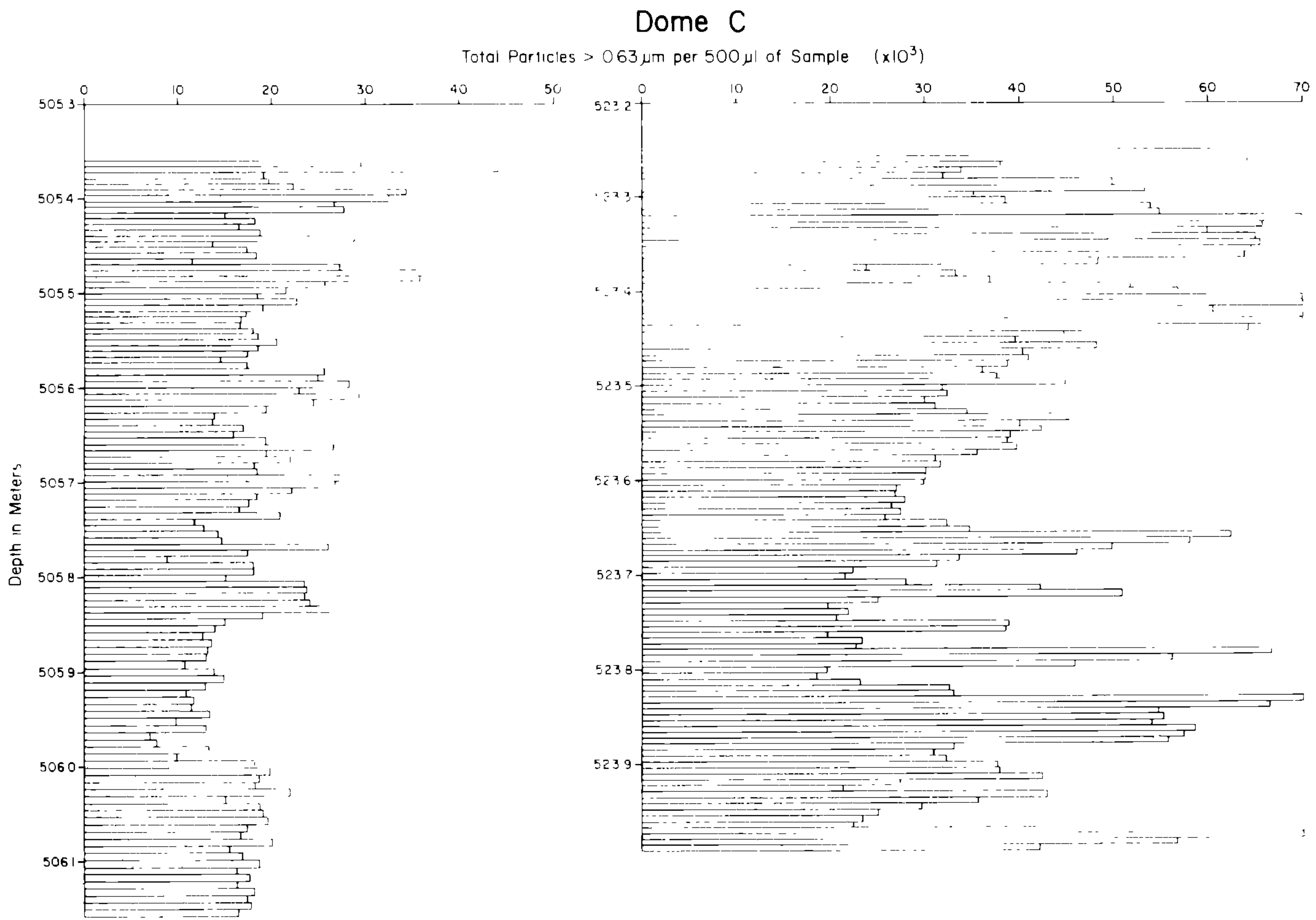

Fig.4 The concentration of particles with diameters 0.63 μm per 500 μl sample in two sections of the Dome C, Antarctica core. The section at 505.3 m comes from the middle of the transition from Late Wisconsin to Holocene and the section at 523.2 m represents the beginning of the transition from the Late Wisconsin to Holocene interpreted from the $\delta^{18}O$ profile.

