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Particle transport to the snow surface at the South Pole: the beginning of a tropospheric history

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ABSTRACT

Sodium concentration measurements in recent south polar snow by Legrand and Kirchener have been compared with surface aerosol measurements by Bodhaine, Shanahan and Samson et al., made at the South Pole Station. When a 180-day lag is applied, to allow spring/summer aerosols to be precipitated and incorporated into the autumn/winter snow layer, very good correspondence exists between mean aerosol concentration in air and mean sodium concentration in snow. This paper describes analyses of meteorological and glaciological processes to define glaciological and meteorological years, which justify the use of this 180 day lag. The accumulation rate of snow on the South Polar Plateau has been established through pit and core analysis during the occupation of the South Pole station, and through direct snow stake accumulation measurement. Precipitation has not been routinely measured, but is estimated through analysis of the station meteorological record and application of the cold air precipitation rates derived from the literature. The estimated precipitation is compared with measured accumulation to investigate lag between time of precipitation and accumulation, and to examine other possible sources of accumulated ice substance (riming, drifting, and direct sublimation) to define the glaciological year. Precipitation of sodium and other particles, through coagulation and other ice crystal attachment processes, is discussed relative to the meteorological year. The results of this work indicate that additional measurements relative to the gradients of temperature, wind, precipitation, and accumulation on the Polar Plateau are essential to the formal establishment of a theory relating glacio-chemical accumulation to meteorological processes, and formulating tropospheric history from glacial deposition.

1. Introduction

The antarctic ice sheet provides a unique environment to record changes in meteorological processes, on time scales varying from that of a single storm to that of a climatic change. The ice shelves and peripheral ice fields of less than 1-km elevation reflect the influence of annual ice cover through seasonal interaction exchange and modification within the mP (polar maritime) and mA (antarctic maritime) air masses, according to Van Loon (1972). The cA (antarctic continental) air mass is isolated from all other air masses by the surrounding mP and mA air masses. It is generally confined to the interior ice sheet above 1 km in elevation, and is derived from air of recent mP or mA history that has been advected into the interior of Antarctica as organized cyclonic storms, or through weak exchange with the surrounding polar air masses. Here we examine evidence that this air mass represents the "end point" of vapor and particle exchange and removal processes in the atmosphere, and that the residue of these vapors and particles deposited in the near-surface snow and firn represent the recent history of this air mass.

An instrumental meteorological record, including soundings of the air aloft, was begun at the South Pole Station in January 1957 (Flowers, 1960; Hansen, 1960) Glaciological surveys of the rate of snow accumulation (Giovinetto, 1960; Gow, 1965) and measurements of the physical and stable isotopic characteristics of the accumulated snow by Epstein et al. (1965) were also initiated through cooperation of the station meteorologists. Several research programs were directed toward measurement of atmospheric constituents, and a systematic study of the elemental composition of the Antarctic aerosol was begun by Zoller et al. (1974) in the early 1970s. Pack (1973) established the Geophysical Monitoring for Climatic Change (GMCC, now Climate Monitoring and Diagnostics Laboratory, CMDL) series of aerosol and atmospheric chemical measurements, which have continuously increased in sophistication and accuracy, and provide the basis for comparison of these atmospheric properties with the meteorological and glaciological record. We will compare portions of the CMDL and other aerosol records, meteorological records, and glacial records to examine relations among chronologies coexisting in the troposphere and in accumulated snow.

An examination of the initial year of aerosol data by Hogan and Nelson (1975) and Hogan and Barnard (1978) showed a distinct seasonal variation in aerosol concentration that was further modulated by "frontal" disturbances. Analysis of the initial five years of synoptic aerosol and meteorological data (Hogan et al., 1982) showed that surface aerosol concentration, air temperature, and water vapor concentration were co-related functions of the surface wind direction; ten years of surface observations provided sufficient data (Riley, 1987) to relate both aerosol concentration and aerosol electrical charge to surface air temperature and barometric pressure. The annual mean aerosol concentration was almost invariant during the decade of the 1970s, but diminished with respect to increasing time during the 1980s. Independent analysis by Bodhaine and Shanahan (1990) and Samson et al. (1990) have verified this diminution, which has been attributed to a fluctuation in late winter/early summer circulation by Hogan et al. (1992).

An integrated mean concentration of sodium aerosol has been calculated from the concentration and size observed, using the method described by Hogan et al. (1984). Some of the specific assumptions and approximations used will be given in Section VI. Aerosol sodium has been computed from the observation record and compared with sodium concentrations measured in recent snow and firn from a shallow pit corresponding in age to the aerosol record by Legrand and Kirchener (1988). A comparison of the sodium concentration in south polar snow, with the previous summer's mean surface aerosol concentration, from Hogan et al. (1990), is given in Fig. 1. This figure indicates a relation among meteorologic and glaciologic processes during this period. We will review these processes to examine its significance.

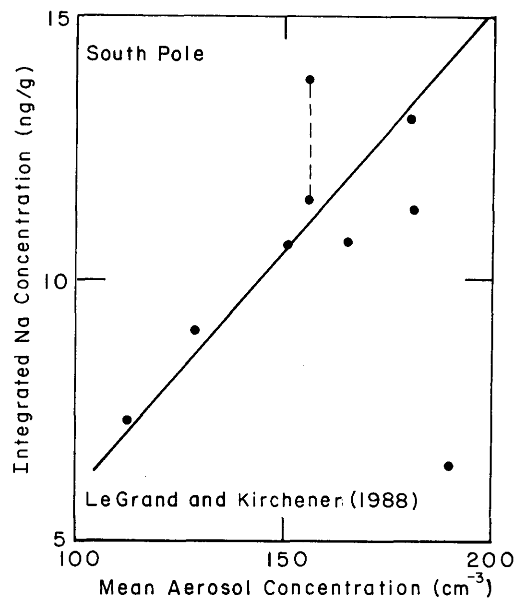

Fig. 1. Comparison of observed aerosol concentration and glaciochemical analysis of sodium in corresponding snow accumulation at South Pole Station, from Hogan et al. (1991). The two points connected by a broken line indicate a difficult point to interpret in the original publication.

2. A review of atmospheric exchange and particle precipitation processes on the polar plateau

Lettau (1971) proposed the hypothesis that the antarctic atmosphere was the least complex on earth and as such could provide a "test tube" for examination of meteorological theories. Recent work (Hogan et al., 1990) has established the uniqueness of cA air mass and its aerosol mass in this respect, showing in-phase and out-of-phase relationships of atmospheric constituents above the Polar Plateau. We present these hypotheses to establish some fundamental considerations relative to atmosphere/firn exchange in the interior of Antarctica, with the caveat that they may only be applicable to this unique air mass.

(A) The Antarctic Plateau is a nearly sourceless plain which contributes little or no heat, water vapor, or chemical constituents to the cA air mass which resides over it. Surrounding mP air masses are the sources of heat, water vapor, and particulate matter to cA air, and these components are conservatively exchanged into the air mass. This is well established, meteorologically, through the work of Dalrymple (1967), Lettau et al. (1977), and for particulate material by Hogan and Barnard (1978), Hogan et al. (1982), Hogan (1986), Bodhaine et al. (1986) and Polian et al. (1986).

(B) The cA air mass contributes cold dry air to surrounding air masses through katabatic flow, in the form of large streams, as shown by Mather and Miller (1966) and Parish and Bromwich (1987), or as well defined down-glacier air streams often seen in satellite photos. Some return flow is needed to balance this outflow, according to Schwerdtfeger (1984), but this return flow probably occurs in the lower troposphere, and is slowly exchanged into the boundary layer.

(C) As the cA air mass ages it simultaneously cools through radiation, generating a strong surface inversion, and loses mass through katabatic outflow. This produces the unusual but typical antarctic condition where diminishing barometric pressure accompanies fine weather. The air radiatively cools above the plateau, becoming saturated with respect to ice, and ice crystals are observed in apparently "clear sky" conditions. The precipitating ice crystals contribute clay mineral particles, apparently from the upper troposphere, and salt particles which were their nuclei, to the surface snow according to Kumai (1976). The strong near surface inversion and relatively weak winds beneath inhibit "dry" or eddy deposition of particulate matter to the snow surface. The small size of the particles, as determined by Hogan et al. (1984), combined with the minimal concentration coincident with these meteorological conditions, limits the mass rate of sedimentation of particles to the surface to very small values. This is the prevailing condition on the Polar Plateau, accounting for 222 of the year's days in Dalrymple's (1967) climatology.

(D) Most inputs of external, more particle-laden air into the cA air mass occur as discrete events where cyclonic storms, remnants of storms, or warm highs (Schwerdtfeger, 1984) result in widespread warming as shown by Alvarez and Lieskes (1960) and Sinclair (1981). Aerosol measurements made during these warmings have caused them to be labeled as "salt storms" by Parungo et al. (1979) and Bodhaine et al. (1986). The dissipation of the antarctic vortex, each November, is accompanied by prolonged "warming events" with very similar aerosol characteristics. These two types of warmings occur on perhaps 20 to 60 days each year and must account not only for the water precipitated to the plateau (Lettau, 1969; Bromwich, 1979; Bromwich, 1988), but the marine particulate matter as well.

(E) The total number of times each season that the surface temperature observed at the South Pole Station increases in association with near-surface winds from the western hemisphere side of the continent can be used as an exchange index to estimate the amount of non-cA air advected to the Polar Plateau.

