Accumulation At South Pole: Comparison of two 900-year records

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Abstract. Two 900-year records of annual accumulation at South Pole are compared to evaluate the origin and significance of observed variations. Despite difficulties establishing absolute timescales, due to problems identifying annual layer markers, the two records can be correlated with confidence after moderate smoothing. This correlation shows that over the time period considered (1050-1956 A.D.) no climatically significant changes in accumulation occurred. Instead, fluctuations preserved in the two cores reflect spatial variations in snow accumulation, associated with nonuniform deposition induced by surface relief on the scale of several kilometers.

1. Introduction

A much debated issue is whether human activities are perturbing the global climate system and whether 20th century climate trends fall outside the natural range of past variability. Addressing these questions requires long paleoclimate records that are spatially and temporally representative of the area of interest. Instrumental records of air temperature and precipitation typically date back a few hundred years to the late seventeenth century [e.g., *Van den Dool et al.,* 1978]. Using ancillary written records, such as wine harvest dates in Western Europe [*Le Roy Ladurie and Baulant,* 1980], local climate histories can be extended back a few hundred years more, to the Middle Ages. However, longer records exist only for few places, mostly in western Europe, and for most of the Earth, instrumental records are absent or span only a short time period. In data sparse regions, knowledge of climate history comes from proxy records such as those from tree rings, corals, laminated lake and ocean sediments and ice cores, and direct inversion of borehole temperatures.

Ice cores have been used to derive detailed records of past temperature, CO_2, and other atmospheric constituents [e.g., *Jouzel et al.,* 1987; *Barnola et al.,* 1987]. Some of these records extend back several glacial cycles [*Petit et al.,* 1997]. In reality, interpretation of climate records from ice cores is not straightforward, as the measured signal is a convolution of both large-scale and small-scale processes acting over a spectrum of temporal scales. For example, at a specific site, a regional change in accumulation over multiple decades will also contain shorter-term fluctuations reflecting local surface processes that modulate deposition and preservation. In addition, the stratigraphic record is affected by the flow of ice, so that material at depth is slowly moved away from the original deposition site. This convolution is particularly evident if time series of annual accumulation rate are compared. Such records show large interannual variability owing to climate fluctuations and surface irregularities [*Van der Veen and Bolzan,* 1999] which may obscure significant changes in climate. To properly interpret accumulation records, it is important to recognize the various contributions to the record and to assess how representative the very local record encapsulated in a core with a typical diameter of ~100 mm is for a larger region. Several studies have addressed this issue by combining spatial and temporal records [e.g., *Mosley-Thompson et al.,* 1985; *McConnell et al.,* 1997; *Kuhns et al.,* 1997; *Van der Veen and Bolzan,* 1999].

The consensus view expressed in most studies is that multiple-core records are needed to reliably retrieve climatically significant changes in accumulation rate. If only a single core is available, averages over longer periods are needed. For example, *Mosley-Thompson et al.* [1985] combine visible stratigraphy with measurements of microparticles, oxygen-isotope ratio, and β-radioactivity in a series of pits at South Pole, to determine how representative records preserved in snow strata are for a larger region. They conclude that information about regional trends in accumulation can only be made if the record is averaged over sufficiently long time periods to eliminate topographic effects. *Kuhns et al.* [1997] provide a more quantitative assessment of spatial variability using accumulation measurements from a 100-pole stake farm, automatic accumulation monitors, and 17 shallow firn cores. For the Summit region in central Greenland, these authors argue that an averaging interval of ~30 years is needed to extract a signal representative for a region with a length scale of ~30 km from a single ice core record. *McConnell et al.* [1997] suggest that significantly

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longer averaging periods (a few hundred years at South Pole) are needed to eliminate large fluctuations that may exist because of variations in the seasonal distribution of accumulation archived in the core.

None of the studies mentioned above addresses quantitatively the effects of large-scale topography on accumulation rate due to the interaction between winds in the surface layer and surface relief on the scale of a few kilometers or larger [*Black and Budd*, 1964; *Gow and Rowland*, 1965; *Benson*, 1971; *Whillans*, 1975]. Smaller surface features, such as sastrugi, are generally too small to affect near-surface winds. Moreover, these features are transient, with a typically short life span of the order of 1 year or shorter, and contribute to interannual variability in accumulation [*Van der Veen and Bolzan*, 1999]. In contrast, the larger-scale topographic relief may lead to longer-term trends in accumulation. For example, low-frequency variation in net accumulation measured in the Dye 3 core in southern Greenland strongly reflects the undulating surface topography upstream of the borehole [*Reeh et al.*, 1985]. The studies mentioned above advocate averaging over longer time periods to eliminate these topographic effects. In doing so, climatically significant effects may be eliminated from the record because topographic and climatic effects are superimposed and cannot be separated if only one core is considered.

To correctly interpret an ice core record, it is important to note that it may not reflect the in situ climate signal, unless the core is drilled at a stable ice divide. Elsewhere, the ice at depth will have originated as surface snow upstream of the borehole. Theoretically, surface topography leads to locally varying accumulation with above average snow deposition in areas where the large-scale surface slope decreases in the direction of prevailing winds [*Whillans*, 1975] and as the ice is moving, this spatial pattern is preserved in the ice core record. The picture may be further complicated because the prevailing wind direction need not coincide with the ice flow direction and because topographic features may migrate over time as surface hollows are slowly filled and surface highs are eroded or deflated. *Black and Budd* [1965] estimate an upwind migration rate of ~25 m/yr in the area of Wilkes Land, East Antarctica, while *Whillans* [1975] arrives at a migration rate of ~20 m/yr along the Byrd Station strain network, West Antarctica. This upwind migration may be countered in part by advection of the surface undulations in the direction of ice flow.

