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# Late 20th Century increase in South Pole snow accumulation

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**Abstract**. A compilation of the 37-year history of net accumulation at the South Pole [*Mosley-Thompson et al.,* 1995] suggests an increase in net annual accumulation since 1965. This record is sporadic and its quality is compromised by spatially restricted observations and nonsystematic measurement procedures. Results from a new, spatially extensive network of 236 accumulation poles document that the current 5-year (1992-1997) average annual net accumulation at the South Pole is 84.5±8.9 mm water equivalent (w.e.). This accumulation rate reflects a 30% increase since the 1960s when the best, although not optimal, records indicate that it was 65 mm w.e. Identification of two prominent beta radioactivity horizons (1954/1955 and 1964/1965) in six firn cores confirms an increase in accumulation since 1965. Viewed from a longer perspective of accumulation provided by ice cores and a snow mine study, the net accumulation of the 30-year period, 1965-1994, is the highest 30-year average of this millennium. Limited data suggest this recent accumulation increase extends beyond the South Pole region and may be characteristic of the high East Antarctic Plateau. Enhanced accumulation over the polar ice sheets has been identified as a potential early indicator of warmer sea surface temperatures and may offset a portion of the current rise in global sea level.

## 1. Introduction

Net annual snow accumulation has been measured discontinuously at Amundsen-Scott South Pole Station (SPS) by a variety of techniques since the International Geophysical Year (IGY) (1957-58). Knowledge of the amount of snow accumulating annually in a region is a primary glaciological characteristic necessary for scientific inquiry, as well as engineering applications. Net accumulation of snow is the major input of mass to Antarctica and an essential element for mass balance calculations. Thus accumulation has been measured as part of most glaciological investigations and traverses since the IGY [*Mellor,* 1959; *Meier,* 1967; *Bull,* 1971; *Giovinetto and Bull,* 1987]. A comprehensive discussion of the various measurement techniques and results was first provided by *Bull* [1971] and remains remarkably consistent with current practices. The various techniques include pole height measurements, identification of total beta radioactivity horizons and isolation of seasonally varying parameters such as dust concentrations, specific chemical species, and stable isotopic ratios in pits and shallow cores. Accumulation studies at Dome C [*Petit et al.,* 1982] and SPS [*Mosley-Thompson et al.,* 1995] illustrate the use of multiple techniques to assess net accumulation. Detailed methodological discussions of each technique are available elsewhere [*Bull,* 1971; *Mosley-Thompson et al.,* 1995].

A review of all SPS accumulation data since 1957 reveals the use of various methods and an absence of a single continuous set of observations. Primary difficulties with the assessment of net snow accumulation include (1) the effect of the station on the pattern of snow drift and accumulation due to wind obstruction, (2) the effect of small-scale topographic features such as sastrugi on the depositional regime, and (3) the effect of larger-scale (wavelengths ≈10-15 km) surface features on the longer (≈decades) depositional history. A summary of all SPS accumulation observations prior to installation of the OSU network in 1992 is presented elsewhere [*Mosley-Thompson et al.,* 1995]. The current study is limited to data that are most spatially representative and least likely to be disturbed. Thus except for the new observations along the Ohio State University (OSU) 1992 network, only data upwind of the station (Figures 1a, 1b) and encompassing a measurement period of 5 years or longer are included as they provide a more "climatological" representation of net accumulation.

## 2. Net Accumulation Observations at SPS

The four best data sets include (1) the 42-pole pentagon, (2) the 40 poles along the upwind arm of the 7-mile cross array, (3) beta radioactivity horizons from 10 cores, and (4) the 1992 OSU network of 236 poles. Figure 2 illustrates the average and standard deviation (σ) for each set of observations described in detail below.

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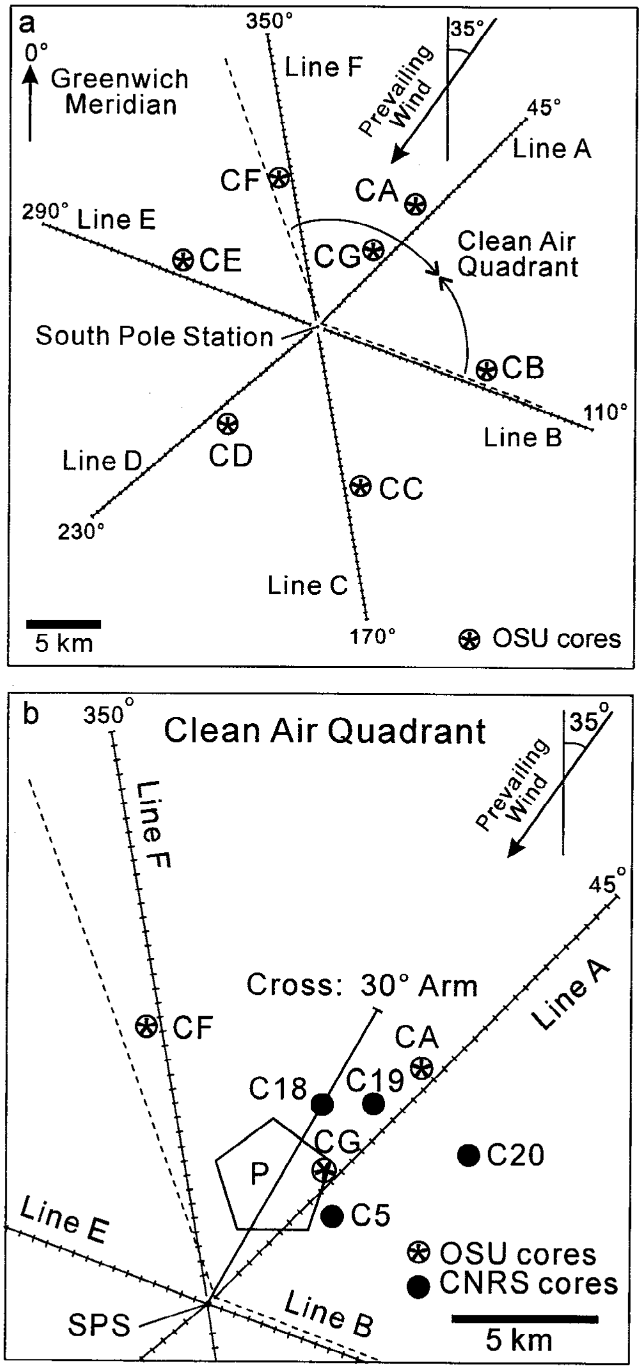

**Figure 1.** (a) Orientations of the six lines (A-F) of the OSU 1992 South Pole Station (SPS) accumulation network are shown along with the location of the six 1994 cores analyzed for beta radioactivity horizons and the 1996 core (CG) containing the Tambora sulfate layer. The prevailing wind is shown along with the edges of the clean cir quadrant, a restricted area, which are the dashed lines. (b) Enlargement of the clean air quadrant illustrates the locations of all accumulation networks (Pentagon (P); grid 030° arm of 7-mile cross; OSU 1992 network line A) and the cores (CA, CF, CG, C5, C18, C19, C20) from which accumulation data unaffected by the station's presence were obtained.