(F) Precipitation is not measured by the South Pole meteorologists, but snow-fall or obscuration of visible references by snow are occasionally noted. Accumulation of water substance is measured stratigraphically, in conjunction with snow density, in snow pits or in extracted ice cores. The relative height of the snow surface at a given date with reference to witness marks on a number of stakes, arranged in a geometric pattern, has been used by Giovinetto (1961) and Gow (1965) to measure accumulation and/or surface ablation. Stake measurements indicate that snow deposited during the previous winter is redistributed during the ensuing summer and a distinctive depth hoar layer is formed by sublimation during the fall or early winter. Details of this depth hoar forming process are given in Gow (1965). Stratigraphic analysis of snow or firn in pits or cores determines the accumulation during a glaciologic "year," which is the accumulation period between two depth hoar layers. The glaciological year at South Pole appears to most frequently coincide with the calendar period March through March. The temperature rarely exceeds $-15°C$ on the Antarctic Plateau, preventing any melting. The crust formed atop the depth hoar layer each fall and winter is considered an impermeable barrier, limiting exchange of precipitated material among annual layers.

(G) During winter months air temperatures of less than $-80°C$ and aerosol concentrations of less than 3 cm^{-3} are observed on the Polar Plateau. These are the minimum values measured in the lower troposphere, and indicate that nearly all of the heat, water vapor, and particles transported to the interior of Antarctica must be precipitated there to produce these minimal values. Water vapor and aerosol concentration in air have been shown to be related to air temperature supporting this. The precipitated amounts of these substances should then have some relationship to the temperature history of the plateau during the period they were precipitated.

The abbreviation (a) is defined as the favored designation for year in this and other journals. The "year" designated is the astronomical year (a) of 365-1/4 days. It is obvious that the meteorological, aerosol and snow accumulation years on the south polar plateau do not necessarily coincide with astronomical years. A major portion of the problem of extracting aerosol history from the glacial record involves establishment of analytical techniques which permit comparison of these "years" chronologies. The remainder of the paper will present cumulative data in terms of specified years, rather than (a) astronomical years.

3. The temperature and precipitation regime of the polar plateau, with relation to the meteorological and accumulation years

Bromwich (1979) examined the water vapor decrement that occurred as tropospheric air passed over Antarctica, using soundings made at the several meteorological stations located around the periphery of the continent. His analysis accounted for the mass of precipitation in the interior. Generalized maps, as given in Fig. 2 showing accumulation of water substance in Antarctica, have been prepared from pit, core, and stake accumulation data by Giovinetto (1964), Giovinetto and Bentley (1985) and Bromwich (1988).

Examination of the original stratigraphic accu-

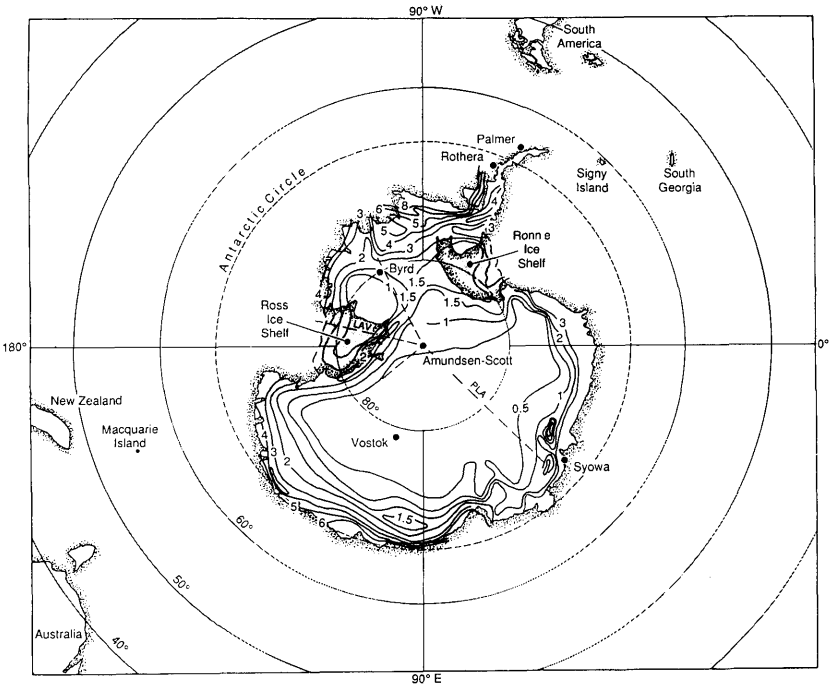

Fig. 2. Map of Antarctica adapted from Bromwich (1988) showing location of stations mentioned in the text, and the accumulation of water substance (in units of 100 kg/m^2 accumulation year) in the interior of Antarctica.

mulation records obtained on traverses of the Antarctic by Fujiwara and Endoh (1971), Taylor (1971), and Picciotto et al. (1971). Heap and Rundle (1964) and Giovinetto (1963) shows that a variation of more than a factor of two over relatively short distances occurs in snow accumulation south of 87°S latitude. Pit and core analysis of recent firn near South Pole Station, by Legrand and Kirchener (1988), Mosely-Thompson et al. (1985) and Jouzel et al. (1981), show eight-fold variation in yearly accumulation since 1954. The stake field of Giovinetto showed 25-fold variations in accumulation, in addition to hiatus periods when negative, or zero, change occurred at many of the stakes (Epstein et al., 1965). Fig. 3 is a photograph of the wall of a pit excavated by Gow (1965) next to one of Giovinetto's stakes showing the virtual hiatus or lack of accumulation during the of 1959–60 period.

The accumulation observed at a point does not uniquely reflect the precipitation that has occurred there. It is quite important to examine the variation in temperature and accumulation about the interior of Antarctica to understand the accumulation regime, and identify possible source regions for the precipitation that has eventually accumulated in the vicinity of South Pole Station.

Fig. 4 presents mean temperature observed at many places in Antarctica, plotted against the elevation of the station at which the temperature was measured. The elevation of the antarctic surface is shown for reference in Fig. 5 from Bromwich (1988) and Drewry (1983). Mean annual air temperatures, obtained at established stations and tabulated by Schwerdtfeger (1984) are denoted in Fig. 4 by large crosses, and the three letter identification of Schwerdtfeger. The other points are 10-m firn temperatures from along a traverse from Syowa via Plateau Station to South Pole by JARE 1968-69 (Fujiwara and Endoh, 1971), and along two traverses from Pole toward the transantarctic mountains by Taylor (1971). The lower plotted line is a dry adiabat, which intersects the elevation and long-term mean surface air temperature at SPO, the South Pole Station. The points designated by triangles are 10-m firn temperatures observed along 40°E longitude between Syowa and (PLA) Plateau station. Note that these temperatures lie near the same adiabat as (MIZ) Mizuho, and (PIO) Pionerskaya Stations. Upon crossing the Fuji

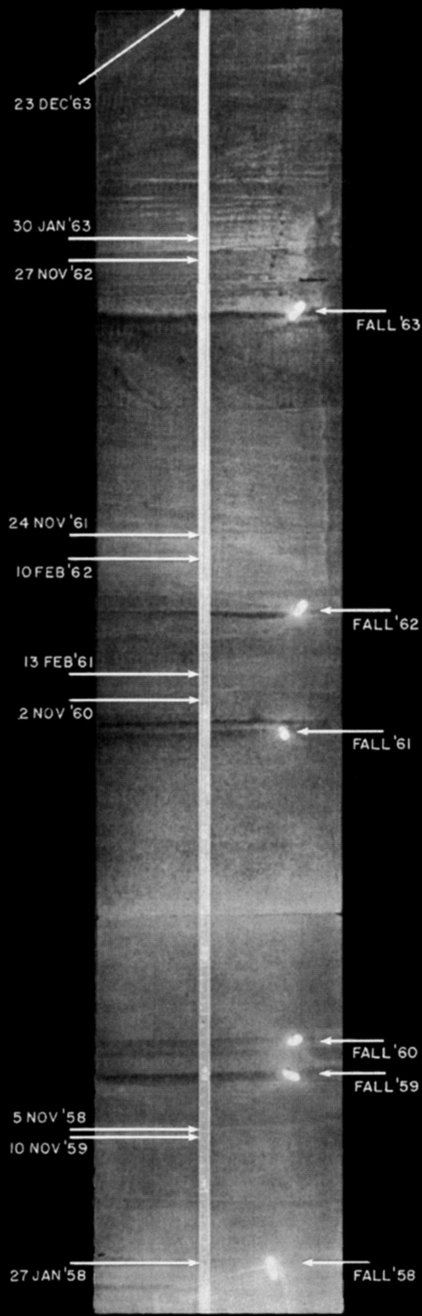

Fig. 3. Photograph of stratigraphy in the wall of a pit dug next to a stake in the Giovinetto array at the South Pole. The distinctive layers of depth hoar (marked with pegs) are formed each autumn, and the thickness of snow between two such layers represent an accumulation year. Note the hiatus or absence of accumulation, corresponding to 1959–60 (from Gow, 1965).