Recent emphasis on the reconstruction of high temporal resolution (annual to decadal scale) information from ice cores makes the issue of both regional and temporal representativity critical. Such assessments require comparison of multiple records from the same area; however, the expense of drilling long cores often results in the retrieval of only one core per drill site. South Pole Station is a notable exception, as there have been a number of ice cores drilled, surface snow accumulation has been measured intermittently since the International Geophysical Year (1957/1958), and, recently, Global Positioning System technology was used to map the surface topography. Here we examine the degree of correspondence between two annually resolved ~900-year ice core records of accumulation and explore the processes producing their observed differences. This helps address the degree to which an individual ice core record can be expected to reflect large-scale processes such as a change in the regional precipitation regime.

2. Available Accumulation Records

In 1974, a 101-m firn core (henceforth EMT) was retrieved and analyzed continuously for microparticle concentrations [*Mosley-Thompson*, 1980; *Mosley-Thompson and Thompson*, 1982]. Roughly 370 m away (Figure 1) a second core (henceforth GOW), containing >2000 visible annual layers, was drilled in 1982 [*Kuivinen et al.*, 1982; *Hogan and Gow*, 1997]. The annual accumulation histories for the period common to both cores, 1050-1956 A.D., form the basis of this study. A third record of 200 annual snow layers observed in a snow mine near South Pole is also available [*Giovinetto*, 1960; *Giovinetto and Schwerdtfeger*, 1966] but is not considered here.

For the GOW and EMT records, annual layer thicknesses were identified using different techniques, both of which have limitations. Prior to a meaningful comparison of the accumulation histories, it is necessary to discuss the quality of these records and the factors that limit their accuracy. The GOW chronology is based substantially on visible stratigraphy of low-density depth hoar layers which form each fall or a coarse-grained equivalent overlain by fine-grained winter snow. While this layer densifies as it is buried by successive snowfall, the layer retains distinct visual and optical properties, thus providing an annual horizon [*Gow*, 1965; *Hogan and Gow*, 1997]. Dating of the EMT core is based on seasonal variations in microparticle (dust) concentrations, so that successive accumulation years can be identified by spring peaks in dust concentra-
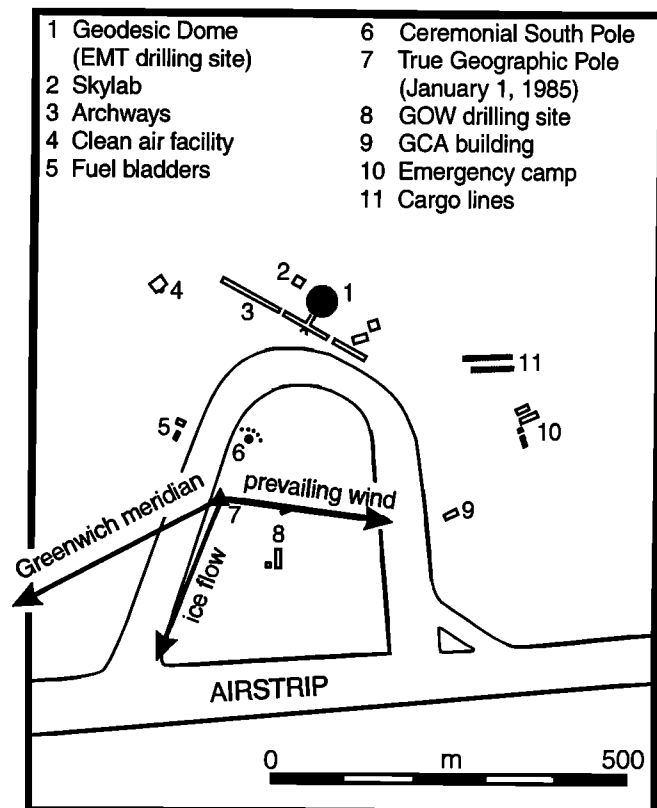

Figure 1. Map of Amundsen-Scott South Pole Station (based on a U.S. Geological Survey aerial photograph taken December 31, 1983) showing the location of the two drilling sites.
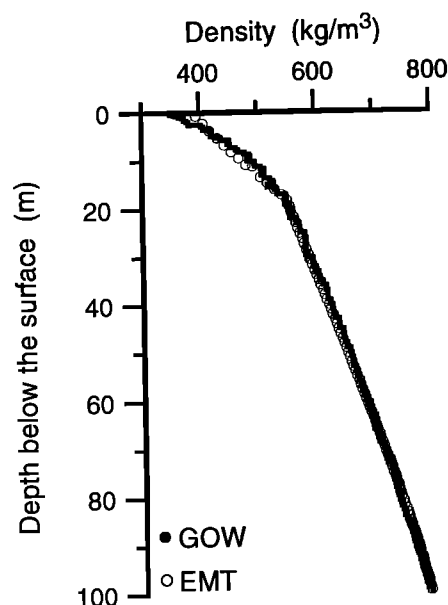
Density (kg/m³)

Figure 2. Depth density profiles measured along the GOW core (solid circles) and used for the EMT core (open circles).

tions [*Mosley-Thompson*, 1980; *Mosley-Thompson and Thompson*, 1982]. For both methods, some subjectivity is unavoidable, either in identifying visible layers or in assigning dust peaks to specific years.

Corrections to account for vertical strain due to ice flow were not made to either core. Using the model of *Paterson and Waddington* [1984], the error thus introduced is estimated at a few percent at 100 m depth. At South Pole, the effect may be much less because the top 100 m of firn is permeable and compactable. Compared to other uncertainties, the effect of vertical strain is small and may be neglected.

To account for densification, the measured layer thicknesses are converted to water equivalent (w.e.) thicknesses using the corresponding densities for each depth interval. *Hogan and Gow* [1997] used a combination of density measurements made by A.J. Gow [*Kuivinen et al.*, 1982] and *Giovinetto* [1960]. *Mosley-Thompson* [1980] densities were derived from a theoretical depth-density relationship (W. Dansgaard, personal communication, 1977) later verified empirically [*Mosley-Thompson*, 1980]. Both profiles are shown in Figure 2, and there are no important differences at depths greater than ~15 m. For the near-surface layers, the profiles of firn density are somewhat different, which could affect calculated accumulation rates since ~1900 A.D. The resulting accumulation records (Figure 3) are dominated by interannual fluctuations obscuring any significant long-term trends. Before eliminating this noise by filtering or averaging, it is important to discuss the potential for missing layers and limitations to layer identification.

