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Spatial variability of climate and past atmospheric circulation patterns from central West Antarctic glaciochemistry

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Abstract. Atmospheric circulation patterns and the spatial variability of atmospheric chemistry and moisture transport in central West Antarctica are investigated using new 40 year long (1954-1994 A.D.) glaciochemical and accumulation rate records developed from four firn cores from this region. The core sites lie on a 200 km traverse from 82° 22' S, 119° 17' W to 81° 22' S, 107° 17' W. The glaciochemical records represent the major ionic species present in Antarctic snow: Na^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, NO_3^-, and SO_4^{2-}. High spatial variability appears in comparisons of full record averages and poor intersite linear correlation results. Accumulation rates show 50-100% changes over distances of 50-100 km and sea-salt concentrations drop by 50% between the middle two sites. One likely contributor to the high variability seen at this spatial scale is variability in synoptic- and finer-scale meteorology. Empirical orthogonal function (EOF) analysis shows that 80% or more of the variance in site chemistry can be attributed to two types of air masses: winter season air (50-70% of site variance) with a strong marine signature (heavy loading of sea-salt species) and summer season air (21% of the variance), marked by marine biogenic non-sea-salt SO_4 plus NO_3. This pattern of winter and summer regimes appears at other West Antarctic sites suggesting it may apply to the entire region. We show that a general picture of the patterns of variability in West Antarctica can best be drawn by using an analysis technique that fully exploits high resolution, multiparameter, multisite data sets.

1. Introduction

The global climate system is inherently complex and the details of its functioning remain poorly understood. Direct observational and instrumental records are limited both spatially and temporally, extending back approximately 200 years in the Northern Hemisphere and only 30-40 years in the Antarctic. Thus to better understand the details of global climate requires both improved spatial coverage and longer proxy records. Antarctic ice cores provide one means to extend the proxy record.

Antarctica plays a vital role in dynamic linkages connecting the complex components of the global climate system (for example, atmosphere, cryosphere, hydrosphere) [*U.S. ITASE Steering Committee*, 1996]. West Antarctica, in particular, may be the most climatologically and glaciologically dynamic area of the continent [*WAIS Committee*, 1995]. This sector receives about 40% of the moisture transported into the continent [*Bromwich*, 1988] and has the Antarctic's highest interannual variability, possibly because of an El Niño-Southern Oscillation (ENSO) connection [*Cullather et al.*, 1996]. Yet the scarcity of climate records keeps this region relatively poorly understood.

Evidence from instrumental records indicates that different parts of the continent are affected by separate components of the atmospheric circulation [*U.S. ITASE Steering Committee*, 1996]. The high interior plateau is influenced by vertical transport from the upper troposphere and stratosphere. The remainder of the continent is connected more to lower tropospheric transport, such as the cyclonic systems around Antarctica which often move southward over the ice sheet. Central West Antarctica, in particular, is strongly influenced by warm air advecting southward and upslope onto the polar plateau as seen in automatic weather station (AWS) and other regional weather data [*Hogan*, 1997]. This warm air brings higher concentrations of marine aerosols and a significant amount of the moisture transported to this region [*Bromwich*, 1988; *Hogan*, 1997].

To better understand the complex climatology of West Antarctica, high-resolution glaciochemical and accumulation rate records have been developed from firn cores at four sites in central West Antarctica (CWA) for the period 1954-1994 A.D. The sites (Table 1 and Figure 1) are located along a 200 km traverse in central West Antarctica, gaining elevation from 950 to 1930 m. Originally labeled BC2, BC5, BC3, and BC4 in the field, the site names have been changed to Sites A, B, C, and D, respectively, for ease of understanding. Site A is at the lowest elevation and closest to the Ross Sea. The sites are referred to collectively as the CWA sites.

2. Methods

2.1. Sample Preparation and Laboratory Analysis

High-resolution, subannual sampling was performed on each core from the surface down to a depth of 11 to 18 m depending on site accumulation rate (initially estimated from *Bull* [1971]

Table 1. CWA Core Sites

	Depth, m	Latitude, °S	Longitude, °W	Elevation, m
Site A (BC2)[a]	93.53	82 22.03'	119 17.13'	950
Site B (BC5)	90.05	82 05.51'	115 13.34'	1310
Site C (BC3)	50.24	81 46.82'	111 20.19'	1690
Site D (BC4)	50.56	81 22.34'	107 16.50'	1930

[a] Original site names as assigned in the field.

and refined using average accumulation rates calculated from β-activity profiles). Core subsections were cut lengthwise to a 3.5 x 3.5 cm cross-section, scraped to remove surface contamination, then cut into 3 cm long continuous samples. At 8 to 12 samples per year, depending on depth, this resulted in 1811 samples (for the study period 1954-1994) for laboratory analysis.