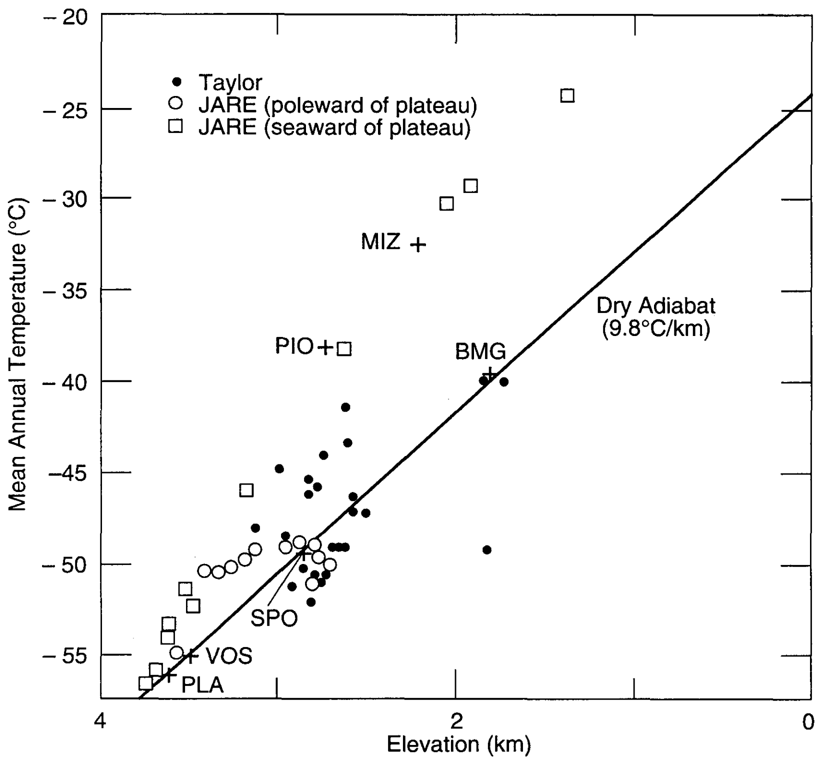

Fig. 4. Mean temperature at several Antarctic stations. The mean temperature is the instrumental mean air temperature, from Schwerdtfeger (1984) for named stations. The mean temperature, inferred from −10-m firn temperature is designated by a symbol at the measurement point. The plotted line is a dry adiabat (−9.8°C/km) intersecting the South Pole Station data.

divide, the temperatures depart from the warmer adiabat and join the South Pole adiabat in the vicinity of Plateau Station. Firn temperatures measured between PLA and SPO by JARE are noted by circles, and firn temperatures obtained by Taylor (1971) are shown as small solid circles.

We attribute the temperature conformity of the three observing stations on the polar plateau along a single adiabat to the rather uniform ventilation of a homogeneous, high albedo surface with air of minimal latent heat due to its very small absolute humidity. The warmer air at the peripheral stations is attributed to more frequent advection of mP air to those stations.

The snow accumulations observed along the JARE transect and near the same 40° E longitude route by the Marie Byrd-Queen Maud Land traverse 1964–68 (Picciotto et al., 1971) are shown in Fig. 6 as a function of latitude rather than elevation. Western hemisphere accumulation, along 120° W in the vicinity of Byrd Station and along 165° W across the Ross Ice Shelf, from Clausen and Dansgaard (1977) is also given. The mean accumulation amounts established for Little America V, Byrd, South Pole, and Plateau Stations are plotted as short lines corresponding to the station latitude. The variability in accumulation found in the vicinity of the South Pole seems to reflect the variability in temperature found along these same transects in Fig. 4. Precipitation on the Ross Ice Shelf is generally less than at the same latitude in Marie Byrd Land, as pointed out by Clausen and Dansgaard (1977), but the single ice shelf station near the base of the transantarctic mountains exceeds all other non-coastal accumulations. The accumulations between 85 and

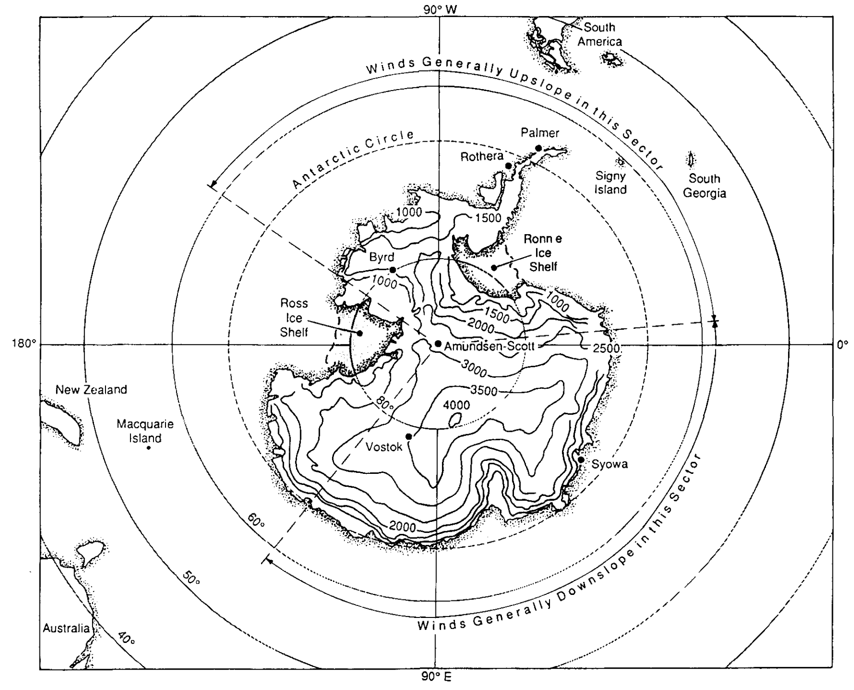

Fig. 5. Elevation of the Antarctic surface adapted from Drewry (1983). Transects, which are sources of temperature, accumulation and sodium concentration data in the text, are overlain. The approximate sectors from which winds arrive at South Pole from upslope and downslope directions are circumscribed.

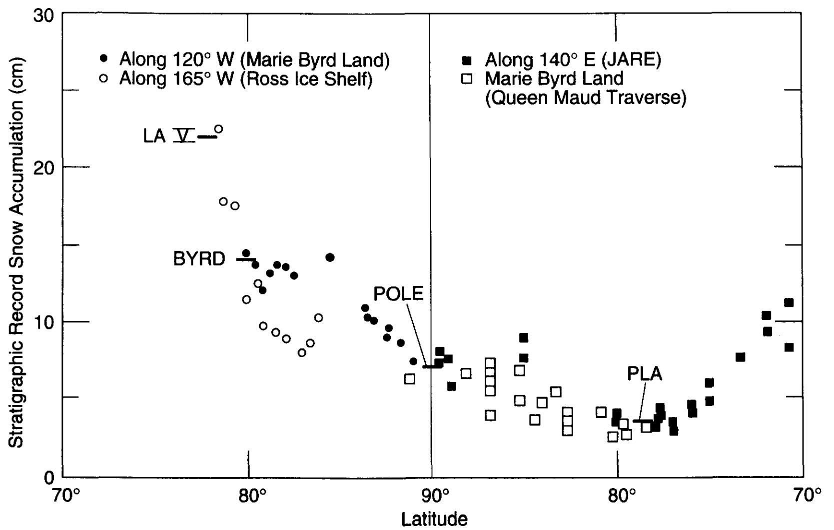

Fig. 6. Snow accumulation, measured along several transects, plotted as a function of latitude, projected to the transect lines 120° W longitude and 40° E longitude.

88° S latitude along 120° W also exceed those at lower latitude on the shelf and all others on the planteau.

The 10-m firn temperatures observed by Taylor (1971) and by Fujiwara and Endoh (1971) are plotted in coordination with the snow accumulations at the traverse points in Fig. 7. The relation between 10-m temperature and accumulation appears to be quite clear from Fig. 7 and independent of elevation or latitude. The accumulation along 120° W in the vicinity of Byrd station exceeds that along the Ross Ice Shelf at equal latitude because the marine moisture is forced to move upslope along 120° W, toward Byrd Station, but is actually subsiding slightly along the typical storm track across Marie Byrd Land to the ice shelf in the vicinity of 165° W. This is very apparent in satellite images that show intense low centers over Marie Byrd Land that dissipate in the "Cyclonic Graveyard" (Schwerdtfeger, 1984) and then reform as they approach the transantarctic mountains. The increase in accumulation on the shelf south of 83° S is apparently due to orographic regeneration of some of these centers, probably due to the barrier jet induced by the transantarctic mountains. The accumulation maxima at 85° to 88° S may be due to mountain enhancement as well.

Aerosol observations made at South Pole are coordinated with radiosonde releases to allow meteorological analysis of aerosol variation. At the South Pole the warmest, wettest, most particle-laden air arrives as surface wind turns through the sector from 45° W longitude through the Date Line, and snow grains or blowing snow are often noted concurrently by the surface observers. Murphey et al. (1991) examined a cyclonic system that brought a record maximum September temperature, as well as enhanced marine aerosol at South Pole Station during the period 10–15 September 1983, after bringing marine aerosol of 12 μm diameter to Ross Island. A similar system, which entered Antarctica during late September 1987, was traced along the surface to South Pole Station using Automatic Weather Station (AWS) data by Hogan et al. (1992), and again brought greatly enhanced aerosol concentration to the polar plateau along with warming and precipitation. Winds from the western hemisphere flow upslope to the South Pole and, as they turn through increasing west longitude, appear to become more coupled to the warmer tropospheric flow above. During the September 1983 event uncharacteristically warm air flooded the plateau from the ice shelf direction, in conjunction with winds along the date line at all tropospheric and lower stratospheric levels. These analyses indicate warmings on the plateau, are associated with cyclonic systems over the Ross Sea and Shelf, and often are accompanied by both observed precipitation and increased aerosol concentration.

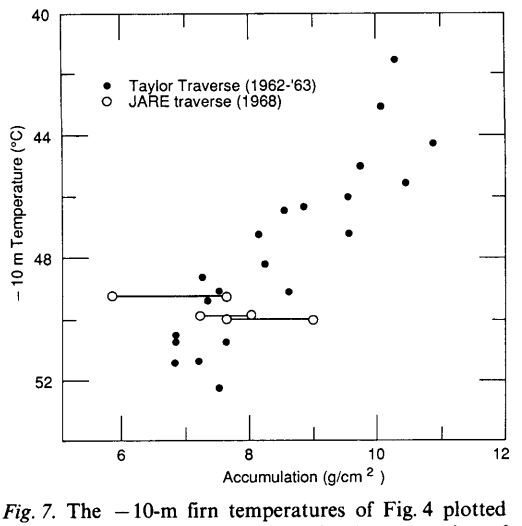

Fig. 7. The −10-m firn temperatures of Fig. 4 plotted versus the snow accumulation data for the same points of Fig. 6.