Dating errors arise when an annual layer (1) is missed during the counting, (2) is absent from the core and thus unknown to the analyst, and/or (3) is considered annual when, in reality, the layer represents only part of a year. Layers may be missed in the core for two reasons. First, during core drilling some fraction of the core is not recovered as some of the firn may be

chipped and shattered at the beginning of each drill run. Second, core loss may occur where the core breaks, either between drill runs or within individual sections recovered in each drill run. Breaks in one core section can occur at zones of weakness, which in cold, dry snow are commonly associated with the depth hoar layers. In this case, there is a potential for both a loss of mass and, to a lesser extent, the removal of an annual marker (e.g., depth hoar layer). It is also possible that a break in the core will occur where the annual dust peaks exists (a more random process).

Missing annual layers pose a problem for all cores, regardless of the method of layer identification. During some years, an entire annual layer may be missing as a result of wind scour and erosion or because of lack of accumulation [*Gow*, 1965]. The effect of such a hiatus in the record is an underestimation of the age of deeper layers. For South Pole, a 6-year record of annual accumulation along a 42-pole pentagon established in January 1958 [*Giovinetto and Schwerdtfeger*, 1966] indicates ~4% probability for a hiatus year to occur [*Mosley-Thompson et al.*, 1995]. A more recent analysis of 236 stake-height measurements for 5 years (1992-1997) suggests a lower probability, ~1% [*Mosley-Thompson et al.*, 1999]. These measurements also indicate a significantly higher accumulation rate in recent years so this lower estimate for the number of missing years may not apply to most of the period covered by the core records. Moreover, estimates of missing years are based on comparatively small numbers of observations and the actual percentage may be larger than estimated from the pole measurements. For the present discussion, a pessimistic estimate of 5% for zero-accumulation years is adopted.

Annual layers in the core may not be identified if the snow containing the "seasonal" marker is missing. For example, a
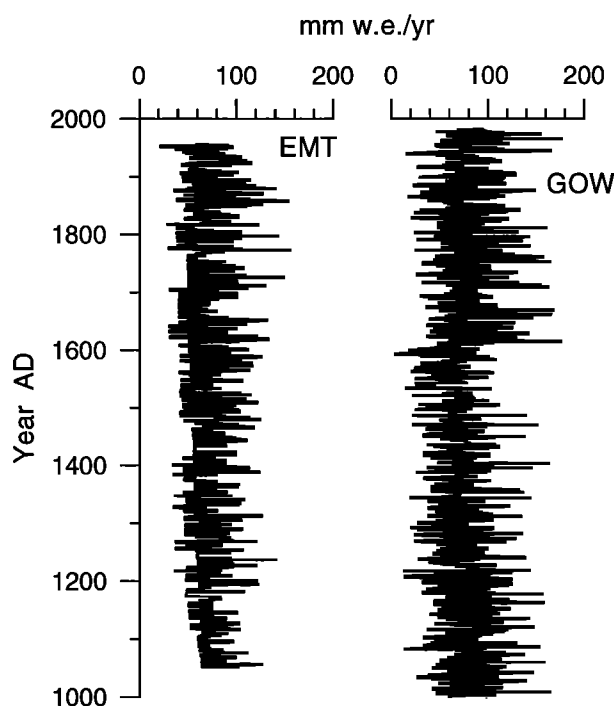

Figure 3. Two records of annual accumulation considered in this study.

year could be missed if no fall depth hoar or its coarse-grained equivalent formed or if the spring "dust-rich" snow is preferentially removed or never deposited at the site. The result would be an unusually thick annual layer. Conversely, during some years, a secondary peak in dust concentration or multiple depth hoar units may be erroneously identified as an annual horizon, resulting in an overestimation of the number of years. For neither core were attempts made to establish absolute dating horizons (e.g., by identifying volcanic ash layers or their chemical signatures), and it is not possible to quantify the effect of ambiguous stratigraphic markers on the derived timescale.

No seasonal indicator, whether chemical or physical, is 100% faithful, as all are subject to some degree of disturbance. Ideally, one would like to measure multiple indicators on a single core but this is not always practical. Constraining cores with known time-stratigraphic horizons (e.g., volcanic eruptions) is an excellent approach but can also be tricky, particularly when there are multiple, closely spaced events and the core is not analyzed continuously from top to bottom. In fact, during the 13th century, there were three volcanic events that distributed aerosols globally. *Langway et al.* [1988] found a volcanic time marker dated 1259 A.D. in ice cores from Greenland and Antarctica. At South Pole, this signal was found at a depth of 87.8 m in a core collected in 1978. In a core collected 5 years later (1983), a very strong acid signal was detected at 87.9 m [*Delmas et al.*, 1992]. In the 1984 GOW core, the date of 1259 A.D. is at a depth of 86.10 m. These differences in depth of the contemporaneous horizon most likely reflect spatial differences in accumulation, since the cores were drilled at different locations in the vicinity of South Pole Station. In the EMT record, the 1259 A.D. horizon was assigned to a depth of 81.7 m. Accounting for additional surface accumulation from 1974 to 1984 would increase this depth by ~2 m of firn. It is not immediately obvious whether this shallower depth of the 1259 time horizon in the EMT core is significant, as it was drilled in 1974 exactly at the construction site for the South Pole Dome. Thus it is very likely that the EMT drill site was compressed by the movement of heavy equipment in the area, and, in fact, the access pipe to this drill hole is located directly under the dome. Since 1974, the entire area has been disturbed by vehicle traffic and construction and maintenance of the runway and possible wind effects from the station itself. Simply comparing depths of a known horizon in different cores ignores these complications and cannot be used solely as a reliable indicator for the quality of any single-core record. A better approach for assessing reliability is to consider the frequency distribution of annual layer thickness (Figure 4).