Chemical measurements made on all the collected samples included all major ionic species present in Antarctic snow (Na^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, NO_3^-, SO_4^{2-}) [*Legrand and Delmas*, 1984]. Determination of anions and cations at trace levels was performed by ion chromatography (for example, [*Mayewski et al.*, 1987]). Samples were analyzed on a Dionex 4000 series instrument using suppressed ion chromatography. Cations were analyzed with a CS12 column, 0.125 μL loop, and 20 mM MSA eluent. Anions were analyzed on a Dionex AS11 column with a 75 μL loop; the eluent was 6 mM NaOH.

Utilizing the standard seawater ratios of Na, Cl, Ca, K, Mg, and SO_4, these species were partitioned into sea-salt (ss) and non-sea-salt (nss) components yielding new series for dating and analysis (see *O'Brien et al.* [1995] for details). The sea-salt fraction is a tracer for the marine influence on air masses, that is, the fraction of the aerosols that is of marine origin. The non-sea-salt fraction represents other sources for these species, for example, biogenic, crustal, volcanic, or anthropogenic.

2.2. Dating

The samples were dated with a combination of seasonal peaks present in the chemistry data and chronostratigraphic horizons provided by atomic bomb testing fallout peaks as verification points to check the accuracy of annual peak counts. Fallout peaks were found by measuring the gross β-activity of 25 cm long samples for the depth range 6-16 m (Figure 2). Antarctic β-activity profiles have an absolute maximum during the austral summer of 1964/1965 [*Crozaz*, 1969] representing the global peak level reached prior to the 1963 Atmospheric Test Ban Treaty. There is an approximate one year delay in transport to Antarctica for fallout products [*Picciotto and Wilgain*, 1963]. The next most prominent peak in the β-activity profiles is in 1954/1955 and is due to the thermonuclear tests of March 1954 (the Castle series) and the subsequent temporary atmospheric testing moratorium of November 1958 to September 1961 [*Koide et al.*, 1982; *Pourchet et al.*, 1983]. This deeper peak is seen at Sites A and C (Figure 2), but higher accumulation rates at Sites B and D place this horizon below the range sampled for β-activity.

Annual peaks were identified using four seasonal indicators ($nssSO_4$, NO_3, ssNa, and the Cl/Na ratio) derived from the original and partitioned chemistry species. Since the cores were collected during December 1994/January 1995, the surface samples tie the start of the time series to austral summer. Each of these indicators has been used for dating at other sites in

Antarctica (for example, South Pole [*Whitlow et al.*, 1992]) and verification of similar species timing at the CWA sites required only a simple comparison of the near-surface samples to their expected summer season values. Missing surface core at Sites A and B (the top 17 and 25 cm, respectively) made the verification more subjective at these sites.

Non-sea-salt SO_4 (summer) and NO_3 (spring/summer) comprise the primary seasonal indicators. The main contributor to $nssSO_4$ seasonal variability in Antarctica is marine biogenic emissions which peak during the summer season [*Herron*, 1982; *Whitlow et al.*, 1992]. Surface values at the CWA sites show either a distinct recent peak or a well-developed upward trend confirming the summer season peak. Nitrate peaks during spring/summer in Antarctica [*Mayewski and Legrand*, 1990; *Mulvaney and Wolff*, 1993; *Whitlow et al.*, 1992] though the linkages between atmospheric NO_3 concentrations and snow concentrations are not well understood [*Legrand and Kirchner*, 1990; *Wolff*, 1995]. The spring/summer NO_3 peak is likely related to the sedimentation of polar stratospheric clouds (PSCs) which releases NO_3 into the polar troposphere where it can be removed by precipitation to the snow surface [*Mayewski and Legrand*, 1990]. Nitrate surface values behave similarly to $nssSO_4$ surface values at the CWA sites, confirming the seasonal timing for this species.