We interpret the correlation between accumulation and 10-m temperature in Fig. 7 to be due to recurrences of the co-related warming, precipitation, enhanced aerosol concentration events observed at South Pole. The vigor of these events may be enhanced by slope and aspect at some points about the plateau. It is now necessary to examine the frequency and amount of polar precipitation to determine if these events can be integrated to express an accumulation year.

4. Estimation of polar precipitation from meteorological records

The concentration of particles measured near the surface at South Pole Station has been shown to vary concurrently with surface wind and air temperature, both on the single event time scale, by Parungo et al. (1979), Hogan et al. (1984) and

Table 1. *Meteorological observations at South Pole station, 10–15 September 1983*

Date	Temperature Min (°C)	Temperature Max (°C)	Wind mean speed (m/s)	Wind fastest Mile (m/s)	Wind prevailing dir. (°)	Fraction of time cloud cover occurred <0.3	0.5	>0.8
10	−65.3	−53.1	5.0	11.0/020	040	0.8	0.2	0.0
11	−65.9	−45.4	5.4	10.2/330	360	0.2	0.3	0.5
12	−45.6	−39.7	4.1	8.7/310	310			1.0
13	−41.7	−29.6	3.7	6.8/330	290			1.0
14	−46.4	−29.8	7.0	16.3/120	160			1.0
15	−52.0	−45.8	10.7	17.0/050	070		0.5	0.5

Bodhaine et al. (1986), and on the seasonal time scale by Hogan et al. (1982). Fig. 7 indicates that snow accumulation on the Polar Plateau is related to local surface temperature on the climatic time scale. An analytical technique that relates yearly accumulation to daily weather would provide a powerful tool for comparing chemical (particle) accumulation in seasonal or annual firn layers to the daily instrumental record of aerosol concentration observed at the polar snow surface. We will review some meteorological data and attempt to formulate such a technique.

There are no surface measurements of precipitation included in the South Pole meteorological protocol, although unusual amounts of blowing or falling snow are sometimes noted. Most of the cloud physics research at South Pole Station has been performed in summer, although the temperatures observed in winter storms indicate that summer antarctic, winter arctic, and midlatitude mountain ice crystal observations may be applied to the analysis of winter antarctic snowfall. An example of surface conditions measured by the US National Weather Service (NWS) at South Pole Station during the storm of September 1983 and cited by Murphey et al. (1991) is tabulated in Table 1. Wind directions in Table 1 are reckoned relative to the Greenwich (0°) Meridian.

Snow, blowing snow, and visibility limited by snow and ice crystals in the air were noted by the NWS and GMCC observers during this time. Temperature, cloud cover and wind speed increased as the surface wind direction entered the western hemisphere, and the warmest air was present as the surface wind passed through the date-line direction. This injection of warm air remained on the plateau on 15 September, but had begun to cool by radiation and continued to pass over the pole from the eastern hemisphere sector, with a temperature several degrees higher than typical for that direction. Although the air was relatively warm and moist, it was flowing down-

Table 2. *Meteorological criteria for estimating precipitation rate on polar plateau*

Category	Wind	Temperature	Clouds
(1) (0.01 mm/h)	Fastest or prevailing from western hemisphere	Increasing last 24 h < −40°C	>0.5
(2) (0.03 mm/h)	Fastest or prevailing from western hemisphere	Increasing or steady last 24 h > −40°C	>0.5
	[multiple day events must exceed 0.8 mean cloud]		
(3) (0.1 mm/h)	Prevailing from western hemisphere	Increasing or steady last 24 h > −35°C	>0.5
	[Multiple day events must exceed 0.8 mean cloud]		

slope and this provided sufficient subsident motion to reduce the cloud cover to 0.5 as the day progressed. This was a record warm intrusion, but the relative changes in wind temperatures and cloud cover are typical of warming events.

We have formulated an analytical technique that uses the temperature, wind and cloud cover trends of observed storms, as typified above, in conjunction with precipitation rates estimated by Kikuchi and Hogan (1976), Sato et al. (1981), and Townsend (1985), and from previously unpublished observations of arctic and antarctic snow-fall rates of one (AWH) author. Townsend (1985) measured the precipitation rate of hexagonal plates typical of "clear sky precipitation" at South Pole and found it to be on the order of 0.001 mm/h. If this clear sky precipitation were continuous, it would produce less than one cm of water precipitation per year, and it is not considered in our analysis. We present an objective analysis technique, which uses daily numerical inputs from the monthly South Pole climatic summary, to determine days on which precipitation may occur. There is an additional temperature related influence on precipitation rate included in Table 2.

The number of days in each category is tabulated for each month and the number of days in category 1 multiplied by 0.024, category 2 by 0.072, and category 3 by 0.24 to obtain the monthly precipitation ($g\,cm^{-2}$). The rate in each category is primarily temperature dependent, and the wind direction and cloud cover criteria are essentially yes/no inputs. Category 1 probably contributes little of the year's precipitation but cannot be excluded, as observers sometimes note periods of precipitation on these days. The multipliers used represent continuous precipitation through 24 hours and should err toward overestimating the total day's precipitation.

The meteorological record for the period January 1957 through March 1984, which overlaps the accumulation periods of the several snow pits and core logs available, was analyzed in this manner. The mean annual precipitation calculated for the 27-year period is $5.76\,g\,cm^{-2}\,yr^{-1}$ (Standard Deviation 1.83). This is somewhat less than the "consensus" value of accumulation in the vicinity of South Pole of $7\,g\,cm^{-2}\,yr^{-1}$, but sufficiently close to apply to some additional analysis.

Examination of stake field records of Giovinetto (1960), Gow (1965), and Epstein et al. (1965), as well as the station temperature record and the 20-year harmonic temperature analysis of Schwerdtfeger (1977), indicate that depth hoar probably forms some time in March, to mark the new yearly snow layer, at South Pole. We define the typical precipitation year as April through March from this consideration.

The calculated monthly values of precipitation have been organized and retabulated on the basis of April through March precipitation years. March 1982 has been designated as the surface, and the empirical densification curve measured near South Pole by Jouzel et al. (1981) has been applied to

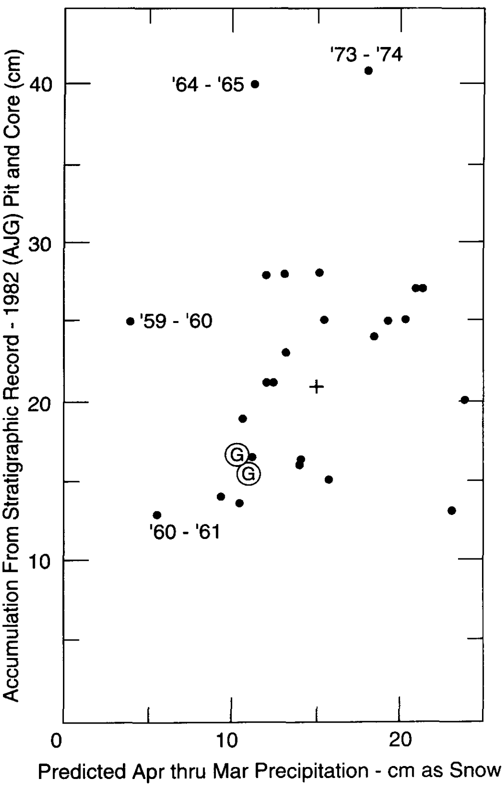

Fig. 8. Strata measured by pit and core analysis at South Pole Station (strata are from previously unpublished data of A.J.G.). The thickness of measured strata are compared with the precipitation amount calculated from the meteorological record, corrected for densification. The two points noted by G are accumulation records, from the Giovinetto Stake Field, and the plotted cross denotes the mean value of the two data sets.

the calculated precipitation masses to generate "strata" accumulated since April 1957. These "strata" are compared in Fig. 8 to the actual strata measured in 1982 in a pit and core near South Pole by one author (AJG) using depth hoar layers as annual accumulation markers. Note that a "Hiatus Year," as observed during calender year 1959–1960, would not alter amounts of precipitation measured but might bias the given date of subsequent strata.

Discussion of the contribution of riming and hoar frost formation (Hogan and Kikuchi, 1976), and drifting snow to the accumulation on the South Polar Plateau is certainly in order, and would be essential to a precise accumulation model. The variability of pit strata obtained at a single point, relative to the range of accumulation in a surrounding stake field (Epstein et al., 1965; Giovinetto, 1960), is comparable to variation between glaciological observation and meteorological prediction shown in Fig. 8. A more thorough test of the meteorological technique is certainly in order, but Fig. 8 indicates that an April–March precipitation year is reflected in the accumulation record more than one half of the time.