A problem of the EMT record is highlighted by the discreet minimum levels of accumulation (Figure 3). Moreover, the EMT record lacks years of near-zero accumulation, and there are no accumulation values less than 20 mm water equivalent per year (mm w.e./yr) (Figure 4). These accumulation minima result from the discrete nature of the sample sizes cut for the dust analyses. Samples ranged in length from 15 to 18 mm and were cut as small as possible to still meet the volume requirement for the Coulter counter analysis. On average, years with accumulation less than ~30 mm w.e. cannot be resolved. The GOW record contains 45 annual layers with a thickness of 30 mm w.e. or less, while according to EMT, there are seven such layers. Thus the dust identification technique may have missed ~40 years.

Comparison of the two frequency distributions in Figure 4 shows that GOW includes a greater number of thick layers than
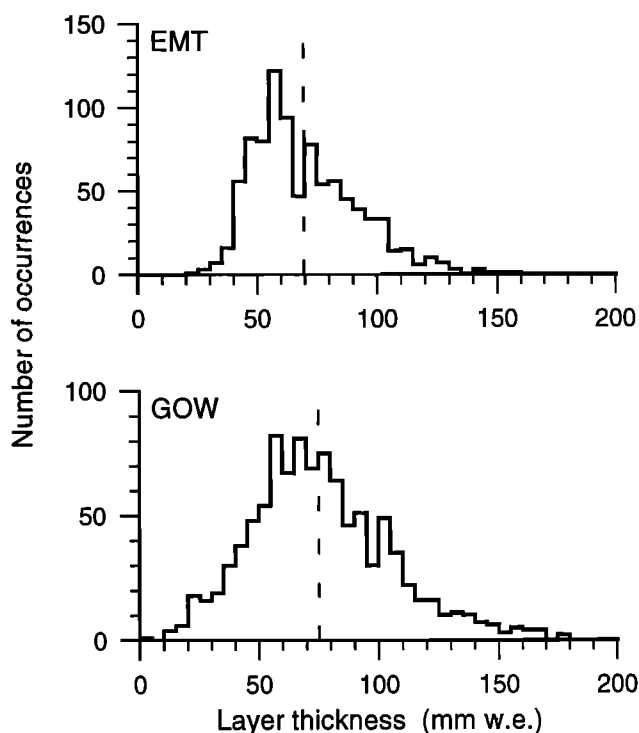

Figure 4. Frequency distribution of the two accumulation records shown in Figure 3.

EMT. There may be two explanations. It is possible that during high accumulation years, a secondary peak in dust is deposited and erroneously identified, adding an extra year to the record. On the other hand, there may be certain visible stratigraphic layers that were missed. This would lead to an overestimate of the layer thickness. Either possibility is likely. Considering the long-term average accumulation rate of each core allows the relative number of years missing or added to each core to be evaluated.

The average accumulation rate using dust is somewhat smaller (70 mm w.e./yr) than using depth hoar/coarse-grained equivalent layers (75 mm w.e./yr). Given the close proximity of the two records and the length of time considered (906 years), these averages should be the same. This is because the spatial pattern of surface accumulation is advected across both drill sites and preserved in the records with a time lag much smaller than the length of each record. Assuming that the EMT value is closer to the true average, a total of ~70 years appears to be missing from the GOW record (in addition to missing years with zero accumulation). On the other hand, if the GOW average is more realistic, the EMT record must contain ~64 years too many.

Summarizing, there are some possibly significant uncertainties associated with the timescales of both records. As a result, even the long-term average accumulation rate is not well constrained. It is not immediately obvious how these uncertainties affect the interpretation of the core records and their correlations. To evaluate the importance of these effects, the true accumulation history must be known, but this cannot be inferred from the records because of the unknown number of missing layers. However, the procedure may be reversed and "synthetic" records of accumulation can be analyzed.

The question to be addressed is how well the true accumulation signal is preserved in each core record. To investigate this,
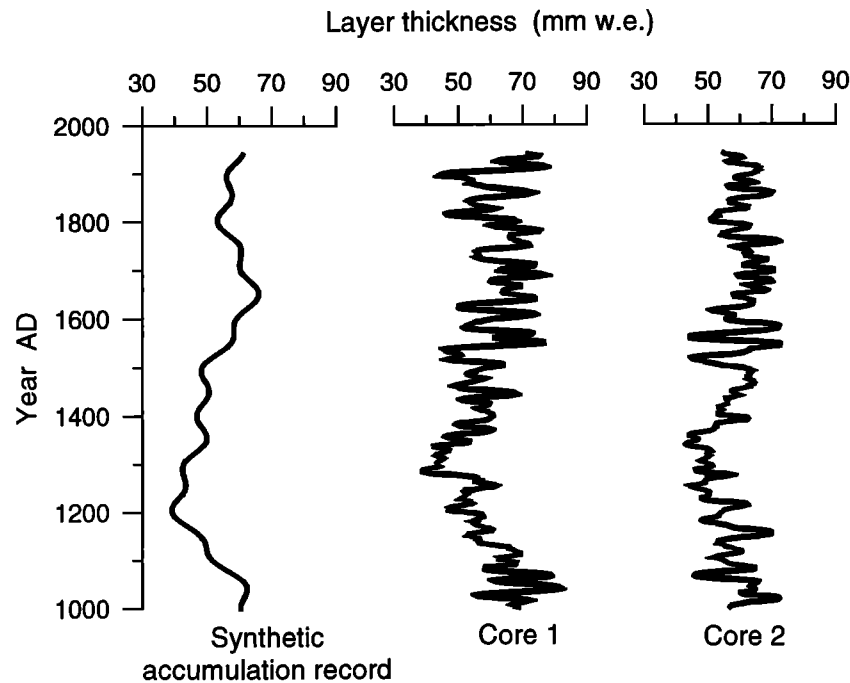
Figure 5. Original accumulation signal (left) and two artificial core records (smoothed with a 5-year Gaussian filter) containing the original signal plus contributions from random variability, the effect of surface irregularities and interpretation errors. For further explanation, see text.