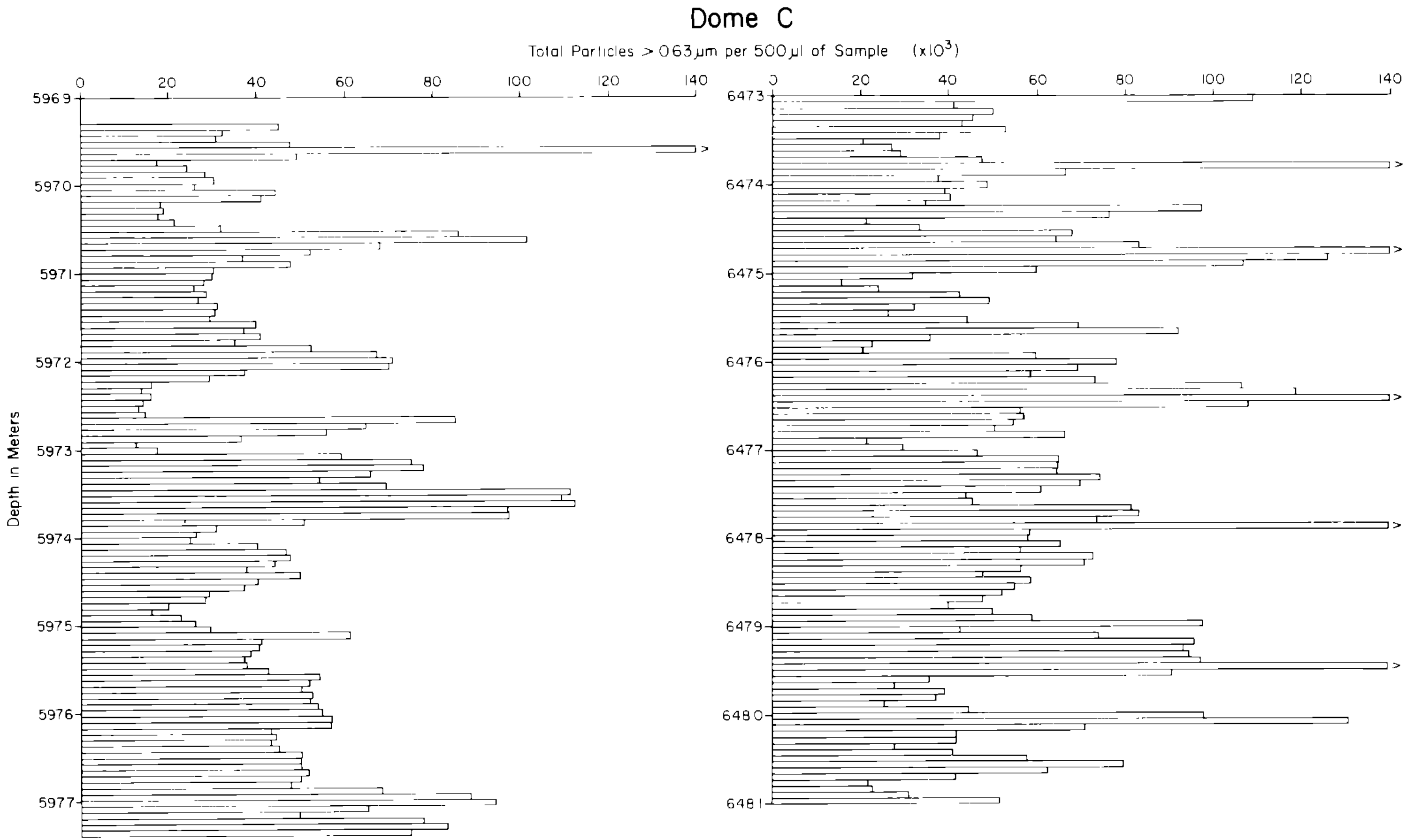

Fig.5. The concentration of particles with diameters $\geqslant 0.63$ μm per 500 μl sample in two sections from the Wisconsin portion of Dome C, Antarctica core. The abscissa has been expanded to accommodate the substantial increase in particle concentration characterizing the Wisconsin portion of the core.