The accumulation obtained by Legrand and Kirchener (1988) in a shallow snow pit near the South Pole is compared to the same meteorologically derived "strata" in Fig. 9. The strata in Fig. 9 were obtained in the same pit as the sodium concentrations presented in Fig. 1. The aerosol concentration above the South Pole, and its marine component, were shown in several of the works cited earlier to be a function of temperature and wind direction observed concurrently with the

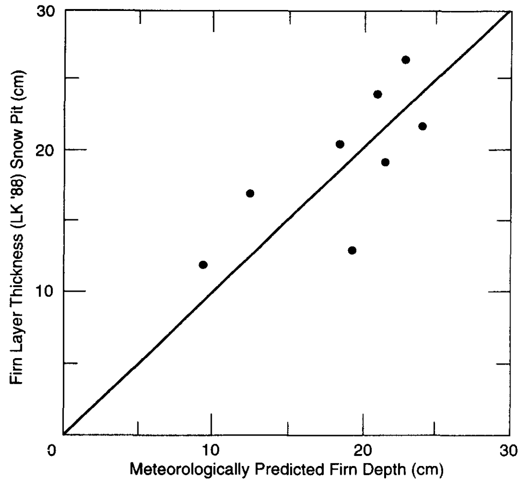

Fig. 9. Comparison of strata in pit from which Legrand and Kirchener's (1988) sodium concentrations were obtained, with meteorologically calculated precipitation for the period.

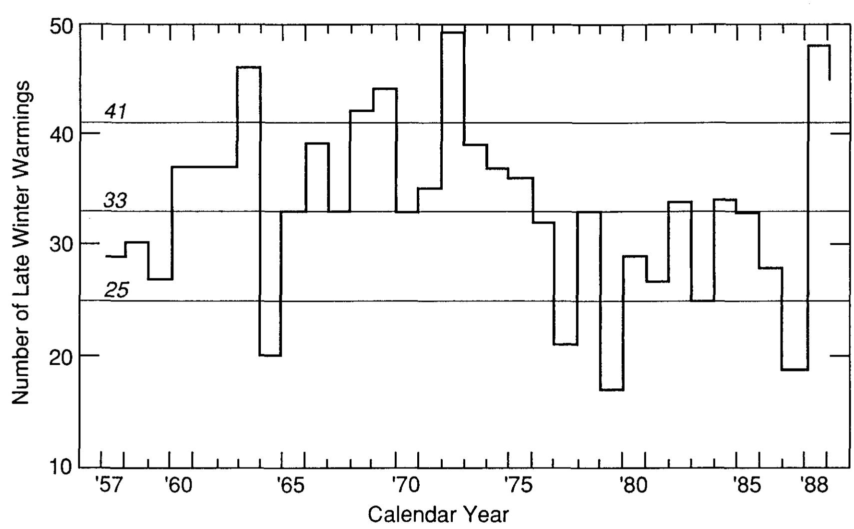

Fig. 10. Occurrence of later winter (August–September–October) warmings in the surface meteorological record of South Pole Station.

aerosol observation. Surface aerosol concentration and surface air temperature increase as the surface wind direction turns through the western hemisphere. The same temperature and wind direction parameters produce increases in precipitation in the calculation model described above. The similarity of sodium concentration measured in recent snow, to that calculated from observed aerosol concentration, snow accumulation and meteorological conditions, enhances the hypothesis that recent meteorological history can be reconstructed through snow strata analysis. This is a relatively strong argument that the correspondence of deposited sodium and observed aerosol concentration is not due to chance.

Fig. 10, reproduced from Hogan et al. (1991), shows the number of late winter warmings occurring at South Pole since surface temperature observations began in 1957. There is a systematic change in the number of events when the years prior to 1975 are compared to the later years. The precipitation calculation model described here is most responsive to the number of days with temperature greater than −40°C in the analysis period. This may be indicative that the chemical tracers within the snow and firn also respond to the number of warming events, which is in agreement with the exchange index postulated in Section 2. The gross chemical properties of recent snow accumulated on the Antarctic Plateau appear to reflect properties of the aerosol advected over the plateau during the time of snow accumulation, perhaps due to the common dependence of these variables on warming events generated by cyclonic systems about Antarctica. It is necessary to examine exchange and precipitation mechanisms of sodium to determine if the relative amount of substance precipitated is of significant magnitude to be considered representative of transport.

5. Analysis of sodium transport and precipitation

A cross-sectional analysis of sodium concentration in recent snow and firn, from measurements made along 160° W by Warburton and Linkletter (1978), and along 40E by Murozumi et al. (1971), are shown in Fig. 11. With the exception of some stations near the edge of the Ross Ice Shelf, mean sodium concentrations in recent snow and firn poleward of 80° S latitude are within the range of 1 to 4×10^{-8} g(Na)/g(H_2O). Legrand and Kirchener (1988) examined thin layers of each individual strata within the upper 5 m of snow near South Pole and measured concentrations

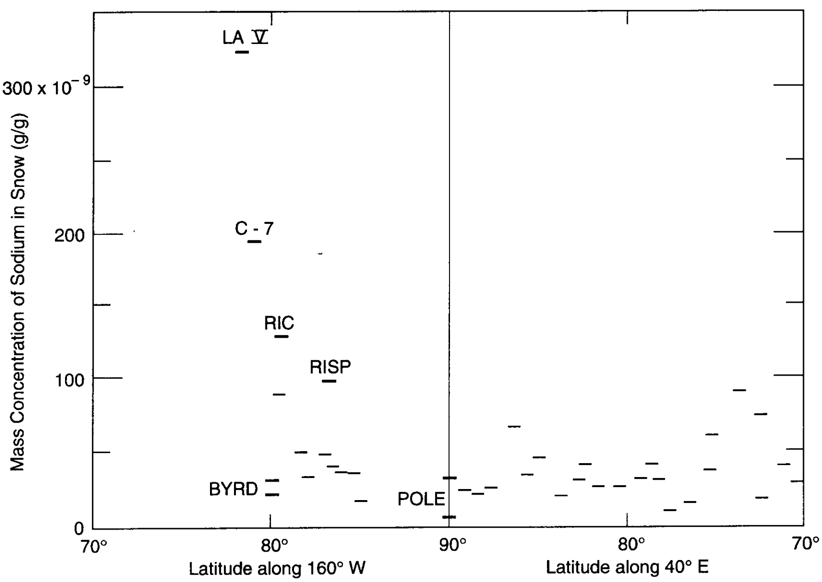

Fig. 11. Sodium concentration in snow, measured along the same transects shown in Fig. 2.

which varied from 2×10^{-9} to 3×10^{-8} g/g, with 1 to 2×10^{-8} g/g being the most frequently reported values. The concentrations from Legrand and Kirchener (1988) plotted in Fig. 1 are integrated "yearly" means calculated from the several values between depth hoar layers representative of the 1976–1984 era and are distributed about 1×10^{-8} g/g.

The precipitation rate of sodium P(Na) can be inferred from the concentration in surface snow, C, and the water accumulation rate, $P(H_2O)$, using the relationship,

$$P(\text{Na}) = C^* \text{P}(\text{H}_2\text{O}). \quad (1)$$

This indicates that 3 to 15×10^{-4} g(Na)(m^{-2} yr^{-1} were precipitated on the Polar Plateau during the period over which Legrand and Kirchener's snow strata coincided with observed aerosol concentration. This precipitation rate must be compared with the rate of sodium aerosol transport over the Polar Plateau.

The seasonal variation of aerosol concentration in the boundary layer over the Polar Plateau is well established by Zoller et al. (1974), Tuncel et al. (1989), Samson et al. (1990) and Bodhaine and Shanahan (1990). Hogan et al. (1984) determined that 0.1 of that aerosol mass was sodium on clear days, and that the sodium fraction increased to 0.2 during cloudy days. A calculation in this same paper showed that polar aerosol mass, the aerosol scattering coefficient measured by Bodhaine's nephelometer, and the number of charged particles measured by the Rich (1966) technique were related. Riley (1987) prepared a climatology of the fraction of charged particles, including the era in which the strata in Legrand and Kirchener's sodium analysis were deposited, which facilitates calculation of the aerosol sodium flux over South Pole. The flux parameters are tabulated in Table 3, which includes aerosol and sodium concentration measured during summer 1974–75 by Maenhaut et al. (1979) for comparison to the Hogan et al. (1984) estimate. The mean wind speed quoted reflects the whole boundary layer.

The extreme right column is the total mass of sodium aerosol passing through a hypothetical window, one meter wide, extending from the surface to the inversion capping the boundary layer. Extending the one meter wide window along 120° W to Byrd Station would make a rectangular channel with a floor area of 2.2×10^6 m^2. Precipitation of all of the sodium transported through this channel (from the right column of Table 3) would yield yearly precipitation of

$$P = [500 \text{ g/m year}]/[2.22 \times 10^6 \text{ m}]$$
$$= 2.25 \times 10^{-4} \text{ g m}^{-2} \text{ yr}^{-1} \quad (2)$$

on the "floor" of this channel. This is approximately the mean sodium precipitation rate at the south pole, but it is exceeded in many individual firn layers.

Lambert et al. (1983) measured 210 Pb in air

Table 3. *Annual aerosol and sodium flux through a meter-wide window in the boundary layer*

Season length	Concentration: charged particles (cm^{-3})	Concentration: aerosol mass (g/m^3)	Concentration: sodium mass (g/m^3)	Boundary layer height (m)	Sodium column (g/m^2)	Mean wind (m/s)	Mean flux window (g/m yr)
winter (123 d)	<5	$<10^{-8}$	$<1 \times 10^{-9}$	600	6×10^{-9}	10	111
summer (123 d)	25–35	$4\text{–}5 \times 10^{-8}$	$3\text{–}5 \times 10^{-9}$	350	$1\text{–}2 \times 10^{-9}$	7	96
warmings (20 d)	25–75	$4\text{–}12 \times 10^{-8}$	$8\text{–}24 \times 10^{-9}$	500	$4\text{–}8 \times 10^{-9}$	15	96/288
summer 74/75 from Maenhaut et al. (1979)		$785\text{–}10 \times 10^{-8}$	$1.7\text{–}4.4 \times 10^{-9}$				

and snow at South Pole Station. They estimated that six-tenths of 210 Pb was dry deposited at the surface through attachment to submicron particles. Sodium is a fairly major component of the submicron aerosol, and might be considered a surrogate of the 210 Pb dry flux. The sodium concentrations beneath the inversion, and numbers of days constituting the meteorological season, from Table 3, have been combined with Lambert et al. (1983) deposition velocities to estimate the dry deposition of sodium in Table 4.