All pole height changes and layer thicknesses were converted to water equivalent (w.e.) thicknesses using an empirical relationship between depth and density established from numerous density observations at SPS and verified as a good estimate of the relationship for the upper 15 m of firn [*Mosley-Thompson et al.*, 1995]. Depth in water equivalent ($D_w$) is given by

$$D_w = {}^1/_3AZ^3 + {}^1/_2BZ^2 + CZ \qquad (1)$$

where $A$ is -4.8 ($10^{-4}$), $B$ is 0.0196, $C$ is 0.350, and $Z$ and $D_w$ are depths in meters of firn and water equivalent, respectively. Although the actual depth-density relationship at a given site is influenced by changes in temperature and accumulation, the effect is likely to be small over the period of application (1954 to present). Unless indicated otherwise, this relationship was used to convert all snow accumulation heights and firn layer thicknesses presented here into water equivalent (w.e.) depths. The ratio between $D_w$ and $Z$ gives the mean density of the layer from the surface to depth $Z$. Henceforth all accumulations ($A_n$) are in millimeters water equivalent unless otherwise noted.

### 2.1. Forty-two-pole Pentagon Array

One of the best early estimates of South Pole accumulation is from an array of 36 bamboo poles (25 mm diameter) and 6 stakes (50 mm square) established in January 1958 [*Giovinetto*, 1960]. Shaped as a pentagon, the center was located 3 km windward of SPS (Figure 1b), and the stakes and poles were 300 m apart along its 12.6 km perimeter. The six stake heights were measured only once (11 months after installation), but heights of the 36 bamboo poles were measured at least once a year until November 1964. Thus only data from the 36 bamboo poles are presented (Table 1). The 6-year (November 1958 to October 1964) average accumulation was ≈64.0 mm $a^{-1}$ w.e. [*Giovinetto and Schwerdtfeger*, 1966]. Data in Table 1 illustrate the large interannual variability, 57 to 78 mm $a^{-1}$ w.e. for the 36 sites. The large standard deviation ($\sigma$) for each year, ranging from 29 to 39 mm w.e., largely reflects the roughness of the snow surface which controls local deposition. This limits the degree to which a single $A_n$ value reconstructed from an ice core may be considered spatially representative. As the data indicate, the thickness of any annual layer reconstructed from an SPS ice core will reflect strongly the local accumulation conditions which are controlled principally by the surface topography. When averaged over the entire 6 year period, $A_n$ for the network is 63.7 mm $a^{-1}$ with a $\sigma$ of ±10.0 mm $a^{-1}$, a variability of ±16% (Table 1, Figure 2). Increasing the averaging interval, six years in this case, substantially reduces $\sigma$ and the percent variation (Table 1). Thus the effect of spatial variability is reduced by increasing the time- averaging interval [*Mosley-Thompson et al.*, 1995]. Of the 216 individual annual measurements (36 poles x 6 years), zero or negative accumulation was recorded 9 times representing 4.1% of all observations. Knowledge of the statistical potential for missing years is particularly important when considering accumulation histories reconstructed from a single ice core as a missing year leaves no trace in the chemical and dust records. *Gow* (1965) suggested that unusually thick (40-50 mm) depth hoar layers may reflect a missing year, but such features do not always guarantee the existence a missing year.

From a climatological perspective the pentagon record is particularly valuable as pole heights were measured twice a year during 3 of the 7 years, providing insight to the distribution of accumulation throughout the year. For example, well-dated ice core records may be used to estimate the annual flux of chemical constituents (e.g., $SO_4^{2-}$ or $Cl^-$) or the annual average $\delta^{18}O$ record often provides a proxy history for temperature. Such calculations require that the distribution of accumulation throughout the year be known; otherwise it is tacitly assumed that accumulation occurs

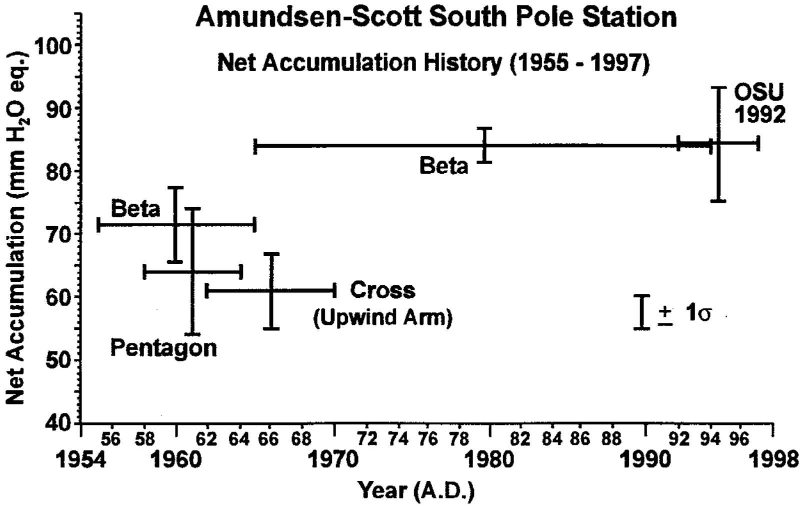

**Figure 2.** History of SPS net accumulation since 1955 is shown. All data, except the OSU 1992 average, are from sources at least 3 km upwind of the station. Length of the bar indicates the period of record and the vertical bar is ±1σ. Each record is discussed in the text.

consistently throughout the year. Observations at SPS led *Gow* [1965] to suggest that spring is the time of greatest surface roughness and that surface lowering is a summer process. During 3 years the pentagon pole heights were measured in both November and again in February of the same accumulation year. These summer (November to February) accumulations (*Mosley-Thompson et al.*, 1995, Table 2) confirm that summer accumulation is very low, ranging from 4 to 10% of the annual total, consistent with *Gow's* [1965] observation.