Two secondary seasonal indicators are ssNa (winter) and the Cl/Na ratio (summer). As seen at coastal sites (for example, Neumayer [*Wagenbach*, 1996]), near-coastal sites (for example, J-9 [*Herron*, 1981]) and at South Pole [*Whitlow et al.*, 1992], ssNa reaches its peak in Antarctica due to increased winter storm activity. The timing of ssNa is confirmed by the low values seen in the near-surface samples at the CWA sites. The Cl/Na ratio is useful as a secondary summer indicator [*Whitlow et al.*, 1992] because additional summertime input of Cl as HCl [*Legrand and Delmas*, 1988] keeps the relative level of Cl higher resulting in a summer peak in the Cl/Na ratio. Surface values at Site C showed the expected high levels. The other sites were ambiguous at the surface but matched well with deeper $nssSO_4$ peaks. Both of these indicators were used only to confirm peaks found in $nssSO_4$ and NO_3 because ssNa had multiple peaks during some years (likely due to nonwinter season storms) which also affected the Cl/Na ratio.

Initial counting of years was done using $nssSO_4$ and NO_3 independently to produce two sets of annual peaks. The two sets were merged by combining the $nssSO_4$ peaks and the unique NO_3 peaks (those that did not match a $nssSO_4$ peak). Each of the annual peaks from the merged peak set was then matched to a peak in the Cl/Na ratio and a trough in ssNa to be sure that there was at least one cycle present in these records between each proposed annual peak. Of the 160 annual peaks (four cores by 40 years), 84% were identified in both $nssSO_4$ and NO_3; the remainder (18 peaks) were found in just one of these species. Verification of the annual peak counts against chronostratigraphic horizons in the β-activity profiles indicates a dating uncertainty of approximately one year for all of the cores. Subannual uncertainty is present in all cores because we do not have enough knowledge about species arrival times within each season to know how to assign the seasonal peaks more accurately.