The tabulations and calculations above require that *all* of the sodium transported through the boundary layer over the interior of Antarctica must be precipitated there to balance yearly accumulation. The maximum dry deposition velocity of 3.7×10^{-3} m/s would result in all material being deposited from the boundary layer on warm and summer days, and dry deposition is probably somewhat overestimated in the calculation. Table 4 shows that the increase in concentration that occurs during warming events would cause a doubling of precipitated sodium in those years when a larger number of warming events occur, but cannot provide sufficient sodium to produce the maximum concentrations found in winter strata by Legrand and Kirchener (1988). It is clear that these estimates of sodium flux based on surface mass measurements do not account for the sodium flux needed to explain the maximum concentration of sodium in recent snow.

Murphey et al. (1991) measured sodium concentration in a cyclonic storm at Ross Island in September 1983. They found marine aerosol particles of 12-μm maximum dimension flowing from the shelfward direction, in air that had mixed to sufficient depth to acquire an ozone concentration exceeding 100 ppb. Their meteorological cross-section analysis shows that warm air flowed in an organized stream through the layers below 250 mb along the date line, flooding the interior of Antarctica with warm air in the manner described by Alvarez and Lieskes (1960) and Sinclair (1981), and producing the warmest (-29.3°C) September surface air ever observed at South Pole Station. The aerosol record of Bodhaine and Shanahan (1990) shows a maximum concentration of both aerosol number and scattering component coincident with this warm air. Station records show visibility reduced by snow grains.

Although the aerosol concentration measured at the surface exceeded the September mean value by a factor of two, it would only be the equivalent of the minimum concentration measured in warming events as shown in Table 3, and would not have been a major precipitator of sodium. Surface measurements may not reflect the full magnitude of major transport events during warming. The surface inversion weakens and allows some exchange of warmer aerosol-laden air to the surface during these events but does not appear to allow coupling of the surface with lower tropospheric flow. Precipitation falls freely through the inversion, depositing water substance and former aerosol from unmeasured layers above and may provide precipitation with a greater sodium mixing ratio than would be anticipated from surface concentration measurements.

Table 4. *Dry deposition of sodium aerosol to the polar plateau*

Season	Mean sodium concentration 10^{-9} (g/m^3)	Deposition speed from Lambert et al. (1983) (m/s)	Precipitation rate g(Na) (m^{-2} yr^{-1})
winter (222 d)	<1	1.7×10^{-3}	3×10^{-5}
	<1	3.7×10^{-3}	7×10^{-5}
summer (123 d)	4	1.7×10^{-3}	7×10^{-5}
	4	3.7×10^{-3}	1.5×10^{-4}
warm events (20 d)	8–24	1.7×10^{-3}	$2–7 \times 10^{-5}$
	8–24	3.7×10^{-3}	$5 \times 10^{-5}–1.5 \times 10^{-4}$
yearly accumulation range, 345 clear days			$1–2.2 \times 10^{-4}$
yearly accumulation range, 20 event days			$0.2–1.5 \times 10^{-4}$

The "clear-sky" ice crystal precipitation, which has been well studied with respect to optical effects, produces little precipitation mass. Application of a coagulation theory based on the two-component coagulation theory of Fuchs (1964) shows clear-sky precipitation to contain only one part in 10^{11} of collected particle mass.

One author (AWH) has observed falls of 3 to 30 mm (as snow) during 24-hr periods at South Pole Station, which consisted of dendritic, columnar, side plane, and aggregated dendritic crystals. Air temperatures of $-15°$ to $-30°C$ were present above the station during these falls. Kikuchi and Uyeda (1979) replicated snow falling in a similar temperature regime ($-30°$ to $-40°$ at the surface, overlain by ice and water saturated layers of $-18°$ to $-35°C$ in the lower km) at Inuvik, NWT, Canada. Several photomicrographs of snowflakes replicated in these conditions are shown by Kikuchi and Uyeda (1979), and have significant rime deposits on them. Borys et al. (1983) have also found rimed crystals in relatively cold environments and attributed enhanced particle scavenging to the presence of rime.

A snow mensuration program has been assembled to facilitate calculation of physical properties of precipitating snow. The program utilizes snowflake mass/diameter/fallspeed relationships of Locatelli and Hobbs (1974), Heymsfield and Kajikawa (1987), Mitchell et al. (1990), Harimaya and Sato (1989) and Zikmunda and Vali (1972) to calculate the suspended mass and area as a function of precipitation rate. The increase in mass resulting from riming a specified fraction of the snowflake's area is calculated using the size distribution of rime drops on snowflakes given by Grunow and Huefner (1959), Nakaya (1954), or the size distribution of Antarctic cloud drops given by Saxena and Ruggiero (1990). The relative fraction of the ice crystal surface covered by rime was determined by measuring the relative area of rime to ice crystal in photographs published by Nakaya (1954) and Harimaya and Sato (1989). Nakaya considered an ice crystal with about 0.01 of its surface covered to have few drops and one with about 0.035 covered to have numerous drops; he shows a hexagonal crystal with 0.504 coverage that thoroughly obscures the type of extensions. Nakaya's photographs of rimed columns and needles show them nearly totally covered by rime drops. Kikuchi and Uyeda (1979) show a spatial dendrite with 0.135 coverage and a plate with broad branches of 0.47 coverage replicated at Inuvik in temperature strata similar to that expected in warmings at the south pole.

The snow mensuration program will calculate the mixing ratio of former condensation nuclei in rimed snow flakes (assuming one condensation nucleus per rime drop) from the above, using a specified nucleus composition and size distribution. Some examples of former marine aerosol concentration in rimed antarctic snowflakes, based on aerosol size distributions measured by the Sinclair (1972) and Rich (1966) techniques at the south pole surface (Hogan et al., 1984), are given in Table 5. These are integrated over snowflakes having a diameter distribution with a geometric standard deviation of 1.4, and diameters reflecting those observed in regimes of similar cloud temperature.

A large number of observations were made at the South Pole surface during both summer and winter using size-sensitive, single-particle counting optical particle counters. Particles of greater than 3×10^{-5} cm diameter are relatively rare at the South Pole surface, the concentration usually remaining at less than one per liter. Simulation of the polar aerosol by Black (1986) showed the equivalent sizes measured by transmission through the Rich (1966) and Sinclair (1972) devices to be less than 2.4×10^{-5} cm diameter.

The storm of 13 September 1983 transported and exchanged very large marine nuclei over the Ross Ice Shelf, according to Murphey et al. (1991). The South Pole record shows a minor increase in aerosol concentration at the surface, and Murphey's analysis showed no significant increase in ozone concentration at the South polar surface. This indicates that, although sufficient heat was exchanged to the surface to increase temperature by 30°C, the surface layer remained decoupled from the major advection of mP air above the station.

Table 5 shows that nuclei of maximum size 2 to 3×10^{-5} cm diameter convey sufficient marine material to account for the minimum sodium concentrations found in recent snow by Legrand and Kirchener (1988). The maximum sodium concentrations found in some strata exceed the tabulated values. Additional riming might increase the deposition of sodium, but will have little influence on the mass concentration. It would appear from

Table 5. *Antecedent nuclei concentration in rimed snow using Saxena and Ruggiero (1991) antarctic drop dimensions*

Crystal classification	Median crystal diameter (cm)	Fraction crystal area rimed	Maximum nuclei diameter (cm)	Nuclei mixing ratio in rimed snow (g/g)	Approximate sodium mixing ratio in rimed snow
C1h, thick plates	0.04	0.01	3.2×10^{-5}	7.2×10^{-9}	10^{-10}
		0.1	6.4×10^{-5}	5.9×10^{-8}	
		0.1	3.2×10^{-5}	6.1×10^{-8}	
		0.1	6.4×10^{-5}	5.0×10^{-7}	
		1.0	3.2×10^{-5}	2.4×10^{-7}	
		1.0	6.4×10^{-5}	2.0×10^{-6}	3×10^{-7}
P2E plate with extensions	0.10	0.01	3.2×10^{-5}	2.9×10^{-8}	3×10^{-7}
		0.01	6.4×10^{-5}	2.3×10^{-7}	
		0.1	3.2×10^{-5}	1.7×10^{-7}	
		0.1	6.4×10^{-5}	1.4×10^{-6}	2×10^{-7}
P7b radiating assemblages of dendrites	0.16	0.01	3.2×10^{-5}	4.3×10^{-8}	6×10^{-9}
		0.01	6.4×10^{-5}	3.6×10^{-7}	
		0.1	3.2×10^{-5}	2.1×10^{-7}	
		0.1	6.4×10^{-5}	1.7×10^{-6}	2×10^{-7}

Table 5 that a few large nuclei, or a modification of the size distribution favoring larger nuclei, arriving in the precipitating layers, coincident with the surface salt storms of Parungo et al. (1979), and Bodhaine et al. (1986), might be the most productive speculation to account for the maximum concentration of sodium in recent polar snow.