### 2.2. Upwind Arm of 7-mile Cross Array

An accumulation network in the form of a cross with 7-mile-long arms was established at SPS in February 1962. The arms extended along grids 030°, 120°, 210°, and 300°, were centered on the station, and consisted of 35 poles along each arm with a pole spacing of approximately 300 m. This network was remeasured in January 1970, providing an 8-year average of accumulation and an opportunity to examine whether the station affects the spatial distribution of $A_n$. The thickness of the firn layer accumulated over 8 years at each pole was converted to $H_2O$ equivalent using equation 1. Pole 1 in each leg is closest to the station and pole 5 of the 210° leg coincides with the runway. Data from poles 1-5 of 210° leg were eliminated from the record due to obvious disturbance. The network was subsequently abandoned and lost.

The prevailing wind direction (Figure 1a) is centered on grid 35°, closely coinciding with the 030° leg of the cross. At SPS, prevailing winds are very constant [*Bodhaine*, 1986] with 98% of the observations (1977-1983) from 330° to 120°. The 8-year (February 1962 to January 1970) $A_n$ of 61±. 6 mm w.e. for the leg upwind of the station (030°) is substantially lower than $A_n$ for the other three legs. The downwind leg (210°) has the highest $A_n$ (79±6 mm $a^{-1}$), while the other two legs (120° and 300°), oriented more perpendicular to the prevailing wind, have $A_n$ of 77±9 mm $a^{-1}$ and 72±5 mm $a^{-1}$, respectively. The details of accumulation along each line are discussed by *Mosley-Thompson et al.* [1995], but to avoid data likely to be affected by the presence of the station, only results from the upwind arm (030°) are included in Figure 2.

### 2.3. Beta Radioactivity Horizons

Atmospheric thermonuclear testing during the 1950s and 1960s produced fission products that were globally dispersed and deposited within the snow on both polar ice caps. The timing of deposition of $^{137}Cs$ and $^{90}Sr$ from the major tests is well established, making the radioactive layers valuable as time-stratigraphic markers. Antarctic beta profiles generally exhibit two distinct maxima in the concentration of radioactive material: the austral spring/summer horizons of 1954-1955 and 1964-1965 [*Picciotto and Wilgain,* 1963; *Crozaz,* 1969; *Pourchet et al.,* 1983]. Identification of these horizons allows assessment of changes in net snow accumulation.

Prior to 1994, beta measurements were conducted for 16 SPS cores [*Mosley-Thompson et al.*, 1995, Figure 1 and Table 3]. Of these, only four cores were upwind and more than 5 km from the station. Those cores, drilled in 1984, were analyzed for beta concentrations at Centre National De La Recherche Scientifique (CNRS). The approximate locations of these cores, labeled C5,

**Table 1.** Annual Net Accumulation for 36 Poles of the 42-Pole Pentagon

| Measurement Period | Annual Average (mm $H_2O$ eq.) | Standard Deviation (σ) | Percent Variation (σ/mean) |
|---|---|---|---|
| 1958/1958* | 78.0 | ±35. | 45. |
| 1958/1959 | 57.0 | ±36. | 63. |
| 1959/1960 | 76.0 | ±34. | 26. |
| 1960/1961 | 53.0 | ±29. | 54. |
| 1961/1962 | 58.0 | ±36. | 62. |
| 1962/1963 | 67.0 | ±30. | 48. |
| 1963/1964 | 57.0 | ±39. | 68. |
| 6 years† | 63.7† | ±10.† | 16.† |

*Not a full accumulation year: January 27, 1958 to November 5, 1958.
†These statistics are for six full accumulation years (November 1958 to October 1964) and are not based upon the individual annual averages or standard deviations.

C18, C19, and C20, are shown in Figure 1b. As part of a recent project to establish a network of poles for long-term monitoring of SPS accumulation, six 20-m cores were drilled in 1994 specifically for identification of the beta radioactivity horizons. One core was drilled along each of the six arms of the OSU 1992 network (section 2.4) at distances between 9.5 and 11 km from the station. The locations of these cores, labeled CA (core on Line A) to CF (core on Line F), are shown in Figure 1a. The beta horizons and accumulation data from these six cores are shown in Figure 3. In general, the depths (in water equivalent) of the contemporaneous bomb horizons are fairly consistent among the six cores, suggesting that an averaging interval of 30 years is sufficient to eliminate much of the spatial variability of $A_n$ which is quite high for annual observations (section 2.4). The shallowest 1965 bomb pulse, and hence the lowest $A_n$, is in Core A (Figure 3), located 10.5 km from SPS in the upwind quadrant where accumulation is least likely to be affected by the presence of station structures.

Identification of the 1955 and 1964 beta radioactivity horizons allows calculation of $A_n$ from 1955 to 1964, from 1965 to 1984 (four CNRS), and 1965 to 1994 (six OSU cores), as shown in Table 2. Averaging the $A_n$ values for the four CNRS cores suggests a 21% increase from the 1955 to 1964 average of 69.3 mm w.e. to the 1965 to 1984 average of 83.3 mm w.e., equivalent to a 21% increase in accumulation. Averaging the $A_n$ values for the six OSU cores indicates an increase of 15.5% from the 1955 to 1964 average of 73.5 mm w.e. to the 1965 to 1994 average of 84.8 mm w.e. The 1965-1984 mean of 83.3 is very similar to the 1965-1994 mean of 84.8, suggesting that much of the increase in $A_n$ occurred between 1965 and 1984, and there has been little change since the mid-1980s. Combining the data from all 10 cores (four CNRS and six OSU) gives an average of 71.6±5.8 mm w.e. from 1955 to 1964. Although the four CNRS cores extend only to 1984, their post 1964 average is nearly identical to that from the six OSU cores (Table 2) extending to 1994; therefore it is reasonable to average these data. This gives an average of 84.2±2.7 (Figure 2) from 1965 to 1994.

### 2.4. New 236-Pole Accumulation Network

The compilation of data presented here (Figure 2) reveals that $A_n$ has increased by 15 to 20% in the last two decades. Unfortunately, none of the earlier accumulation pole networks were preserved. The one line existing in 1990, OSU 1978, consisted of only 12 poles and was too short (6 km) and too spatially restricted (a single line along grid 130°) to provide a statistically sound baseline for $A_n$ at SPS [*Mosley-Thompson et al.*, 1995]. It has since been abandoned. In addition, a small (50 m by 60 m) field of 50 accumulation poles, located about 400 m from SPS, is measured monthly as part of the meteorology program. Regrettably, it is suboptimal for monitoring "undisturbed" SPS accumulation due to the small area covered, the tight spacing (5 to 10 m) of the poles, the monthly disturbance required to measure it, and proximity to the SPS Dome. These data do confirm earlier observations (section 2.1) that winter is the accumulation season and summer is the ablation season.