two artificial core records are considered. First, the synthetic accumulation signal shown in Figure 5 (left) was created by adding four arbitrarily chosen harmonic components (with periods 100, 300, 700, and 1200 years). This signal represents long-term trends in accumulation associated with climate variations and surface topographic effects. For the present analysis, the precise form of this record is not important. Second, random fluctuations associated with interannual variability in snowfall are superimposed on the climate signal. These fluctuations are the same for both cores and can be included by adding a random term generated using standard random-number generators [*Press et al.*, 1992, p. 270ff] scaled to give a standard deviation of 20 mm w.e./yr. Third, the contribution to noise in the stratigraphic record from small-scale surface irregularities such as sastrugi is included by adding another random term, different for each core. The standard deviation of this contribution is also 20 mm w.e./yr, so the net standard deviation of the two records is 28 mm w.e./yr, comparable to the values obtained directly from the two core records (EMT, 22 mm w.e./yr; GOW, 29 mm w.e./yr). The result of this procedure is two stratigraphic records of the true synthetic accumulation history.

The next step is to create core records by accounting for the dating errors discussed above. First, all layers with zero or negative accumulation (~55 for the 1000-year records, corresponding to the pessimistic estimate of 5% as discussed above) are eliminated in both cores. For core 1, 50 randomly chosen layers are combined with the preceding layer (to preserve net accumulation) to account for missed stratigraphic horizons. For core 2, all layers with a thickness <20 mm w.e. (~70 additional layers) are merged with the layer above. This elimination of thinner layers describes approximately the effect of the discrete sampling method used for the EMT record. In addition, 50 ran-

domly chosen layers with a thickness >80 mm w.e. are split in two to account for secondary microparticle peaks misidentified as annual markers in core 2. Because the accumulation signal shown in Figure 5 (left) is of primary interest, each final core record is correlated with this signal to evaluate the accuracy of these records. Results of these correlations are given in Table 1.

The correlation coefficients in Table 1 show that only a modest amount of smoothing is sufficient to bring out the actual accumulation signal. This is further illustrated by the two smoothed records in Figure 5. Thus, despite considerable difficulties associated with establishing accurate timescales for ice cores, it appears that accumulation records derived from cores are sufficiently well correlated with the true accumulation history to preserve the important trends.

Table 1. Coefficients of Determination r^2 of the Linear Fit Between the Synthetic Accumulation Record and Two Synthetic Ice Core Records Obtained as Discussed in Text.

Width years	Core 1	Core 2
0	0.818	0.865
2	0.964	0.974
5	0.985	0.986
10	0.992	0.991
20	0.994	0.993

The width refers to the standard deviation of the Gaussian smoothing function.

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3. Correlation Between the South Pole Records

Interannual variability dominates both the EMT and GOW records (Figure 3), making it necessary to perform some smoothing or filtering to reduce the noise level. *Mosley-Thompson* [1980] applies filtering in the frequency domain. That is, Fourier transformation is applied to the original data to determine all frequencies contributing to the measured record. After removing frequencies corresponding to periods <10 years, the inverse Fourier transformation yields the filtered signal. The problem with this approach is the tendency to introduce or amplify periodicities close to the cutoff frequency, as demonstrated by the filtered record of *Mosley-Thompson and Thompson* [1982, Figure 3]. *Hogan and Gow* [1997] use a 20-year moving average to eliminate interannual noise from their record. However, as pointed out by *Mosley-Thompson and Thompson* [1982], the equally weighted running mean may exhibit a negative response at certain frequencies, turning a maximum into a minimum or vice versa [cf. *Holloway*, 1958]. In the present study, Gaussian smoothing is applied, corresponding to a running-mean average with a Gaussian weighting function (with standard deviation ranging from 2 to 50 years) to eliminate this negative response as much as possible. Other smoothing schemes could be adopted, but because the goal here is to compare the two records, the precise nature of the smoothing procedure is not very important, provided the same process is applied to both records.

Smoothed records of accumulation are shown in Figure 6. On casual inspection, GOW and EMT appear to have little in common and there are no obvious synchronous trends. This suggests that the longer-term variations in accumulation recorded in both cores are primarily associated with the spatial pattern in accumulation. To investigate this possibility in a more quantitative manner, the cross correlation coefficient between the two records needs to be evaluated.

The two accumulation records consist of N annual values G_t and E_t ($t = 1,..., N$; the value of N depends on the width of the Gaussian weighting function). Introducing a time lag of K years, an estimate of the cross-covariance coefficient at lag K is provided by

$$C_{GE}(K) = \begin{cases} \dfrac{1}{N}\sum_{t=1}^{N-K}(G_t - \overline{G})(E_{t+K} - \overline{E}) \\ \qquad\qquad K = 0, 1, 2, ... \\ \dfrac{1}{N}\sum_{t=1}^{N+K}(G_{t-K} - \overline{G})(E_t - \overline{E}) \\ \qquad\qquad K = 0, -1, -2, ... \end{cases}$$

where $\overline{G}$ and $\overline{E}$ represent the sample means of the two series [e.g., *Box et al.*, 1994, p. 411]. Defining

$$S_G = \sqrt{C_{GG}(0)} \quad,$$

$$S_E = \sqrt{C_{EE}(0)} \quad,$$

as estimates for the variance of each record, an estimate for the cross-correlation coefficient at lag K is

$$R_{GE}(K) = \frac{C_{GE}(K)}{S_G S_E} \quad, \quad K = 0, \pm 1, \pm 2, ...$$

To obtain a useful estimate of the cross-correlation coefficient, at least 50 pairs of observations are needed [*Box et al.*, 1994, p. 412]; for the smoothed records, the minimum number of pairs is 707 (50-year Gaussian smoothing).