TABLE

Comparison of average concentration of particles with diameters >0.6 μm ($\bar{C}$) in three deep cores over the last 30 000 years[1]

	Dome C	Byrd Station	Camp Century
Average $\bar{C}$ for Holocene sections	6670	8989	25 713
Average $\bar{C}$ for Wisconsin sections	40 562	27 445	313 507
Ratio $\bar{C}$ in Wisconsin sections to $\bar{C}$ in Holocene sections	6	3	12
Average $\bar{C}$ for all sections analyzed	20 796	15 369	119 411
Number of Holocene sections analyzed	27	11	11
Number of Wisconsin[2] sections analyzed	24	8	8
Meters of core processed	38.74	23.07	11.89
Average sample size (m ice)	0.0067	0.02	0.02

[1] All measurements are conducted for 500 μl samples.
[2] Only sections encompassing the period between 30 000 yr. B.P. and the end of the last glacial are included in these averages making the time intervals comparable with that represented by the Dome C core.

glaciation or Late Wisconsin strata (Fig.6). Fisher (1979) reports a similar increase in particle concentration in two ice cores from the Devon Island ice cap in Arctic Canada. For the three deep cores the ratio of the average $\bar{C}$ in the Late Wisconsin to that in the Holocene (Table I) is 6 for Dome C, 3 for Byrd Station and 12 for Camp Century. Cragin et al. (1977) report a Late Wisconsin/Holocene ratio of 11 for both Al and Si in the Camp Century, Greenland core while for the Byrd Station, Antarctica core ratios are 6.9 for Si and 7.3 for Al. These latter ratios more closely resemble the microparticle ratios for the Dome C core.

This increase in particles during the last glacial maximum is probably due to a corresponding increase in atmospheric particle loading, a reduction in annual net accumulation or some combination of these factors. In each of the cores the particle concentration falls off rapidly during the transition into the Holocene (Fig.6). Either the net accumulation regime at each site was rapidly altered diluting the particles or the particle source was rapidly diminished.

The similarity of Holocene $\bar{C}$ values for Dome C (6670) and Byrd Station (8989) is interesting in view of their different net balance regimes, 0.032 m a^{-1} water (Petit et al., 1979) and 0.14 m a^{-1} water (Bull, 1971), respectively. For all three cores the increase in $\bar{C}$ in the Late Wisconsin strata exceeds