2.3. EOF Analysis

Climate variables are frequently found to be influenced by multiple concurrent processes, for example, the effects of
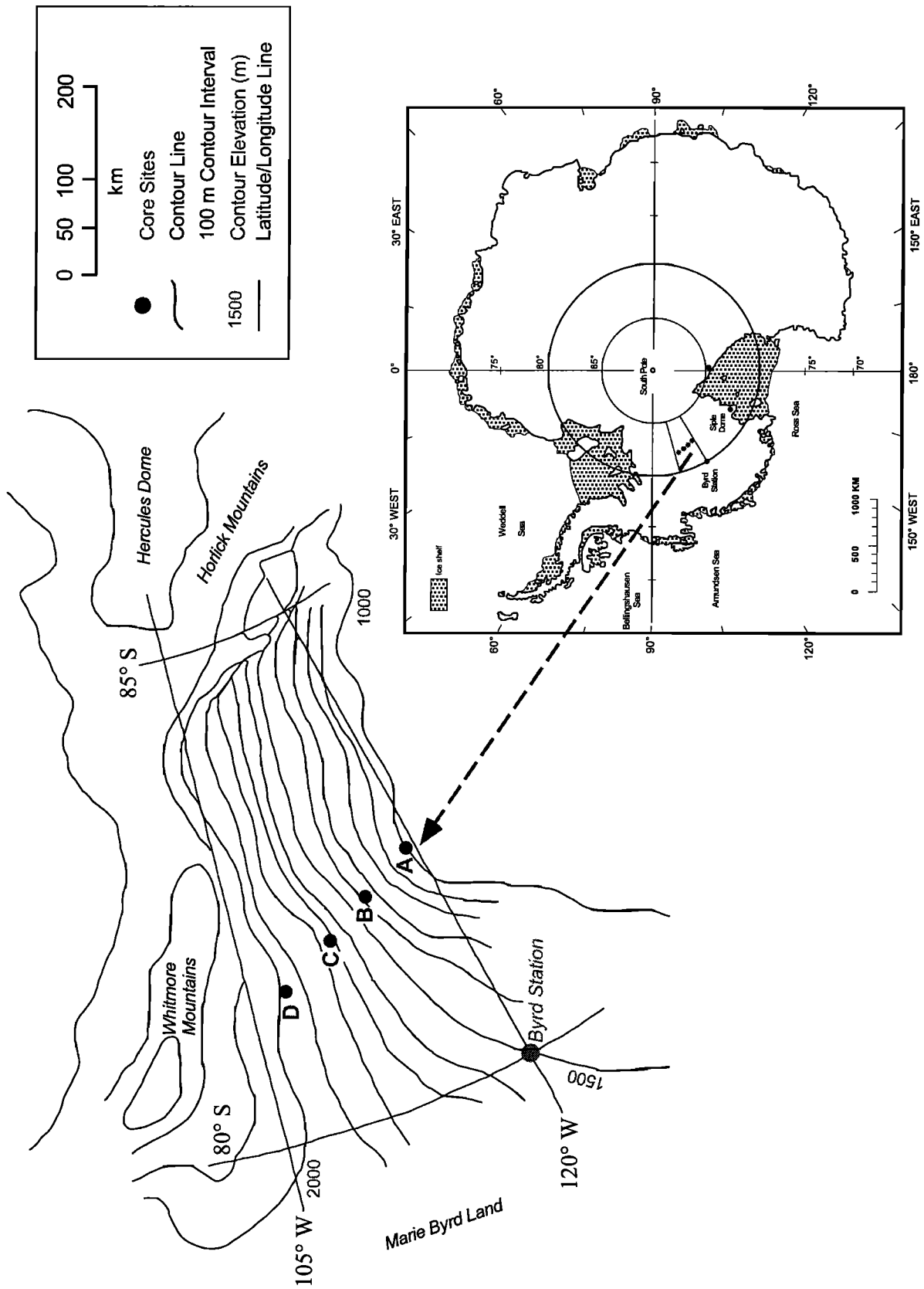
Figure 1. Overview (inset) and detail maps of site locations (A to D). Based on maps in *Scott Polar Research Institute* [1983].
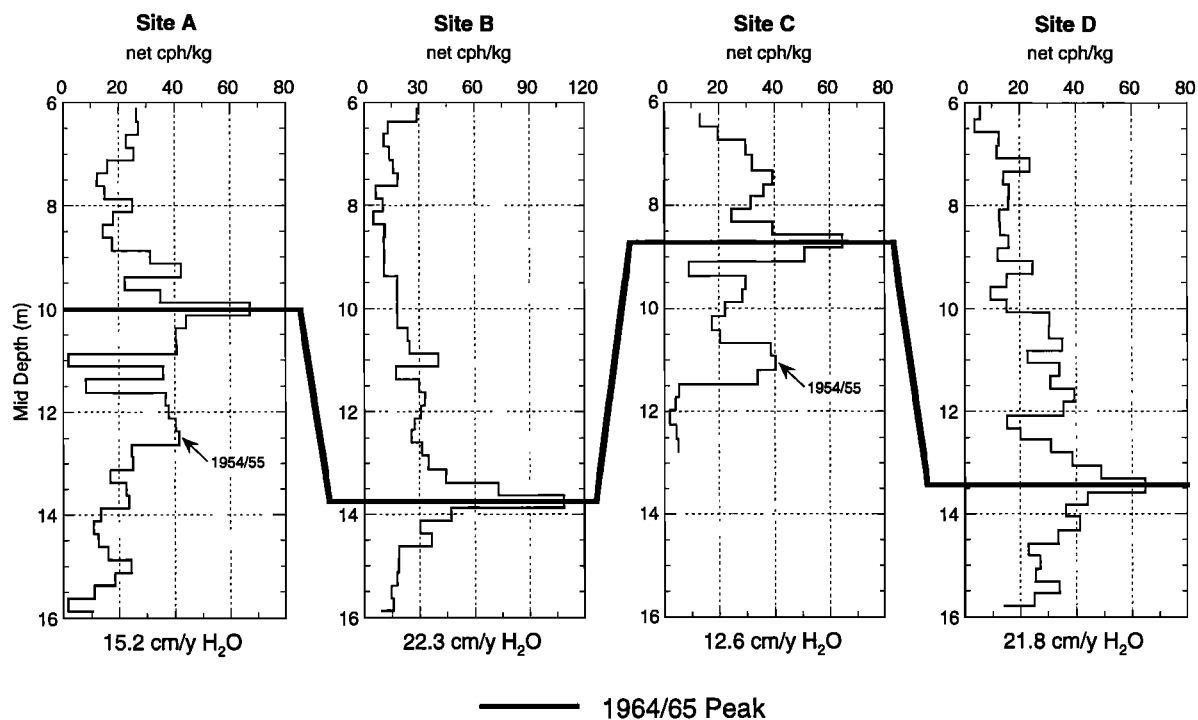
Figure 2. Gross β-activity results for each site based on 25 cm long sampling from 6 to 16 m. Note scale change for Site B. Depth of 1964/1965 chronostratigraphic horizon shown by horizontal line across graphs. Average annual accumulation rate based on depth of this horizon is shown beneath each graph.