Calculated cross correlation coefficients as a function of the lag (in years) are shown in Figure 7. The time lag K between the two cores is defined such that for the negative values along
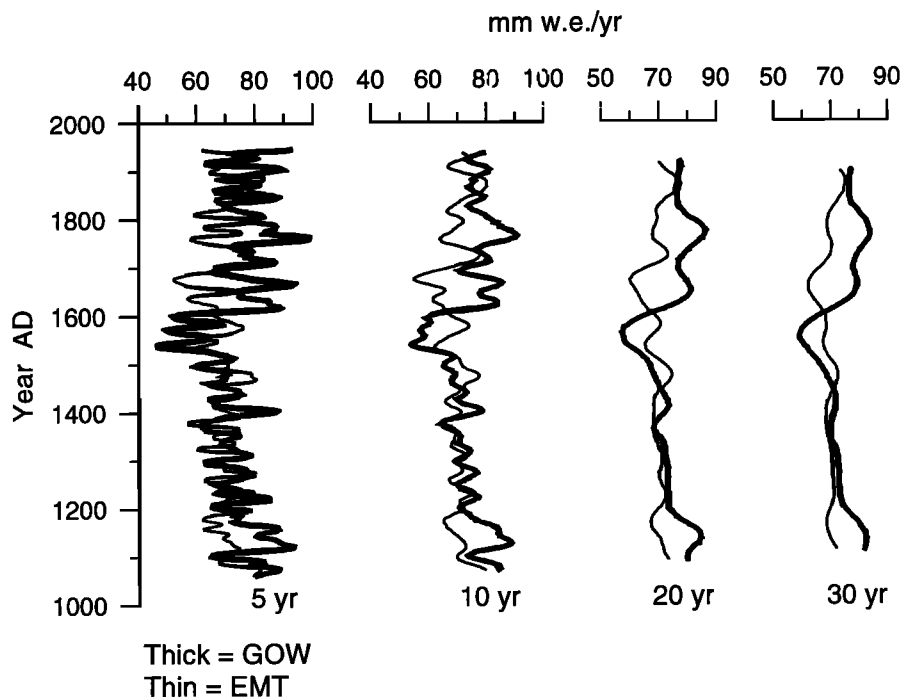
mm w.e./yr

Thick = GOW
Thin = EMT

Figure 6. Comparison between the two South Pole accumulation records using different degrees of smoothing. For each record, Gaussian smoothing was applied, with the labels indicating the standard deviation of the smoothing function.
Figure 7. Correlation between GOW and EMT as a function of lag.
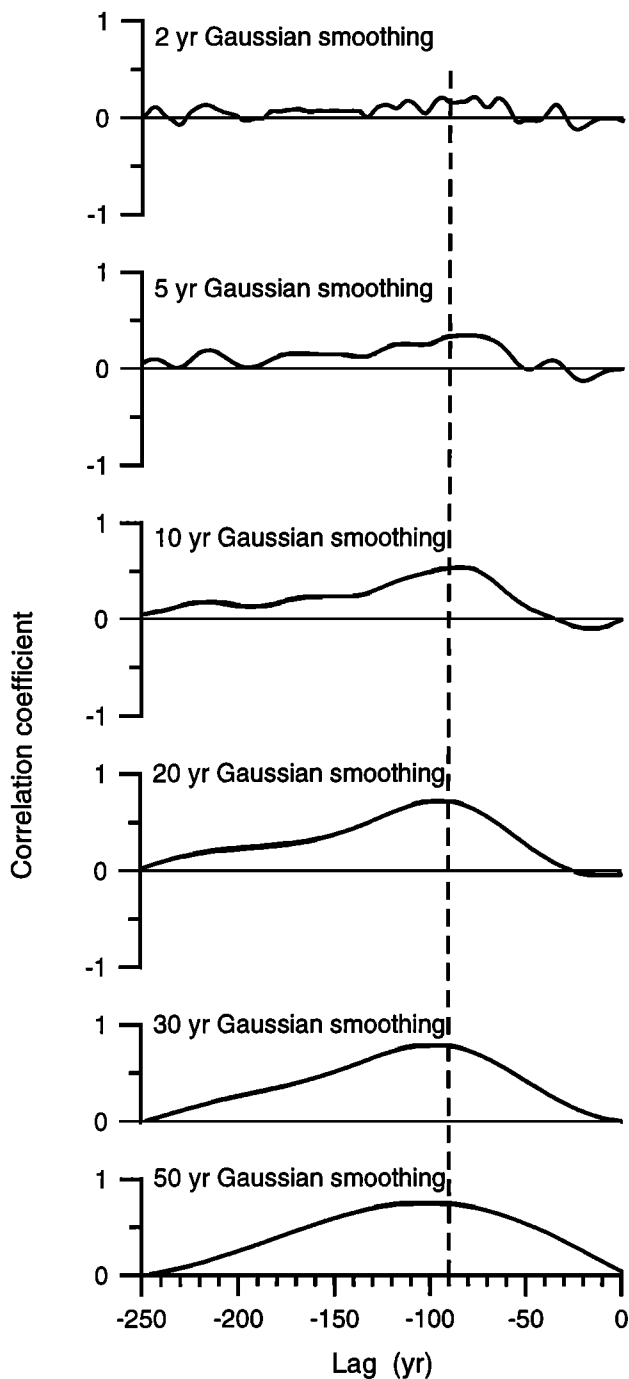
Figure 7. Correlation between GOW and EMT as a function of lag.

the horizontal axis, GOW leads EMT. Further, a positive value of R_{GE} indicates that an increase in GOW is accompanied by an increase in the lagged EMT record.

There are two processes that may contribute to the long-term trends in accumulation evident in the core records (Figure 6), namely, actual changes in accumulation rate and the effect of a topographically induced surface accumulation pattern migrating through each core. Both are expected to result in distinct correlations between the two core records. Ignoring problems associated with dating, the timescale represents the year during which a particular layer was deposited at the surface. Thus any climatic trend in accumulation should result in a correlation at

zero time lag between the two cores. According to the curves in Figure 7, the cores are uncorrelated for zero time lag, indicating that, over the period considered (1050-1956 A.D.), there were no significant changes in accumulation rate at South Pole. Instead, the correlation coefficient increases smoothly as the lag increases, reaching a maximum for a time lag of ~-90 years.