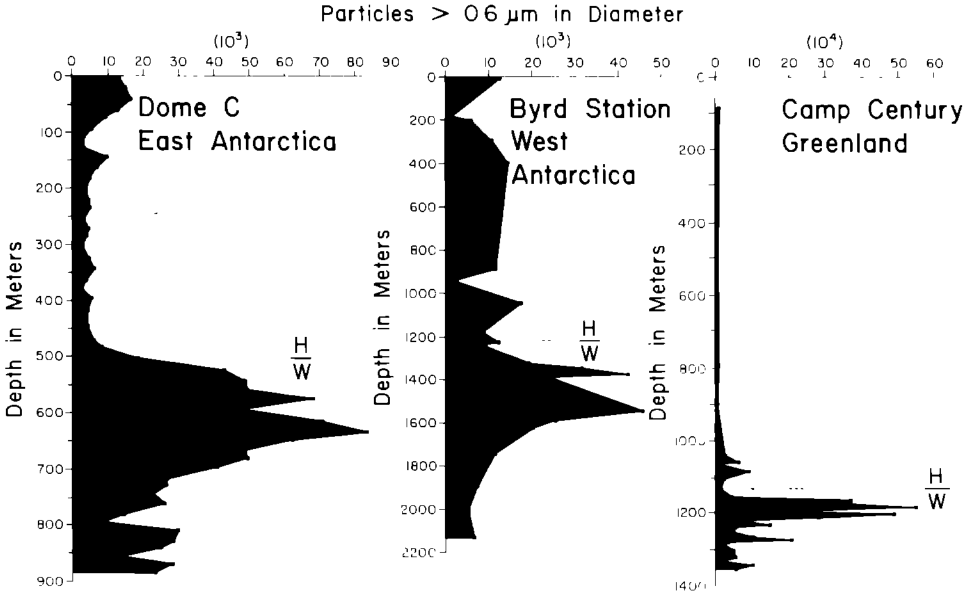

Fig.6 The concentration of particles with diameters >0.6 μm per 500 μl sample averaged for each section of three deep cores encompassing the Late Wisconsin glaciation. The Holocene—Wisconsin transition is based upon the $\delta^{18}O$ record for each of the cores as compiled by Lorius et al. (1979) for the Dome C core, by Epstein et al. (1970) for the Byrd core and by Dansgaard et al. (1971) for the Camp Century core.

that expected merely from a reduction in net accumulation alone. In the Dome C core, for example, the five-fold increase in $\bar{C}$ for Late Wisconsin strata far exceeds any concentration resulting from a 30—40% reduction in net accumulation as is suggested to have occurred (Lorius et al., 1979). In addition, recent data based upon the identification of annual microparticle features in the sections of the Dome C core analyzed suggest no reduction in net accumulation within the Late Wisconsin (Thompson et al., 1981). It is suggested here that the substantial increase in the concentration of particles in the global atmosphere is the primary mechanism producing this corresponding increase in particles within the Late Wisconsin sections of these cores which represent both polar regions.

Smaller particles have longer atmospheric residence times and thus, to obtain an estimate of past background levels of insoluble particles, the concentration of the small particles with diameters between 0.6 and 0.8 μm (C_s) is employed. To reduce potential contamination to the lowest possible level, the average of C_s in the cleanest 10% of the samples ($\bar{C}_{10}$) is calculated for each core section. The use of $\bar{C}_{10}$ instead of C_s is a precautionary step and does not affect the significance levels of the statistics presented in Table II. For exemplary purposes statistics relating log $\bar{C}_{50}$ (C_s in the cleanest 50% of samples in each section) and $\delta^{18}O$ are included in Table II. The $\delta^{18}O$

TABLE II

Statistical results of tests of relatedness among δ, $\bar{C}_{10}$, log $\bar{C}_{10}$ and log $\bar{C}_{50}$ for the Dome C, Antarctica and the Camp Century, Greenland deep cores

Core name	Variables X	Variables Y	Spearman/ significance	Kendall/ significance	Pearson r/ significance	r^2
Dome C	$\bar{C}_{10}$	δ	−.774	−.574	−.819	.672
			.001	.001	.001	
	log $\bar{C}_{10}$	δ	−.774	−.574	−.861	.742
			.001	.001	.001	
	log $\bar{C}_{50}$	δ	−.753	−.555	−.856	.732
			.001	.001	.001	
Byrd Station	$\bar{C}_{10}$	δ	−.888	−.735	−.806	650
			.001	.001	.001	
	log $\bar{C}_{10}$	δ	−.888	−.735	−.891	.794
			001	.001	.001	
	log $\bar{C}_{50}$	δ	−.848	−.681	−.830	.690
			001	.001	.001	
Camp Century	$\bar{C}_{10}$	δ	−.923	−.761	−.767	588
			.001	.001	.001	
	log $\bar{C}_{10}$	δ	−.923	−.761	−.921	.847
			.001	.001	.001	
	log $\bar{C}_{50}$	δ	−.894	−.712	−.866	.750
			.001	.001	.001	

measurements were averaged for each section and plotted with $\bar{C}_{10}$ on scatter diagrams (Figs.7, 8 and 9). Examination of these diagrams reveals that small changes in $\delta^{18}O$ are associated with much larger variations in $\bar{C}_{10}$, suggesting a logarithmic relationship.