The lack of a sufficient system to monitor $A_n$ prompted establishment of a new accumulation network. In November 1992 an array of 236 poles in six 20-km-long lines (Figure 1a), radiating outward from SPS, was installed for permanent, systematic monitoring of the 'natural' snow accumulation. The network, henceforth OSU 1992, was established using standard surveying techniques, and pole locations were verified using the global positioning system (GPS) technology. The spacing between the poles is 500±1 m, and the lines (Figure 1a) lie along the following grid directions: line A (45°, through the clean air quadrant, access restricted); Line B (110°), line C (170°), line D (230°), line E (290°), and line F (350°). Pole 1 is absent in lines A, C, D, and F due to obstructions 500-m from SPS in these directions. All pole heights (from top of pole to the mark at the surface) were initially 72 inches (182.88 cm) and the original pole length (top to bottom of the original pole) was 231 cm. The conversion of the snow depth to water equivalent requires knowing the entire length of the pole as the differential densification of the snow pack must be approximated, as discussed below. The heights of the poles above the snow surface were measured annually in November between 1992 and 1997. Annual measurements of the pole heights and extension of the poles will continue indefinitely.

Net accumulation estimates from most early networks were calculated by converting the newly accumulated layer of snow to water equivalent (w.e.) using an assumed or measured density profile. For OSU 1992 the entire length of the original accumulation pole is known, allowing use of a more robust approach. The change in accumulation since installation is the difference between the thickness (w.e.) of the layer from the bottom of the pole to 1992 (the year of installation) and the thickness (w.e.) of the layer from the bottom of the pole to the current surface (e.g., 1997, the year of last measurement). This approach incorporates

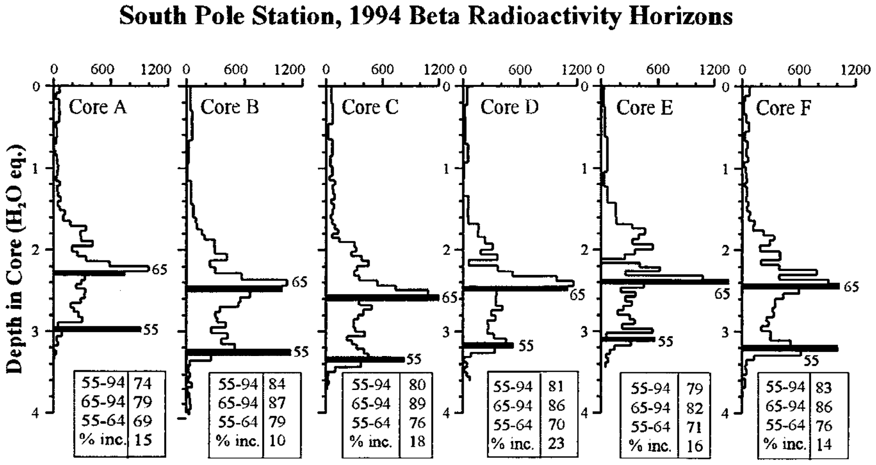
South Pole Station, 1994 Beta Radioactivity Horizons

**Figure 3.** Beta radioactivity horizons (1955 and 1965) are shown for the six cores (Figure 1a) drilled in 1994. Concentrations are in disintegrations $kg^{-1}$ $hr^{-1}$. The box below each core contains $A_n$ for the three time intervals (1955-1994, 1965-1994, 1955-1964) and the percent increase in $A_n$ from 1965 to 1994 relative to the 1955 to 1964 average.

**Table 2.** Average Annual Accumulation (w.e.) Based Upon Beta Radioactivity Horizons in 10 SPS Cores in the Upwind Quadrant

| | Accumulation (mm w.e.) Equivalent | | | | |
|---|---|---|---|---|---|
| Core Name | 1955-1964 Average | 1965-1984 Average | 1965-1994 Average | Percent Change | 1955-1994 Average |
| [CNRS-5] | 69.0 | 82.0 | | 18.8 | |
| [CNRS-18] | 70.0 | 86.0 | | 22.9 | |
| [CNRS-19] | 58.0 | 82.0 | | 41.4 | |
| [CNRS-20] | 80.0 | 83.0 | | 3.8 | |
| Average (four cores) | 69.3 | 83.3 | | 21.7 | |
| Standard deviation | 7.0 | 1.6 | | | |
| OSU-CA | 69.0 | | 79.0 | 14.5 | 74.0 |
| OSU-CB | 79.0 | | 87.0 | 10.1 | 84.0 |
| OSU-CC | 76.0 | | 89.0 | 17.1 | 80.0 |
| OSU-CD | 70.0 | | 86.0 | 22.9 | 81.0 |
| OSU-CE | 71.0 | | 82.0 | 15.5 | 79.0 |
| OSU-CF | 76.0 | | 86.0 | 13.2 | 83.0 |
| Average (six cores) | 73.5 | | 84.8 | 15.5 | 80.2 |
| Standard deviation | 3.7 | | 3.3 | | 3.2 |
| Average (ten cores) | 71.6 | | | | |
| Standard deviation | 5.8 | | | | |

the effect of differential densification of each layer within the snow pack and also assumes that the pole does not sink after emplacement. For example, the height of the snow on a pole in 1997 represents a combination of the thickness of the snow layer which has accumulated since the 1996 reading and the continued densification of lower layers. Unlike most previous networks, here the original length of each pole was known, allowing $A_n$ to be calculated as

$$A_n = \frac{z_2D_2 - z_1D_1}{t_2 - t_1} \qquad (2)$$

where $z_2$ and $z_1$ represent the height of the snow surface on the pole at times $t_2$ and $t_1$ and $D_2$ and $D_1$ are the mean densities between the surface and depths $z_2$ and $z_1$ [*Pettre et al.,* 1986]. The mean density is the ratio of firn depth to water equivalent depth (available from eq. (1)), thus the same depth-density relationship was used for all pole data. Calculating $A_n$ from (2), rather than simply converting the thickness of the newly accumulated layer to water equivalent using the mean density, gives values that are approximately 3% higher but should be more representative of the "real" thickness of newly accumulated snow. The 3% enhancement was determined using both procedures for the calculation of each year's new accumulation for each pole in the network. In either calculation the primary error arises from the conversion of the snow depths to water equivalent depths as this requires knowledge of the depth-density profile at each site. It is impossible to determine this at each site due to the disturbance of the surface which would be necessary and the time involved. For comparative purposes, conversions of firn depth to water equivalent depth were made using eq. (1).