The magnitude of the time lag for which the correlation coefficient between the two records reaches a maximum is of the same order as the uncertainty in the dating. The negative sign of the time lag indicates that GOW leads EMT and the lag could reflect ~90 years missing from EMT. However, as noted above, comparison of the long-term average accumulation rates of each core indicates that either GOW is missing ~70 years or EMT has ~64 years too many. Thus the inferred negative time lag for maximum correlation cannot be explained as being the result of dating uncertainties. Instead, the lagged correlation between the two cores suggests that a spatial pattern of accumulation was advected by ice flow and recorded in each core.

The GOW drill site is ~370 m downstream of the EMT site (Figure 1). The ice speed at South Pole as determined from repeat Global Positioning System measurements in the early 1990s is ~11 m/yr (G. Hamilton, personal communication, 1999), and snow deposited at a given location on the surface is found at greater depth (i.e., farther back in time) in GOW than in EMT. The 900-year record reflects surface deposition over a horizontal distance of ~10 km upstream of the drill sites. With a time lag of 90 years, the speed with which the spatial pattern appears to be advected is ~(370 m / 90 years) or ~4 m/yr. This advection rate is about half the ice advection velocity, indicating that the spatial pattern in accumulation has migrated across the surface. Because the surface topography has a complex two-dimensional structure, the migration rate cannot be estimated. For example, a local circular topographic high may migrate in the upwind direction, as well as being advected with the ice flow. At South Pole, the two directions are nearly perpendicular and the migration rate along the prevailing wind direction cannot be evaluated without full knowledge of the spatial structure of the accumulation distribution. It should be noted, however, that this difficulty does not affect the main conclusion, namely, that variations preserved in both ice core records reflect the effect of a spatial pattern in accumulation migrating across the surface.

4. Surface Topography and Accumulation

In 1992, a network of 236 poles was established at South Pole to study the spatial and temporal variability in accumulation rate [*Mosley-Thompson et al.*, 1995]. The network consists of six lines, each 20 km long and radiating out from the station (centered on Skylab, marked 2 in Figure 1), with poles placed at 500-m intervals. In November 1993, a differentially corrected Global Positioning System (GPS) survey was conducted to determine position and elevation at each pole site. Additional elevation data were acquired in 1994 along two traverses connecting the six pole lines. Because of logistic constraints, these data were obtained using a handheld barometer. Consequently, the derived elevations are less accurate than those from GPS measurements. For the present purpose of describing the topography around South Pole, both data sets were combined to produce the map shown in Figure 8 (first published by *Mark* [1995]).

The topographic map in Figure 8 shows large-scale undulations with a typical amplitude of a few meters and a length scale of several kilometers. According to observations else-
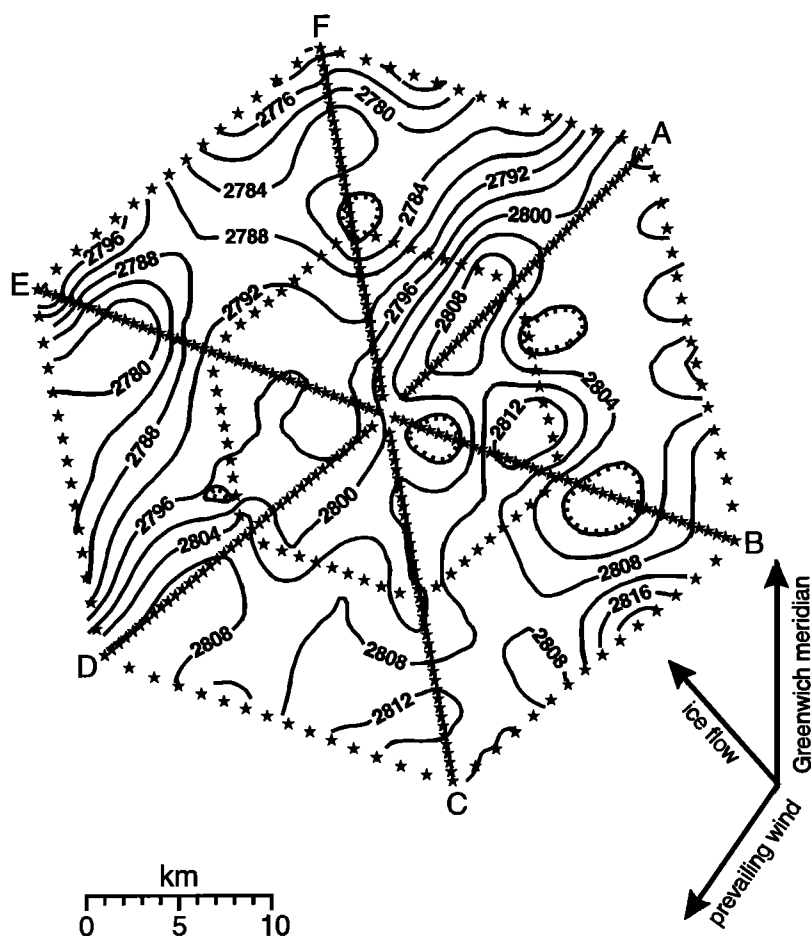
Figure 8. Topographic map of the South Pole region, based on Global Positioning System surveys (radial lines) and barometry (two circular traverses at 10 and 20 km from South Pole). Contour interval is 4 m.

where, such topographic features interact with winds in the surface layer to produce spatial variations in net accumulation [*Black and Budd*, 1964; *Whillans*, 1975]. These observations indicate that accumulation of snow is related to the slope of the surface in the direction of the prevailing wind. *Black and Budd* [1964] found that minimum deposition occurs downwind of surface crests while accumulation maxima occur somewhat downwind of topographic lows. For the South Pole region, the effect of topography on net accumulation can be evaluated by considering data for accumulation and elevation along lines A and D, oriented along the prevailing wind direction (Figure 8).