To test the relatedness of these two variables the Spearman rank correlation coefficient (r_s) and the Kendall tau (τ_k) were evaluated for all three cores. For samples drawn randomly from a normally distributed population, the Pearson product moment correlation coefficient (r_p) is usually employed. Unfortunately, these samples were not randomly selected and it is impossible to know *a priori* whether their respective populations are normally distributed. However, neither of the two non parametric tests r_s and τ_k, requires that the samples be bivariate normal; however, both provide the following: (1) a measure of the strength of the relationship among sample observations, (2) a point estimate of the measure of this strength, and (3) a basis for constructing a confidence interval for this measure (Daniel, 1978).

Table II presents the results of these tests for the correlation between $\delta^{18}O$ and $\bar{C}_{10}$, log $\bar{C}_{10}$ and log $\bar{C}_{50}$. All of the estimates are significant at the 0.001 level which implies that the null hypothesis that these two variables are independent may be rejected with 99.9% confidence. Nevertheless, a cause and effect relationship can not be assumed as the variation in both particle concentration and $\delta^{18}O$ could be produced by some yet undetermined forcing function.

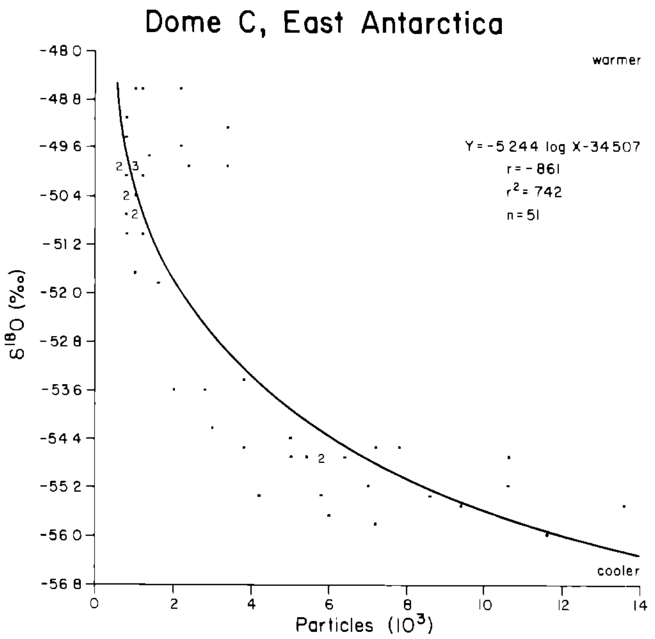

Fig.7. The scatter diagram of the particles with diameters between 0.63 and 0.80 μm in the cleanest 10% of the samples in each section ($\bar{C}_{10}$) of the Dome C, Antarctica core and the corresponding average $\delta^{18}O$ values. The diagram suggests a logarithmic relationship (Table II) expressed by the regression equation and its corresponding curve.

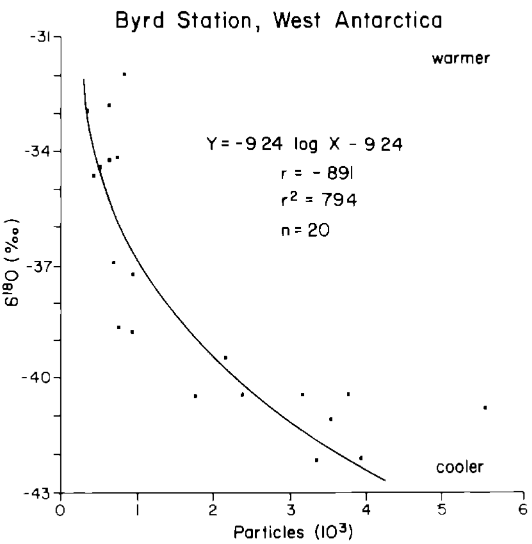

Fig.8. The scatter diagram of $\bar{C}_{10}$ and $\delta^{18}O$ for corresponding sections of the Byrd Station, Antarctica core. The logarithmic relationship (Table II) is expressed by the regression equation plotted in the diagram.