Table 3 presents $A_n$ for each pole from 1992 to 1997, the 5 year average and standard deviation ($\sigma$) for each line, and a grand average and $\sigma$ for the entire network. Thus the single best value representing the current $A_n$ at SPS would be 84.5±8.9 mm w.e. As mentioned previously, the 50-pole network 400 m from SPS is not optimal. The effect of drift due to station proximity is demonstrated by comparison of the 236-pole average of 84.5 mm w.e. (November 1992 to November 1997) to the average of 103 mm w.e. (September 1988 to December 1995) for the small (50 x 60 m) array [*McConnell et al.,* 1997].

Finally, the OSU 1992 network is measured each November, at the end of the accumulation season, but prior to the period of surface leveling discussed by *Gow* [1965]. Five years of annual observations reveal zero or negative accumulation for 10 of the 1180 observations (236 poles x 5 years) for an occurrence percentage of 0.85, less than 1% of all observations. In the first year, 1992-1993, there were no negative or missing years. This probably resulted from unusually high $A_n$, 100.4±27.9 mm w.e., due to modest sinking of the accumulation poles shortly after emplacement. In fact, the first year of accumulation on a new network of poles should be viewed cautiously. Zero or negative accumulation was measured at three poles in both 1993-1994 and 1994-1995 and at two poles in both 1995-1996 and 1996-1997 for a total of 10 observations. There were never two consecutive years of zero or negative accumulation at the same pole, and lines B and C (crosswind and downwind sectors) did not experience any zero or negative accumulations. These data, coupled with the observation of 4.1% zero or negative accumulation for the pentagon array, suggest that an earlier estimate of 1 in 10 missing years [*Gow,* 1965; *Mosley-Thompson and Thompson,* 1982] may be an overestimate for the current SPS accumulation regime. These lower estimates may not be applicable to a long ice core record containing periods of reduced or enhanced accumulation as the frequency of missing (zero or negative $A_n$) years will increase (decrease) during periods of reduced (increased) regional accumulation. Accurate determination of the frequency of missing years in an ice core requires identification of known time-stratigraphic markers over the length of the core.

## 3. A Millennial-Scale (Ice Core) Perspective of 20th Century Accumulation

A limited number of $A_n$ histories have been derived from ice cores and these provide a valuable longer-term perspective to

**Table 3.** Annual Accumulation Average (1992 to 1997) for the 236 Poles of the South Pole OSU 1992 Network

| Pole | Line A | Line B | Line C | Line D | Line E | Line F |
|---|---|---|---|---|---|---|
| 1 | NA | 96.2 | NA | NA | 54.2 | NA |
| 2 | 98.1 | 76.8 | 91.6 | 70.3 | 60.2 | 78.3 |
| 3 | 81.7 | 93.9 | 88.9 | 83.2 | 80.9 | 63.6 |
| 4 | 79.0 | 84.0 | 89.7 | 102.7 | 92.4 | 63.2 |
| 5 | 82.8 | 97.0 | 95.4 | 99.3 | 67.0 | 66.2 |
| 6 | 79.0 | 90.8 | 111.6 | 84.0 | 83.2 | 75.3 |
| 7 | 80.2 | 90.1 | 86.6 | 89.7 | 88.2 | 84.0 |
| 8 | 62.4 | 85.9 | 73.7 | 86.6 | 74.9 | 81.3 |
| 9 | 67.7 | 93.9 | 87.8 | 79.0 | 75.6 | 78.7 |
| 10 | 71.9 | 84.0 | 76.8 | 85.1 | 94.3 | 85.9 |
| 11 | 82.1 | 77.5 | 88.2 | 88.2 | 76.8 | 85.1 |
| 12 | 77.5 | 74.1 | 87.8 | 85.9 | 82.5 | 75.3 |
| 13 | 77.5 | 82.5 | 90.8 | 82.5 | 82.5 | 83.2 |
| 14 | 85.1 | 68.8 | 98.9 | 90.8 | 85.9 | 74.5 |
| 15 | 77.5 | 70.3 | 93.5 | 92.0 | 90.1 | 80.2 |
| 16 | 75.6 | 81.7 | 80.2 | 97.7 | 90.1 | 81.3 |
| 17 | 71.1 | 83.6 | 84.0 | 82.8 | 78.7 | 77.5 |
| 18 | 83.2 | 77.1 | 83.6 | 89.7 | 69.2 | 90.1 |
| 19 | 76.4 | 75.3 | 90.1 | 77.9 | 80.9 | 95.4 |
| 20 | 78.3 | 87.4 | 80.9 | 87.0 | 74.5 | 89.7 |
| 21 | 83.6 | 79.0 | 86.6 | 80.6 | 73.4 | 97.0 |
| 22 | 82.1 | 86.6 | 88.6 | 84.7 | 86.3 | 96.2 |
| 23 | 95.8 | 85.1 | 91.6 | 87.4 | 83.6 | 91.2 |
| 24 | 91.6 | 88.6 | 90.1 | 71.1 | 70.7 | 82.1 |
| 25 | 85.9 | 87.4 | 90.8 | 81.3 | 89.3 | 84.7 |
| 26 | 82.8 | 89.7 | 84.4 | 77.9 | 99.3 | 79.4 |
| 27 | 85.5 | 85.9 | 89.7 | 78.3 | 93.5 | 82.1 |
| 28 | 93.5 | 89.7 | 89.7 | 89.3 | 94.3 | 79.8 |
| 29 | 80.2 | 80.6 | 84.4 | 82.8 | 103.1 | 82.1 |
| 30 | 92.4 | 77.1 | 79.4 | 81.7 | 105.4 | 80.9 |
| 31 | 82.1 | 80.9 | 76.8 | 73.4 | 103.5 | 76.8 |
| 32 | 99.3 | 99.3 | 76.8 | 80.2 | 96.2 | 84.7 |
| 33 | 92.0 | 96.6 | 79.0 | 70.7 | 103.5 | 75.6 |
| 34 | 80.2 | 85.9 | 79.4 | 86.3 | 93.5 | 76.8 |
| 35 | 79.0 | 97.7 | 87.4 | 85.1 | 102.3 | 88.6 |
| 36 | 90.1 | 92.0 | 81.7 | 81.3 | 103.9 | 95.4 |
| 37 | 78.7 | 105.4 | 79.4 | 72.6 | 95.4 | 91.2 |
| 38 | 76.4 | 87.8 | 88.9 | 88.9 | 81.7 | 93.5 |
| 39 | 84.4 | 94.7 | 78.3 | 76.0 | 90.1 | 95.0 |
| 40 | 77.1 | 88.6 | 80.6 | 77.9 | 69.0 | 97.3 |
| Average | 83.1 | 82.5 | 76.7 | 76.7 | 88.4 | 82.6 |
| s.d. | 14.5 | 24.4 | 22.6 | 17.3 | 22.2 | 16.7 |
| 236-pole average | | 84.5 | | | NA, no pole | |
| 236-pole s.d. | | 8.9 | | | | |

address whether the current spatially averaged (236 sites) SPS accumulation of ≈85 mm w.e. is high and represents a recent accumulation increase. The SPS data offer the best opportunity to address the question of enhanced $A_n$ over the high plateau of East Antarctica as it is the only data set of such length and spatial dimension. The longer $A_n$ histories considered here are of two types: (1) those based upon annual layer identification and (2) those based upon identification of emissions from historically dated volcanic eruptions. The latter provide only an average $A_n$ between the time of volcanic aerosol ($H_2SO_4$) deposition and the date of drilling; however, they are not subject to errors in annual layer identification (discussed below).