temperature and elevation on precipitation. Empirical orthogonal function (EOF) analysis provides a means to reconstruct these underlying processes through decomposition of the variability in a multiparameter climatic data set. Unlike simple linear correlations, the variability in the entire data set is examined concurrently by EOF analysis allowing extraction of common responses and simplifying interpretation of underlying processes. EOF modes (orthogonal axes in the data space) describe the linear combinations of observations which are most efficient in explaining the variance in the data [*Meeker et al.*, 1995]. When a given EOF mode accounts for a large amount of the variance in one or more of the variables, it is likely that an underlying physical process is involved [*Peixoto and Oort*, 1992]. EOF analysis is used in an attempt to associate glaciochemical records with underlying climate variables (for example, *Mayewski et al.* [1994]). Associated time series of the EOF modes describe the temporal evolution of the climate variables [*Meeker et al.*, 1995].

2.4. Species Concentration Versus Estimated Species Flux

Estimated species flux has been used to try to account for the effects of accumulation rate on species concentrations [*Meeker et al.*, 1997]. Determining whether to use flux or concentration as the more appropriate measure is an important issue, one that requires testing the relationship between species concentrations and accumulation rate. Linear regression provides a simple test (for example, [*Kreutz and Mayewski*, 1998; *Yang et al.*, 1995]), but EOF analysis of these variables provides more information on the relationship. If these climate variables are related, EOF analysis should produce a mode with high variance for both chemistry and accumulation rate (with an inverse relationship). Analyses of the CWA data showed the variance for concentrations and for accumulation rate in separate modes

indicating no relationship. EOF analysis of first differences of these variables found no relationship between changes in concentration and changes in accumulation rate. These results show that concentration is, at best, only weakly associated with accumulation rate, counter to the simple flux model which predicts an inverse relationship. Thus there is no clear reason to favor estimated flux over concentration, and concentrations appear to be mostly independent of accumulation rate. This implies that the air masses that bring the chemistry are not necessarily accompanied by significant moisture (that is, accumulation). These tests also show that the accumulation records are an additional source of useful information independent of the concentration records. For these reasons, we emphasize analyses based on accumulation rates and species concentrations, not estimated species flux.

3. Results

3.1. Accumulation Rates

Annual accumulation rates in units of cm H_2O equivalent were calculated for each site on the basis of the depths of annual peaks and per meter densities measured for each core (Table 2 and Figure 3). Normalizing to H_2O equivalents removes differences caused by density variations. Full record (1954-1994) averages divide the sites into high (Sites B and D) and low (Sites A and C) accumulation sites. Interannual variability is significant based on the coefficient of variation which varies from 26 to 39% (Table 2). A simple comparison of average accumulation rates for the first half (1954-1973) and second half (1974-1994) of each record shows the largest changes at the lower accumulation sites where the rate decreased by 15-18% in the second half (Table 2).

Table 2. Average Accumulation Rates for 1954-1994 (in cm H_2O equivalent) With Coefficient of Variation, a Measure of Interannual Variability

	Average 1954-1994[a]	Coefficient of Variation	Average 1954-1973	Average 1974-1994	% Change	Average 1955-1980	Average 1985-1994	% Change	Average 1955-1965[b]	Average 1975-1985[b]	% Change[b]	Local Average[a,c]
Site A	13.9 (5.2)	36.8%	15.0	12.8	-15.7	14.7	12.2	-17.0	14.0	13.5	-3.6	15.0 (2.5)
Site B	22.5 (8.2)	36.1%	22.6	22.5	-0.5	24.3	19.2	-21.0	20.6	25.8	25.2	12.6 (2.1)
Site C[d]	11.4 (4.5)	39.3%	12.5	10.2	-18.4	12.0	8.5	-29.2	12.3	11.9	-3.3	12.1 (2.1)
Site D	20.1 (5.2)	25.8%	20.3	20.0	-1.5	19.4	21.0	8.3	20.1	18.9	-6.0	12.8 (2.3)

Averages for 1954-1973 and 1974-1994 show changes between the first and the second halves of the high-resolution records.
[a] One standard deviation shown in parentheses.
[b] For comparison with *Morgan* [1991].
[c] The local average is based on the average accumulation rate for four to seven sites from *Bull* [1971], each within 100 km of each of the CWA sites.
[d] The record for Site C starts in 1955 A.D.