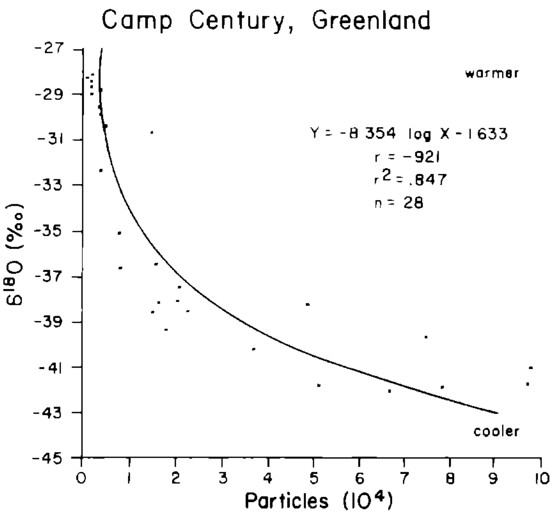

Fig.9. The scatter diagram of $\bar{C}_{10}$ and $\delta^{18}O$ for corresponding sections of the Camp Century, Greenland core. The logarithmic relationship (Table II) is expressed by the regression equation plotted in the diagram.

The examination of individual particles by light microscope and scanning electron microscope coupled with the elemental analysis by an X-ray energy dispersive system (XEDS) is a routine part of the microparticle analysis procedure (Thompson, 1979). These results for the Camp Century and Byrd Station cores are reported by Thompson (1977a, b). The Camp Century core particles were found to be composed primarily of clay minerals, reported simultaneously by Kumai (1977). Both clay fragments and volcanic glasses were found in the Byrd Station core. A greater abundance of these volcanic glasses was found in the Late Wisconsin sections of the Byrd core than in the overlying Holocene sections. It is necessary to note that the XEDS analyses are conducted only for particles with diameters greater than 5 μm as the analysis of smaller particles is unreliable.

The particles in the Dome C core appear to fall into two distinct classes according to size. The smaller particles with diameters less than 2 μm are more abundant by several orders of magnitude while the very large particles between 60 and 80 μm in diameter are predominantly volcanic glass fragments. These large fragments exhibit a much higher frequency of occurrence in sections below 500 m or in Late Wisconsin strata. The glasses which have been analyzed by the electron microprobe are nearly identical in morphology and chemistry to those found within several ash bands in Byrd core and whose source is suggested to be Mt. Takahe, Antarctica (Kyle et al., 1981).

The small fragments in the Dome C core are too small for quantitative chemical analysis and do not exhibit a distinguishable morphology. Their source or sources are unidentified. This material may represent a diverse mixture composed primarily of global stratospheric material brought to the surface by the descending motions over the Antarctic plateau and a smaller component of tropospheric material transported by cyclonic disturbances which periodically penetrate the plateau region.

CONCLUSIONS

A continuous 911-year record of particle concentration from the 101-m South Pole core reveals nearly a two-fold increase between A.D. 1450 and 1850, the period encompassing the latest Neoglacial. The similarity between the gross features of the microparticle record and the available dust veil index suggests a volcanic source for some of the additional material, although further substantiation is required.

The temporal correlation between the insoluble particles and the $^{18}O/^{16}O$ ratios within selected sections of three deep cores indicates that the last glacial or Late Wisconsin glacial stage was characterized by a substantial increase of suspended matter within the global atmosphere. Although a reduction in the net accumulation over both polar regions would serve to concentrate the particles within the snow strata, it has been demonstrated here than even a 40% decrease would be insufficient to account for the large increases in particle concentration found in all three cores.

The particles within these deep cores were examined for morphology and elemental composition. The material in all sections of the Camp Century core is composed primarily of clay minerals while a large number of volcanic glass fragments were found in the Wisconsin sections of the Byrd core. The particles in the Dome C core exhibit two distinct size ranges, diameters less than 2 μm and diameters between 60 and 80 μm. On the basis of morphology and chemistry the large particles appear to be local Antarctic volcanics similar to those found within several ash bands in the Byrd core. The great quantity of small particles are impossible to identify with regard to particular sources.

These microparticle concentration data support the global increase in atmospheric particle concentrations during the Late Wisconsin. This relationship between the increase in particles and the reduction of global temperatures must be satisfactorily resolved by any successful hypothesis addressing the causes of climatic change.

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