Three annually dated $A_n$ SPS histories are used in this study. Two cores drilled at SPS have been dated by identification of annual layers. *Mosley-Thompson and Thompson* [1982] identified 911 annual dust cycles in a 101 m core drilled in 1974 (Ellen Mosley-Thompson (EMT) record) while nearly 2000 visible layers were identified by *Gow* [*Kuivinen et al.*, 1982; *Hogan and Gow*, 1997] in a 200 m core drilled in 1981/1982 (Gow record). Both cores were drilled in close proximity to South Pole Station. Thus to avoid data biased by station activities, the most recent annual layer used in this analysis is 1956-1957. A third sequence of 198 visible annual layers (Giovinetto (GIOV) record) was identified in a snow wall along an inclined trench [*Giovinetto and Schwerdtfeger*, 1966]. Each of these time series is spatially limited, contains some degree of inaccuracy (see discussion below), and is from a different location in the SPS area. The two most severe limitations for such reconstructed histories are (1) the small spatial area for which each annual layer is representative and (2) the misidentification of annual layers. A fourth record, 100 years of SPS accumulation [*Jouzel et al.*, 1983] is excluded from the composite as $A_n$ in the early part of that record (1887-1930) is inconsistent with other $A_n$ records (see discussion in the Appendix).

The spatial representivity of a single ice core record or stratigraphic sequence will vary with the accumulation rate at the deposition site. Cores are generally 100 mm in diameter, so they represent a small footprint on the snow surface. In regions of lower accumulation, large variations in $A_n$ at an individual site from year to year may result from random removal and/or addition of material by drifting snow. Over time, lows will fill and surface highs will deflate resulting in the common observation that annual sequences of low $A_n$ tend to be followed by thicker annual sequences. It is generally observed that the spatial variability of $A_n$ decreases as accumulation increases, as illustrated by observations at Siple Station, Antarctica [*Mosley-Thompson et al.*, 1991] where $A_n$ is 560 mm w.e.

At SPS, where $A_n$ is low (<100 mm w.e.), the thickness of an individual layer in a single core record may largely reflect surface processes and provide little meaningful information about the regional accumulation that year. For example, considering the 5-year average $A_n$ from the 236-pole network (section 2.4), the maximum and minimum values are 111.6 and 54.2 mm w.e., respectively. Neither is representative of the regional 5 year $A_n$ of 84.5 mm w.e. (based on 236 poles). These extremes would be even higher or lower, if the annual and not the 5-year average data were considered. As previously noted, zero and/or negative accumulation was observed for 10 of the 1180 annual observations.

The two SPS core records discussed here contain intervals, extending from a few years to multiple decades, during which accumulation is consistently above or below the long-term spatially averaged mean [*Mosley-Thompson and Thompson*, 1982]. These periods of reduced or enhanced local accumulation reflect the control of topographic features on $A_n$ [*Black and Budd*, 1964; *Gow and Rowland*, 1965; *Gow et al.*, 1972; *Mosley-Thompson et al.*, 1985]. These features may range from large-scale (λ≈5-15 km) surface waves to small-scale, randomly scattered sastrugi. *Gow et al.* [1972] report that surface depressions tend to accumulate 30-50% more snow than areas covered by crusts. *Black and Budd* [1964] suggest that accumulation is closely related to surface slope, so large-scale undulations produce an $A_n$ maximum just downwind of the bottom of the trough and an $A_n$ minimum downwind of the crest. Thus the waves move upslope and influence the local accumulation regime for multiple decades as they pass over a site. The resulting sequence of increasing and decreasing annual layer thicknesses would appear in the accumulation history reconstructed from an ice core subsequently drilled at that location. The unusually high $A_n$ in the early part of the *Jouzel et al.* [1983] record may reflect such an occurrence.

All stratigraphic records are subject to potential error from misidentification of annual layers. Comparison of the longer-term averages for the three SPS records considered in the composite reveal differences that probably arise from misidentification of annual layers. For their period overlap (1760 to 1956), the average $A_n$ from the GIOV, EMT, and Gow records are 65.7, 71.3, and 79 mm w.e. Intuitively, one might expect these to be closer. These differences may arise for two reasons. First, $A_n$ may be influenced by local topographic features as the records are from different locations around the SPS. Second, and equally important, is the likelihood of errors in annual layer identification. The lack of deposition, removal, or smoothing of an annual layer marker (e.g., a dust event or depth hoar layer) also leads to an underestimation of the age of subsequent horizons and an overestimation of $A_n$. Conversely, multiple dust events or depth hoar layers within the same year may be misinterpreted as separate years, thus overestimating the age of deeper layers and underestimating $A_n$. For the 196-year averages (1760-1956), both of these factors are likely to have contributed to the differences. Over much longer periods the topographic influences should diminish and the $A_n$ averages should converge. Nevertheless, for their period of overlap, 1050 to 1956, the $A_n$ averages for the EMT and Gow records are 70 and 75 mm w.e., respectively. These 906-year averages should be closer, suggesting there are definitely some differences in precision of annual layer identification. *Van der Veen et al.* (K. van der Veen, E. Mosley-Thompson, A. J. Gow, and B. G. Mark, Accumulation at South Pole: Comparison of two 900-year records, submitted to *Journal of Geophysical Research*, 1998) explore the processes potentially responsible for this difference but resolving it is beyond the scope of this paper and requires isolating contemporaneous known time stratigraphic horizons (e.g., volcanic horizons) in both cores. As the difference is not significant for the purposes of this paper, a 900-year average $A_n$ of 72.5 mm w.e., the mean of the two records, is adopted for the subsequent discussion.