The averages at the two higher accumulation sites show a negligible (<2%) decrease during the second half. When each record is examined for extended periods of above or below average values, a common time period emerges for Sites A, B and C: average accumulation rates during 1985-1994 were 17 to 29% below the 1955-1980 average for each site. Site D rose by 8% during this period. These changes all fall within one standard deviation of the 1955-1980 mean at each site, suggesting that they are also within the range of normal temporal variability and do not necessarily represent significant change.

Significant temporal changes have been postulated at other Antarctic sites. Accumulation rate data from four East Antarctic sites [*Morgan et al.*, 1991] show a recent minimum around 1960. A comparison of a recent average (1975-1985) to the decade of the minimum at these sites (1955-1965) showed 23-43% increases between these two decades [*Morgan et al.*, 1991]. Comparisons for the same time periods for the CWA data (Table 2) show small decreases (<6%) between these decades at all sites except Site B (which had a 25% increase). These results indicate that at least in the short term, recent accumulation rates have decreased at most of the CWA sites, though the changes are relatively small. The increase at Site B appears to be more the result of two exceptional years (1979-1980) than a reflection of an actual trend (excluding these years reduces the increase to only 5%).

The variety of possible conclusions from using different subintervals of the CWA records suggests that the temporal trends of accumulation rate in West Antarctica cannot be adequately assessed with such relatively short records. Extrapolation of trends to a larger region is questionable because of the significant interannual variability at these sites which makes it unclear whether the observed changes exceed the range of natural variability in this area. Longer records are required to establish the proper context for recent changes.

3.2. Glaciochemistry

Plots of glaciochemistry (Figure 4) and summary statistics (Table 3) show significant variability in all species at all sites. Sodium and Cl concentrations are an order of magnitude higher than the K, Mg, and Ca levels, indicative of a strong marine influence and weak and/or remote crustal sources. The 1963 eruption of Agung appears as a small baseline increase in subsequent years of the SO_4 records. Interannual variability is also high, especially in the sea-salt-dominated species at Site B. Smoothing with robust splines helps to assess variability on decadal timescales (Figure 5). Robust splines smooth time series without being influenced by large sporadic events, unlike running means [*Meeker et al.*, 1995]. Intersite comparisons of smoothed chemistry show a distinct lack of similarity between sites over time as shown by the Na and SO_4 records (Figure 5). While there are some periods when the chemistry at adjacent sites looks similar, there are few times when all sites are the same. The heterogeneity at this scale is examined further using long-term averages, linear correlations, and EOF analysis.