Surface elevation and relative accumulation along these lines are shown in Figure 9. Accumulation rates represent 5-year averages of annual pole-height measurements. To eliminate variability associated with spatial irregularities such as sastrugi, averages from five adjacent poles (a distance of 2 km) are shown in Figure 9. This additional averaging is needed because small-scale surface relief may persist over several years, owing to the low annual accumulation. This surface relief leads to apparent variations in accumulation rate [cf. *Van der Veen and Bolzan*, 1999] that are not relevant to the present discussion.

Comparison of the two curves in Figure 9 shows that there is a relationship between accumulation and surface topography. Generally, accumulation rate decreases on the upwind side of topographic highs. On the lee side of surface hills, more snow

is deposited. The data shown in Figure 9 are insufficient to derive a significant statistical correlation but qualitatively support earlier observations by *Black and Budd* [1964] in the Wilkes Land region of East Antarctica. The stake measurements confirm the existence of important variations in net surface accumulation in association with topographic undulations in the South Pole region.

To correlate the two core records with specific topographic features would require detailed modeling of the evolution of the surface over the past millenium. Because snow is preferentially deposited in areas where the surface slope decreases, the topography evolves over time and undulations may migrate in the upwind direction. *Black and Budd* [1964] estimate that the migration rate is ~25 m/yr in Wilkes Land. Applying their model to the Byrd Station strain network, *Whillans* [1975] arrives at a migration rate of ~20 m/yr. At the same time, the spatial pattern is advected in the downflow direction by glacier flow. The combined results of these two effects is recorded in the ice cores. Without conducting detailed modeling and mapping time variations in topography, the net effect cannot be quantified. Nevertheless, the topographically induced variations in accumulation rate observed along the pole network are comparable to changes recorded in the ice cores. This observation gives credence to the conclusion from the correlation between the EMT and GOW cores, namely, that most of the variations
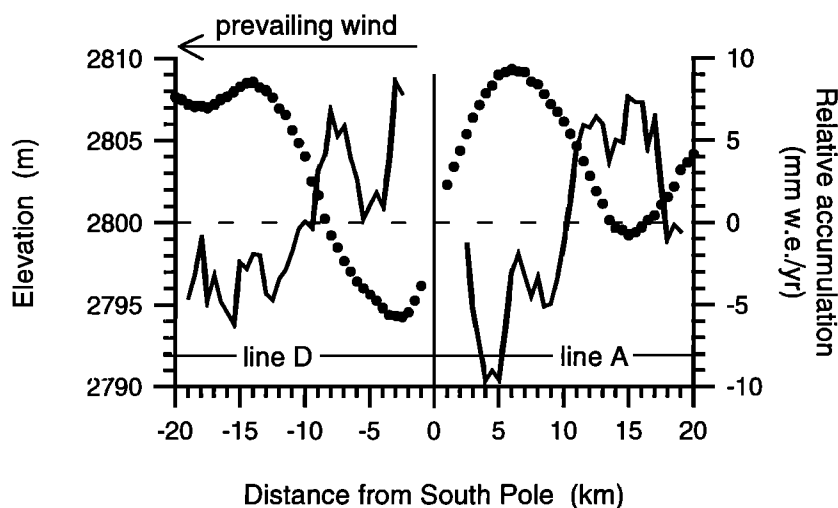
Figure 9. Surface elevation (solid circles, scale at left) and relative accumulation (solid lines, scale at right) along the A and D lines shown in Figure 8.

recorded in these cores are associated with the spatial pattern in accumulation rather than with climate changes.

5 Conclusions

Accumulation records preserved in ice cores are characterized by large interannual variability associated with year-to-year fluctuations in snowfall and with spatial variability from small-scale surface features such as sastrugi. These variations, which are not of interest for studying long-term climate changes, can be removed from the record by applying moderate smoothing (e.g., using a Gaussian weighting function with a standard deviation of ~5 years). The resulting smoothed record represents the convolution of climatically significant trends in snow accumulation and the effect of surface topography on snow deposition. The importance of each effect can be assessed if multiple-core records are available.

Comparison of two 906-year records of annual accumulation shows that no significant climatic changes have occurred at South Pole over the period 1050-1956 A.D. There is no correlation between the two records at zero time lag, as would be expected if large-scale, climatically driven changes in accumulation had occurred. Instead, the maximum correlation coefficient is at a time lag of ~-90 years such that the downflow core (GOW) leads the upflow core (EMT). This result is consistent with a spatial pattern of accumulation being advected by ice flow and preserved in each core.

Studies conducted in other regions of Antarctica have established a relation between surface topography and snow deposition, resulting from the interaction between topographic undulations and winds in the surface layer. Detailed topographic mapping of the South Pole region shows important surface relief as well as a spatial pattern in net accumulation. There appears to be a connection between topography and accumulation, although there are insufficient data to establish a quantitative relation. Apparently, this spatial pattern is documented in the ice core records and appears to be the main contributor to observed accumulation trends in the absence of regional changes driven by climate.

To eliminate topographic effects from a single-core record, significant smoothing would be required, as illustrated by the

smoothed records shown in Figure 6. At South Pole, the spatial scale of surface undulations is of the order of 20 km (Figure 8). If stationary, one wavelength in accumulation would reflect ~1800 years in a single core. Accounting for migration of the pattern in accumulation across the surface, the time period over which a single record would have to be smoothed to eliminate all spatial effects becomes ~3600 years. Such a degree of smoothing would almost certainly eradicate most of the climate signal as well. As it turns out, there are no significant climate trends in the South Pole records, but this result cannot be assumed a priori for other sites. A more satisfactory approach to identifying past changes in climate (e.g., accumulation) is to obtain at least two cores and correlate the resulting records, as done in this study. The benefit of unambiguous interpretation outweighs additional logistical efforts and expenses.

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