Three other estimates of $A_n$ are available from cores in which the prominent 1816 sulfate peak from the 1815 Tambora eruption was identified. These cores provide a single $A_n$ average from 1816 to the date of drilling. Two of the cores [*Delmas et al.*, 1992] were drilled in 1983-1984 at distances of 1 and 4 km from SPS, and the third [J. Cole-Dai and E. Mosley-Thompson, Pinatubo aerosols in antarctic snow: Potential for calibrating ice core volcanic histories, submitted to *Annals of Glaciology*, 1998] was drilled in 1996 6 km upwind of SPS. Their respective averages are 83.3, 79.7, and 77.0 mm w.e.. Although these averages contain slightly different time intervals (e.g., 12 more years in the 1996 core), here they are treated as equivalent in length and are averaged with the 1816 to 1956 averages from the EMT (72.6 mm w.e.), Gow (76.8 mm w.e.), and GIOV (69.6 mm w.e.) data sets. These six cores indicate an average accumulation of 76.5 mm w.e. since 1816 (Figure 4). None of the layer thicknesses presented were corrected for layer thinning with depth. The deepest (oldest) data presented originate from 100 m below the surface of an ice sheet that is nearly 3000 m thick. Using a simple Nye-type calculation [*Paterson*, 1994, p. 277] and assuming steady state conditions, the maximum thinning of a 100-m-deep layer due to vertical strain is ≈3% and is ignored for the purposes of this analysis.

These longer accumulation histories are particularly valuable because they provide an important perspective from which to view the more recent (since 1958) observational record of SPS accumulation. Of these observations the most spatially representative data are (1) the 30-year average (84.8 mm w.e.) from beta horizons (Figure 3) in the six OSU cores (Figure 1a, Table 2) and (2) the 5-year average (84.5 mm w.e.) from the 236-pole network. As the longest time average available from the observational data is 30 years, 30-year averages were constructed from the three annually resolved $A_n$ histories (Table 4) for the period prior to 1960. To provide a more spatially representative perspective, the 30-year averages for the three records are combined. Prior to 1760 the averages are for only the Gow and EMT records. Figure 4 illustrates these 30-year averages from 1060 to 1960 along with the 5-year $A_n$ from the 236-pole network. Also shown in Figure 4 is the average accumulation (76.5 mm w.e.) since 1816 based upon identification of Tambora sulfate deposition in six cores. The 30-year average from beta horizons in six 1994 OSU cores (84.8 mm w.e.) is projected back over the millennium (dashed line), illustrating that the most recent 30-year average SPS accumulation is at an unprecedented high.

This recent increase in accumulation at SPS is supported by a limited number of additional observations at other antarctic locations. On the East Antarctic Plateau, identification of beta radioactivity horizons at 19 sites near Dome C [*Petit et al.*, 1982;

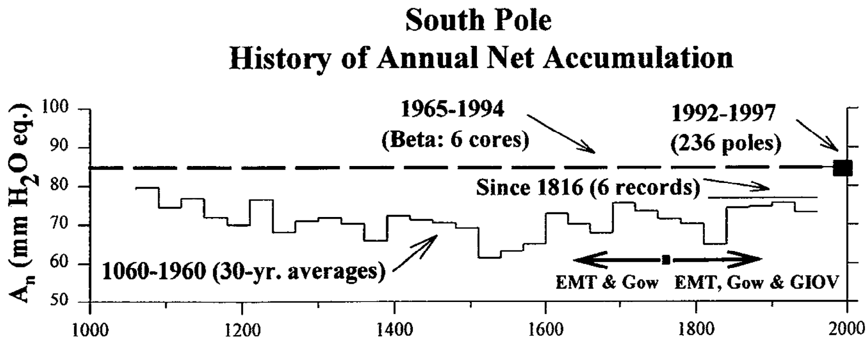

**Figure 4.** The 900-year history of SPS annual net accumulation illustrates that accumulation in the most recent 30 years (1965-1994, dashed line) exceeds that for the last millennium. Included in the figure are (1) 30-year averages (see Table 4) from the Gow, EMT, and GIOV records discussed in the text; (2) accumulation average since 1816 based upon six records (three cores containing the 1816 Tambora sulfate layer and the Gow, EMT, and GIOV annual records); and (3) the 5-year (1992-1997) average for 236 accumulation poles of the new SPS accumulation network. For the Gow and EMT records the most recent year used was 1956-1957 as discussed in text and shown in Table 4.

**Table 4.** Thirty-year Averages of Net Annual Snow Accumulation (in mm w.e.) Given for Giovinetto Snow Mine, 200 m Core Drilled in 1981, and 101 m Core Drilled in 1974

| Midpoint of Averaged Time Interval | Snow Mine Giovinetto | 200 m Core Gow | 101 m Core EMT | Averaage for Three Records |
|---|---|---|---|---|
| 1945* | 74.1 | 81.0 | 64.7 | 73.3 |
| 1915 | 77.7 | 78.0 | 70.9 | 75.5 |
| 1885 | 69.6 | 77.0 | 77.3 | 74.6 |
| 1855 | 68.7 | 78.0 | 76.2 | 74.3 |
| 1825 | 56.4 | 70.0 | 68.2 | 64.9 |
| 1795 | 57.4 | 84.0 | 69.3 | 70.2 |
| 1765 | 53.0 | 94.0 | 67.1 | 71.4 |
| 1735 | | 74.0 | 73.2 | 73.6 |
| 1705 | | 78.0 | 73.0 | 75.5 |
| 1675 | | 81.0 | 54.8 | 67.9 |
| 1645 | | 76.0 | 64.3 | 70.2 |
| 1615 | | 80.0 | 65.9 | 73.0 |
| 1585 | | 58.0 | 72.3 | 65.1 |
| 1555 | | 59.0 | 67.4 | 63.2 |
| 1524 | | 60.0 | 62.8 | 61.4 |
| 1495 | | 66.0 | 72.4 | 69.2 |
| 1465 | | 66.0 | 74.7 | 70.4 |
| 1435 | | 73.0 | 69.3 | 71.2 |
| 1405 | | 76.0 | 68.8 | 72.4 |
| 1375 | | 64.0 | 67.7 | 65.9 |
| 1345 | | 70.0 | 70.7 | 70.3 |
| 1315 | | 75.0 | 68.6 | 71.8 |
| 1285 | | 71.0 | 70.8 | 70.9 |
| 1255 | | 72.0 | 64.4 | 68.2 |
| 1225 | | 77.0 | 76.0 | 76.5 |
| 1195 | | 69.0 | 70.9 | 70.0 |
| 1165 | | 81.0 | 63.0 | 72.0 |
| 1135 | | 83.0 | 70.7 | 76.8 |
| 1105 | | 78.0 | 71.0 | 74.5 |
| 1075 | | 83.0 | 76.4 | 79.7 |

*27 years (1931-1957).