4. Discussion

4.1. Spatial Variability

4.1.1. Moisture transport. The high spatial variability of this region is easily seen in the full record (1954-1994) average accumulation rates, which reflect changes in moisture transport.
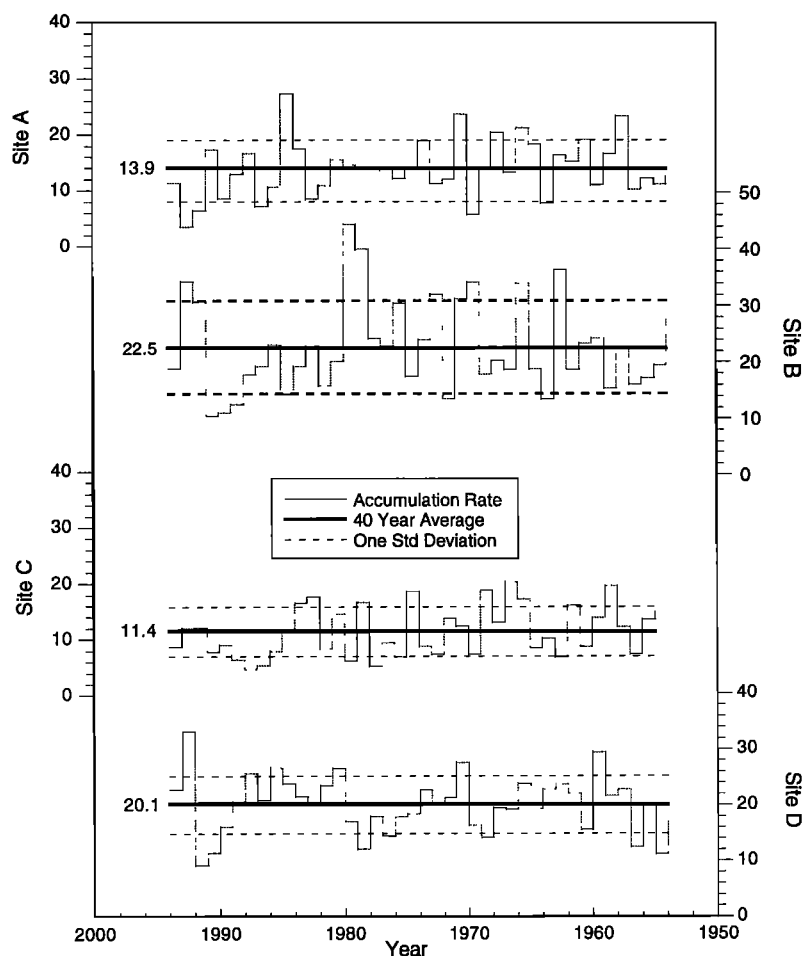
Figure 3. Site annual accumulation rate records in centimeters H_2O equivalent/year. Thick horizontal line represents the full record average (value shown at the left end of the line). Dashed horizontal lines represent one standard deviation from the average.

The site-to-site variability is remarkable with 50-100% changes between one site and the next over distances of 50 to 100 km (Table 2 and Figure 6a). A simple gradient in accumulation rate does not exist along this transect, moving either inland or upslope. Error bars in Figure 6a suggest that Sites B and D (Sites A and C) have comparable high (low) accumulation rates. A limited spatial context is possible through comparison with *Bull's* [1971] compilation of Antarctic accumulation rate data. (This comparison is also limited by not knowing the time periods of the older data.) Table 2 includes an average of sites within 100 km of each of the CWA sites derived from Bull. The lower accumulation CWA sites, Sites A and C, compare well with the older data, while the high accumulation sites, Sites B and D, are both well above the local spatial average. The sites nearest Site B on Bull's accumulation rate map have rates roughly half that of Site B. The differences for Site D are less dramatic, and some years at this site likely fall within the variability of the adjacent sites based on standard deviations. These large spatial variations in accumulation rate may be due to variability in factors such as the location and intensity of the warm air advection pattern [*Hogan*, 1997], ENSO [*Chen et al.*, 1996], the poorly understood small-scale topography of the area, and the strength and frequency of penetration of air masses from the Weddell Sea. This sector of West Antarctica (105°-120° W by 80°-85° S) is

also an area of mesoscale cyclone generation, though at lower frequency than more westerly areas [*Carrasco et al.*, 1997]. Significant precipitation and/or major drifting can result from these storms.