6. Discussion

The comparisons and analysis presented indicate that precipitation of sodium and water substance to the polar plateau are as strongly related to temperature and wind direction as to the surface concentration in air of these substances. This appears to be due to the importation through warm advection of mP air, by cyclonic storms, as the dominant source and transport mechanism for a major fraction of the heat, water vapor, and marine aerosol available for precipitation onto the polar plateau each year. Small amounts of warmer tropospheric air entrained in the antarctic circulation system to balance katabatic outflow may produce sufficient cloud cover to reduce outgoing radiation and allow winter surface temperature to increase to the −50 to −60°C range. Only strong, rapid advection of mP air, with sea level temperatures near 0°C at the ice edge, associated with cyclonic systems, can cause the winter surface temperature to increase to the −30° to −40°C range at the 2835-m elevation of the South Pole.

The yearly (especially the winter) frequency of these warming events is an index of both the source strength and exchange vigor of precipitable substances to the polar plateau. The comparisons presented show that the accumulation of water (as snow) and sodium on the plateau are related to the number of warming events in the winter preceding the formation of the depth hoar layer. This correspondence seems best when an April-to-March accumulation year is used for comparison of the magnitudes of substances fixed between successive depth hoar layers.

Bromwich (1979, 1988) has shown that the major features of precipitation gradient around Antarctica are predictable through mass transport analysis of water vapor. Our analysis has attempted to predict the precipitation of both water and sodium in a small defined area near the South Pole and has fallen somewhat short of a balanced budget in both instances. We attribute this to uncertainty to the areal extent of the inversion which decouples the South Pole from even warmer and more particle-laden air just above the surface during these periods of strong warm advection. Oltmanns and Kohmyr (1975) concluded that the very small variation in ozone concentration at the polar surface was similarly related to weak exchange of near-surface air.

The comparison of 10-m ("MEAN") temperatures and accumulation rates (Fig. 7) in the interior of Antarctica show that some apparently anomalous temperatures along 120° W longitude within 300 km of the South Pole, are related to the accumulation rate of water substance at those locations. We physically connect this enhancement of accumulation with enhanced exchange near the surface, enabled by the relatively greater slope of the ice field (Fig. 4), as shown in this area on the map in Fig. 3, which also enables exchange of warmer air to the surface.

Throughout this presentation we have referred to accumulation of snow on the surface, and precipitation of water substance through meteorological processes. The area along 120° W, within 300 km of South Pole, accumulates about one-third more snow and is a few degrees warmer than the mean temperature recorded at the South Pole. The relationships presented indicate that this snow should also contain more sodium, which is verified by Fig. 11. The precipitation analysis used considers every precipitation day to precipitate continuously at the prescribed rate throughout the day, but systematically underpredicts snow accumulation. The warmest winter days with most remarkable snow accumulation, as in the case of 13 September 1983, have occurred with winds from the sector including 120° W. It is quite possible that warmer, more marine aerosol-laden air precipitates more heavily rimed snowflakes along 120° W, and that this snow is accumulated as wind diminishes concurrent with diminishing terrain aspect relative to this wind, in the vicinity of the South Pole. This mechanism would quite conveniently account for both underprediction of accumulation and insufficient sodium available for precipitation relative to the South Pole glaciochemical record.

This presentation and discussion has demonstrated that a magnificent resource is available in the South Pole meteorological record, the CMDL atmospheric chemical record, and the published and unpublished glaciological records of individual investigators collected at the South Pole since 1957. This analysis indicates that specific events provide the substance to be recorded in glaciochemical storage, and that it is possible to relate the glacial record to observed meteorological events. It would seem very desirable to thoroughly explore the snow strata representative of the period of the station meteorological record in the vicinity of the South Pole to calibrate this record more quantitatively.

7. Conclusions

Comparison of accumulation of water substance, and the residue of sodium aerosol, in recent snow layers at the South Pole shows that these glaciological properties reflect the meteorological history of the frequency of warming events in the period prior to their immobilization as a winter layer. The best correspondence among the glaciological and meteorological records is found using an accumulation year of April through March. The meteorological record of warmings of the prior year is glaciologically recorded in the layers proximate to the depth hoar, which appears to form in March. A great advancement in calibration of the glaciological record would be provided by physically observing the precise period of depth hoar formation.

This analysis continues to verify the uniqueness of the Antarctic atmosphere, and most specifically the cA air mass for the testing of meteorological theories. Because of the limited exchange of the cA air mass with adjacent air masses, almost all precipitable substances are deposited during residence over the polar plateau. This is verified by the small temperatures and near-zero aerosol concentration measured in acclimatized cA air. It provides boundary conditions that allow mathematical simulation of precipitation processes that cannot be attempted in more complex atmospheres. The relatively simple temperature-based precipitation models developed indicate that the atmosphere above does not provide all of the water and sodium accumulated at the South Pole. A fraction must be transported there by drifting snow at the earth's surface.

The number of warming events experienced in a season is very easily derived from the South Pole station meteorological record and appears to be an effective exchange index for prediction of the magnitude of substances accumulated in recent polar snow. This hypothesis could be quite reliably tested by conducting sufficient pit and core analyses to establish a reliable mean value of recent accumulation of snow strata, and comparing this to the existing meteorological record.

It appears that riming of snowflakes in relatively unmodified mP air above the boundary layer is the mechanism most likely to account for the concentration of sodium in recently deposited polar snow. This hypothesis can be tested through replication and examination of freshly fallen snow, but only concurrent with the actual warming event.

We have presented an analysis of the transport and deposition of the most common and conservative marine components of the air, water and sodium, relative to an exchange index dependent only on surface observations. The analysis indicates that, on the Polar Plateau where this uniquely simple cA air mass resides, a record of the meteorological variability of these components is preserved in the ice sheet beneath. This appears to be a beginning of a quantitative method of recovering meteorological history, but cannot be extended to produce climatic history until simultaneous observations on several time and space scales are used to calibrate the observational and glaciological records.

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REFERENCES

Alvarez, J. A. and Lieskes, B. J. 1960. The Little America blizzard of May, 1957. In: *Antarctic meteorology*. Pergamon Press, New York, 1960, 115–127.

Black, J. J. 1986. Evaluation of the ASRC aerosol sampling and measurement at South Pole Station, Antarctica. MS Thesis, Atmospheric Sciences Department, State University of NY at Albany, Albany, NY, May 1986, 96 pages.

Bodhaine, B. A. and Shanahan, M. K. 1990. Condensation nucleus and aerosol scattering extinction measurements at the South Pole observatory: 1979–1988. NOAA Data Report ERL-CMDL-1, Climate monitoring and diagnostics Laboratory, Boulder, CO, 1990.

Bodhaine, B. A., Deluisi, J. J., Harris, J. M., Houmere, P. and Bauman, S. 1986. Aerosol measurements at the South Pole, *Tellus 38B*, 223–235.

Borys, R. D., Demott, P. J., Hindman, E. E. and Feng, D. 1983. The significance of snow crystal and mountain surface riming to the removal of atmospheric trace constituents from cold clouds. In: *Precipitation scavenging, dry deposition and resuspension* (H. R. Pruppacher, R. G. Semonin and W. G. N. Slinn, eds.). Elsevier, New York.

Bromwich, D. H. 1979. *Precipitation and accumulation estimates for east antarctica, derived from rawinsonde information*. Research report, Department of Meteorology Univ. of Wisconsin, Madison WI.

Bromwich, D. H. 1988. Snowfall in high southern latitudes. *Rev. Geophys.*, 149–168.

Clausen, H. B. and Dansgaard, W. 1977. Less surface accumulation on the Ross Ice Shelf than hitherto assumed. In: *Isotopes and impurities in snow and ice*, IAHS PUB 118, 172–175.

Dalrymple, P. 1967. A physical climatology of the Antarctic Plateau. In: *Studies in Antarctic Meteorology*, AGU, 195–231.

Drewry, D. J. 1983. The surface of the antarctic ice sheet. In: *Antarctica, glaciological and geophysical folio* (D. J. Drewry, ed.). Scott Polar Institute, Cambridge England.

Epstein, S., Sharp, R. P. and Gow, A. J. 1965. Six year record of oxygen and hydrogen isotope variations in south pole firn. *J. Geophys. Res. 70*, 1809–1814.

Flowers, E. 1960. The atmosphere from the surface to 50 mb over the south pole during 1957. In: *Antarctic meteorology*. Pergamon Press New York. 1960, 453–462.

Fuchs, N. A. 1964. *The mechanics of aerosols*. Macmillan, New York, 288–332.

Fujiwara, K. and Endoh, Y. 1971. Preliminary report of glaciological studies. In: *Report of the Japanese traverse Syowa, South Pole 1968–69* (M. Murayama, ed.). Polar Research Center Tokyo, March 1971, 68–109.

Giovinetto, M. B. 1960. *Glaciology report for 1958*. South Pole Station. Ohio State University Research Foundation Report 825-2-Part IV.

Giovinetto, M. B. 1961. Mass accumulation in west antarctica. *Trans. AGU 42*, 386–389.

Giovinetto, M. B. 1963. *Glaciological studies on the McMurdo, South Pole traverse, 1960–61*. Institute of

Polar Studies Report 7. Ohio State Univ., Res. Fdn., Columbus, Ohio.

Giovinetto, M. B. 1964. The drainage systems of antarctica: accumulation. In: *Antarctic snow and ice studies*. Ant. Res. Series Vol. 2 (M. Mellor, ed.). 127–155.

Giovinetto, M. B. and Bentley, C. R. 1985. Surface balance in ice drainage systems in Antarctica. *Antarctic J. US 20*, 6–13.

Gow, A. J. 1965. On the accumulation and seasonal stratification of snow at the south pole. *J. Glaciol. 5*, 467–477.

Grunow, J. and Huefner, D. 1959. *Observations and analysis of snow crystals for proving the suitability as aerological sonde*. ASTIA DOC 217431.

Hansen, K. J. 1960. A case study of the explosive stratospheric warming over the Antarctic, October 1958. In: *Antarctic meteorology*. Pergamon Press, New York, 1960, 128–137.