*Pourchet et al.*, 1983] indicates that accumulation since 1965 is ≈30% greater than the 1955-1964 accumulation. Likewise, beta horizons from two sites near Plateau Remote (84°S; 43°E) reveal a 27% increase since 1965 [*Mosley-Thompson*, 1996]. On the basis of annual layers in four cores from the Wilkes Land region, *Morgan et al.* [1991] report that since 1960, accumulation has increased 20% over the longer-term (1930-1985) mean. Two 500-year records of $A_n$ from the Antarctic Peninsula region, the Dyer Plateau core [*Thompson et al.*, 1994; *Raymond et al.*, 1996], and the Siple Station core [*Mosley-Thompson*, 1992] show no long-term $A_n$ increase. At both sites $A_n$ has increased gradually in the last 200 years consistent with observations by *Peel et al.* [1992] in a core from James Ross Island. *Peel et al.* [1992] also report marked increases in $A_n$ since 1950 (relative to their long-term averages) from cores on Dolleman Island and at Gomez Nuntak near the base of the Antarctic Peninsula. For the peninsula region these regionally consistent recent $A_n$ increases are concomitant with a well-documented 44-year warming [*Stark*, 1994] of nearly 2.7°C, with the greatest warming in autumn and winter (~5°C). However, not all investigations of antarctic accumulation reveal a recent increase. *Isaksson et al.* [1996] report results from two annually dated cores inland from the coast of Dronning Maud Land. A 50-year record from the coastal slope shows a decline in $A_n$, which is most pronounced since 1980, while a 130-year record from the EPICA site, 800 km farther inland, shows no significant trend but a pronounced increase since 1980.

## 4. Discussion and Conclusions

Documentation of anthropogenic increases in radiatively active "greenhouse" gases [$CO_2$, $CH_4$, $N_2O$] has resulted in international efforts to (1) establish the current state of our knowledge of the climate system and (2) develop models to predict future global and regional climate changes in response to continued emissions [*Intergovernmental Panel on Climate Change* (*IPCC*), 1996]. Detection of anthropogenic changes will be difficult as they are superimposed upon the natural variability of the climate system. Recent quantitative efforts to detect change and attribute part of it to human activities [*IPCC*, 1996 (chapter 8); *Santer et al.*, 1996] are complemented by investigations that reveal qualitative agreement between observations and model predictions. These allow identification of potential fingerprints of global change [*Schneider*, 1994]. Those for which confidence of a relationship is greatest include reduction in the diurnal temperature range, increases in evaporation and condensation of water vapor over the tropical oceans, rise of global sea level, and increases of high-latitude winter precipitation [*IPCC*, 1996, p. 412].

Attempts to investigate these anticipated changes have highlighted the lack of long, spatially extensive data sets necessary for global change detection [*NAS*, 1988, 1990], and this recognition has resulted in establishment of numerous new observational networks and improvement of existing ones. Observational time series from Antarctica are short, discontinuous, and sparse. Fifty-five percent of the continental area (14 x $10^6$ $km^2$) lies more than 2000 m above sea level on the high east and west plateaus where there is now only one permanent station (SPS).

The apparent increase in recent net accumulation over the antarctic plateau is of interest to those investigating changes in global sea level. Global mean sea level has risen 100 to 250 mm in the last 100 years [*Warrick et al.*, 1996], primarily from thermal expansion of the oceans and melting of land-based ice. The contributions of Antarctica and Greenland to global sea level are unknown with any confidence [*IPCC*, 1996, p.381], but current studies suggest that Antarctica is close to equilibrium (gain = loss) with a likely 20% margin of error [*Huybrechts and Oerlemans*, 1990]. Although Antarctica contains 70 m of water equivalent sea level rise, of more immediate concern is the possibility of an accumulation increase over the high plateau in response to warmer air temperatures. As the additional precipitation would be spread over such a large area, even a small accumulation increase constitutes a large volume of water, probably offsetting some portion of sea level rise. *Fortuin and Oerlemans* [1990] note that any change in accumulation over the antarctic plateau will immediately affect global sea level. Their model studies exploring the sensitivity of Antarctica's mass balance to various temperature changes suggest that accumulation in the interior depends entirely upon precipitation.

*Huybrechts and Oerlemans* [1990] note that precipitation in the antarctic interior is most dependent upon air temperature, which controls the amount of atmospheric water vapor that is advected inland. However, synoptic processes, dominant along the coastal margins [*Steig*, 1997], also respond to changes in atmospheric and sea surface temperatures and may directly affect the advection of warmer, moister air to the high interior. Thus increasing surface temperatures are expected to influence precipitation on the interior plateau through both thermodynamic and dynamic processes.

Model experiments exploring the response of the antarctic ice sheet to global warming scenarios [*Huybrechts and Oerlemans*, 1990; *Warrick et al.*, 1996; *Thompson and Pollard*, 1997] consistently indicate that the initial response (over the next century) will be increased precipitation and ice sheet thickening. These models beg the question asked by *Jacobs* [1992]: Is the antarctic ice sheet growing? He correctly concluded that the data are too limited and too spatially and temporally variable to make a determination. The recent increase in net accumulation at SPS, in concert with limited observations from other inland regions of Antarctica (section 4), suggests that in the last 30 years, accumulation has reached a historic high over the inland plateau. This result provides additional observational evidence for qualitative agreement between observations and model predictions for a warmer Earth scenario. In the future the SPS accumulation network will provide an unprecedented baseline for accumulation, the only such data within a radial distance of 1000 km from SPS.

## Appendix

The 100-year $A_n$ history presented by *Jouzel et al.* [1983] is not included as part of the composite SPS $A_n$ history for the following reasons: The average $A_n$ from 1887 to 1930 is 100 mm w.e., about 30% higher than that for the same period in the other three records (75.5 mm w.e. (Gow), 74.6 mm w.e. (GIOV), 74 mm w.e. (EMT)). For this earlier time interval, *Jouzel et al.* [1983] identified annual layers using δD, which unlike insoluble dust (EMT record) and visible stratigraphy (Gow and GIOV records) is modified postdepositionally by isotopic diffusion, particularly in regions of low accumulation [*Johnsen*, 1977]. The severity of this influence has been debated as it varies from site to site as a function of the local temperature regime, annual accumulation, and the presence of impermeable layers [*Jouzel et al.*, 1983; *Mosley-Thompson et al.*, 1985; *Whillans and Grootes*, 1985]. Although the unusually high accumulation in this portion of their 100-year record may be real and reflect local topographic control of $A_n$, it is equally possible that annual layer ages are underestimated by missing thin units that either have been obscured or obliterated by isotopic diffusion.

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