Harimaya, T. and Sato, M. 1989. *Measurement of the riming amount on snowflakes*. J. Fac. Sci., Hokkaido Univ., VII, 8, 355–366.

Heap, J. A. and Rundle, A. S. 1964. *Snow accumulation on the Ross ice shelf antarctica, antarctic snow and ice studies* (M. Mellor, ed.). Vol. 2, AGU Washington, 119–126.

Heymsfield, A. J. and Kajikawa, M. 1987. An improved approach to calculating terminal velocities of plate like crystals and graupel. *J. Atmos. Sci. 44*, 1088–1099.

Hogan, A. W. 1986. Aerosol exchange in the remote troposphere. *Tellus 38B*, 197–213.

Hogan, A. W. and Nelson, D. 1975. Aerosol observations over the ice cap. *Antarctic J. US 10*, 310–312.

Hogan, A. W. and Kikuchi, K. 1976. Aerosols and precipitation at the South Pole. *Antarctic J. US 11*, 190–191.

Hogan, A. W. and Barnard, S. C. 1978. Seasonal and frontal variation in Antarctic aerosol concentration. *J. Appl. Meteorol. 17*, 1458–1465.

Hogan, A. W., Barnard, S. C., Samson, J. A. and Winters, W. 1982. The transport of heat, water vapor and particulate matter to the south polar plateau. *J. Geophys. Res. 87*, 4287–4292.

Hogan, A. W., Samson, J., Kebschull, K., Townsend, R., Barnard, S., Murphey, B. and Hare, T. 1984. On the interaction of aerosol with meteorology. *J. Rech. Atmos. 18*, 41–67.

Hogan, A. W., Egan, W. G., Samson, J. A., Barnard, S. C., Riley, D. M. and Murphey, B. B. 1990. Seasonal variation of some constituents of antarctic tropospheric air. *Geophys. Res. Lett. 17*, 2365–2368.

Hogan, A., Riley, D., Murphey, B. B., Barnard, S. C. and Samson, J. A. 1991. A polar climatic iteration? Proceedings, *Conference on Polar Regions in Global Changes* (G. Weller, C. L. Wilson, Bab Severin, eds.). UAF, Fairbanks, pp. 681–686.

Jouzel, J., Merlivat, L., Petit, J. R. and Lorius, C. 1981. Climatic information over the last century deduced from a detailed isotopic record in the south polar snow. *J. Geophys. Res. 88*, 2693–2703.

Kikuchi, K. and Hogan, A. W. 1976. Snow crystal observations in summer season at Amundson Scott South Pole Station. J. Fac. Sci. Hokkaido Univ., VII, 5, 1–20.

Kikuchi, K. and Uyeda, H. 1979. Cloud droplets and rain drops collected and frozen on natural snow crystals. *J. Met. Soc. Japan 57*, 273–279.

Kumai, M. 1976. Identification of nuclei and concentration of chemical species in snow crystals sampled at south pole. *J. Atmos. Sci. 33*, 833–841.

Lambert, G., Ardovin, B. and Mesbah-Bendezu, A. 1983. Atmosphere to snow transfers in Antarctica. In: *Precipitation scavenging, dry deposition and resuspension* (H. R. Pruppacher, R. G. Semonin and W. G. N. Slinn, eds.). Elsevier, New York.

Legrand, M. and Kirchener, S. 1988. Polar atmospheric circulation and chemistry of recent (1957–83) south polar precipitation. *Geophys. Res. Lett. 15*, 879–882.

Lettau, B. 1969. The transport of moisture into the Antarctic Interior. *Tellus 21*, 331–340.

Lettau, H. H. 1971. Antarctic atmosphere as a test tube for meteorological theories. In: *Research in the Antarctic* (L. O. Quam, ed.). AAAS Pub 93, Washington, 1971, 443–476.

Lettau, H. H., Riordan, A. J. and Kuhn, M. 1977. Air temperatures and two-dimensional wind profiles in the lowest 32 meters as a function of bulk stability. In: *Meteorological studies at plateau station* (J. A. Businger, ed.). Antarctic Research Series, 25, AGU Washington, 1977, 77–91.

Locatelli, J. D. and Hobbs, P. V. 1974. Fall speeds and masses of solid precipitation particles. *J. Geophys. Res. 15*, 2185–2206.

Maenhaut, W., Zoller, W. H., Duce, R. A. and Hoffman, G. L. 1979. Concentration and size distribution of particulate trace elements in the South Polar atmosphere. *J. Geophys. Res. 84*, 2421–2431.

Mather, K. B. and Miller, G. S. 1966. Wind drainage of the high plateau of eastern Antarctica. *Nature 209*, 281–284.

Mitchell, D. L., Zhang, R. and Pitter, R. L. 1990. Mass-dimensional relationships for ice particles and the influence of riming on snowfall rates. *J. Appl. Meteorol. 29*, 153–163.

Mosely-Thompson, E., Kruss, P. D., Thompson, L. G., Pourchet, M. and Grootes, P. 1985. Snow stratigraphic record at south pole: potential for paleoclimatic reconstruction. *ANN Glaciology 7*, 26–33.

Murozumi, M., Torii, T. and Fujiwara, K. 1971. Sodium, potassium and magnesium concentrations in polar snows. In: *Report of the Japanese traverse Syowa, South Pole, 1968–69* (M. Muryama, ed.). Polar Research Center Tokyo, Mar 1971, 113–114.

Murphey, B. B., Hare, T., Hogan, A. W., Lieser, K., Toman, J. and Woodgates, T. 1991. Vernal atmospheric mixing in the Antarctic. *J. Appl. Meteorol. 30*, 494–507.

Nakaya, U. 1954. *Snow crystals.* Harvard University Press, Cambridge, Mass.

Oltmanns, S. and Komhyr, W. 1975. Surface ozone in Antarctica. *J. Geophys. Res. 811*, 5359–5364.

Pack, D. H. 1973. Geophysical monitoring for climatic change. *Antarctic J. of US 7*, 253–254.

Parish, T. R. and Bromwich, D. H. 1987. The surface windfield over the Antarctic Ice sheets. *Nature 327*, 51–54.

Parungo, F., Ackerman, E., Caldwell, W. and Weickmann, H. K. 1979. Individual particle analysis of Antarctic aerosols. *Tellus 31*, 521–529.

Picciotto, E., Crozaz, G. and De Breuck, W. 1971. Accumulation on the south pole, Queen Maud Land Traverse 1964–68, Antarctic snow and ice studies II (A. P. Crary, ed.), vol. 16. AGU Washington, 257–316.

Polian, G., Lambert, G., Ardovin, B. and Jegou, A. 1986. Long-range transport of continental radon in subantarctic and antarctic areas. *Tellus 38B*, 178–189.

Rich, T. A. 1966. Apparatus and method for measuring the size of aerosols. *J. Rech. Atmos. 2*, 79–86.

Riley, D. C. 1987. *A study of the relationship between the variation of aerosols and meteorological parameters at south pole on synoptic seasonal and climatological time scales.* MS thesis, ASRC Pub 1122. Albany N.Y., May 1987.

Samson, J. A., Barnard, S. C., Obremski, J. S., Riley, D. C., Black, J. J. and Hogan, A. W. 1990. On the systematic variation of surface aerosol concentration at the South Pole. *Atmos. Res. 25*, 385–396.

Sato, N., Kikuchi, K., Barnard, S. C. and Hogan, A. W. 1981. Some characteristic properties of ice crystal precipitation in summer season at South Pole Station, Antarctica. *J. Met. Soc. Japan 59*, 772–780.

Saxena, V. K. and Ruggiero, F. H. 1990. Antarctic coastal stratus clouds: Microstructure and acidity. Contributions to Antarctic Research I. *Antarctic Research Series 50*, 7–18.

Schwerdtfeger, W. 1977. Temperature regime of the South Pole: results of 20 years observation at Amundson Scott Station. *Antarctic J. US 12*, 156–159.

Schwerdtfeger, W. 1984. *Weather and climate of the Antarctic.* Elsevier, N.Y., 261 p.

Sinclair, D. 1972. A portable diffusion battery. *Am. Indust. Hyg. Assn. J. 33*, 729–735.

Sinclair, M. R. 1981. Record high temperatures in Antarctica. A synoptic case study, *Mon. Wea. Rev. 109*, 2234–2242.

Taylor, L. D. 1971. Glaciological studies on the south polar traverse, 1962–63. In: *Antarctic snow and ice studies (II).* (A. P. Crary, ed.), vol. 16. AGU Washington, 209–224.

Townsend, R. 1985. *Growth and precipitation of ice crystals at the South Pole.* MS Thesis, ASRC PUB 1110, Albany, NY, December 1985.

Tuncell, G., Aras, N. K. and Zoller, W. H. 1989. Temporal variation and sources of elements in the south polar atmosphere, 1: Non-enriched and moderatly enriched elements. *J. Geophys. Res. 94*, 13025–13038.

Van Loon, H. 1972. Pressure in the southern hemisphere. In: *Meteorology of the Southern Hemisphere* (C. W. Newton, ed.). *Meteorological Monographs 13*, 59–86.

Warburton, J. A. and Linkletter, G. O. 1978. Atmospheric processes and the chemistry of snow on the Ross Ice Shelf, Antarctica. *J. Glaciol. 20*, 149–162.

Zikmunda, J. and Vali, C. 1972. Fall patterns and fall velocities of rimed ice crystals. *J. Atmos. Sci. 29*, 1334–1347.

Zoller, W. H., Gladney, E. S. and Duce, R. A. 1974. Atmospheric concentrations and sources of trace metals at the south pole. *Science 183*, 198–200.

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