4.1.2. Average concentrations. Full record (1954-1994) averages were also used to examine spatial variability of the glaciochemistry. The topography of the site region (increasing elevation upslope from the Siple Coast, Figure 1) implies that a decreasing gradient in concentration might exist moving inland and upslope from the Ross Sea. Increasing elevation reduces concentrations as species are removed through wet deposition related to orographic effects. Sea-salt-influenced species (Na, Cl, Ca, K, and Mg) also decrease with increasing distance inland as the marine source areas become more remote and coarse sea-salt aerosols are deposited through fallout [*Legrand and Delmas*, 1985]. Implicit in these relationships is an assumption that the average storm track direction in this region is roughly parallel to the line of core sites. This assumption is incorrect as shown by ground observations (for example, [*Weyant*, 1967]), automatic weather stations (AWS), back trajectory analysis of midtropospheric flow [*Harris*, 1992], and satellite data [*Carrasco et al.*, 1997; *Hogan*, 1997]. Data from AWS also indicate that warm air advects from the Amundsen and Bellingshausen Seas across the coast and upslope near the ice divide in central West
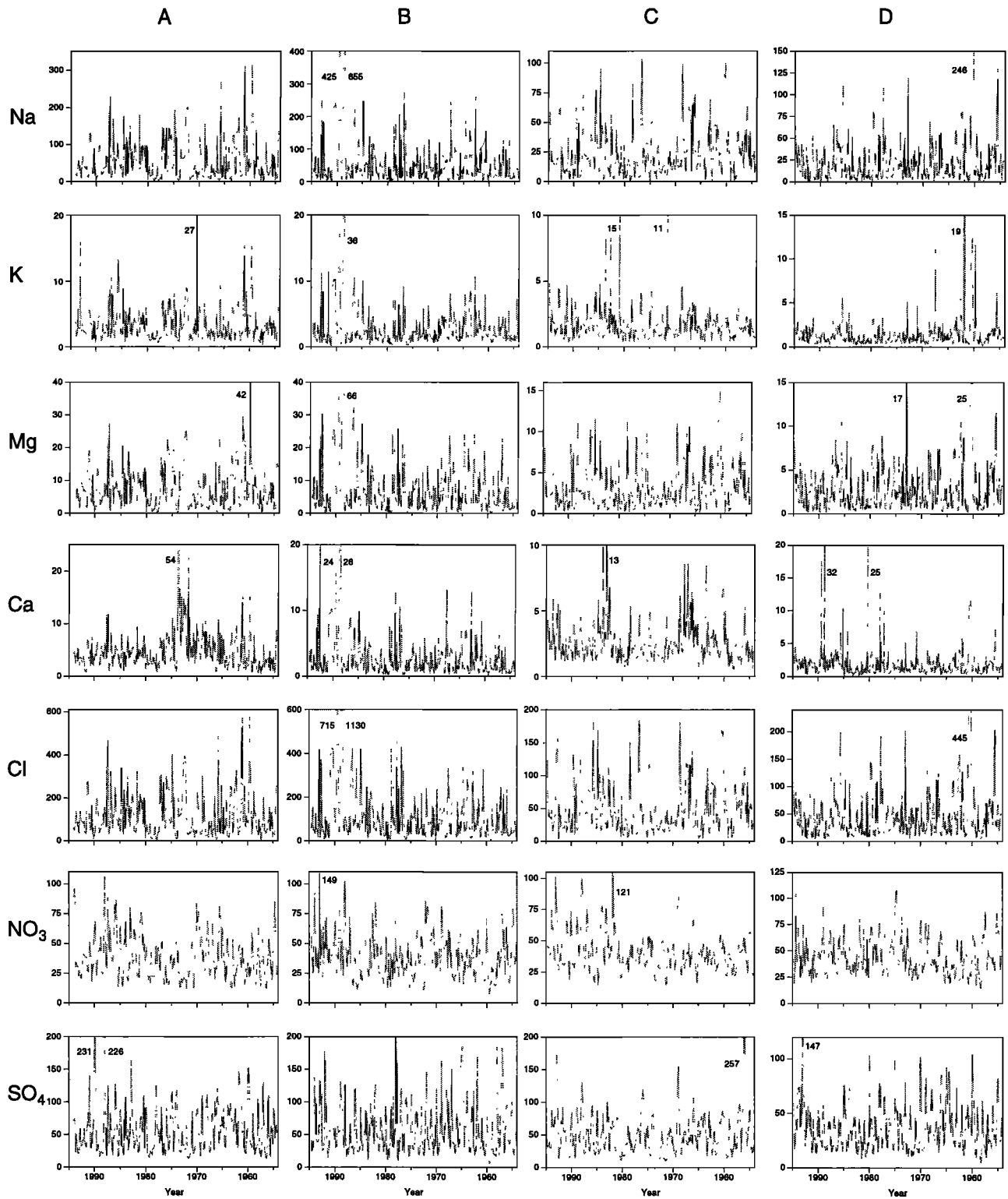
Figure 4. Glaciochemistry by species (rows) and site (columns) for 1954-1994. All values are in ppb (ng/g). Numbers within the plots indicate off-scale values.

Antarctica (upslope from Siple Coast), with diminishing effects downslope toward the Ross Ice Shelf [*Hogan*, 1997]. This implies that the core sites are at least partly exposed to marine air coming from a near-perpendicular direction (from ~120°-150° W versus ~150°-180° W), that is, the Amundsen Sea.

Between Sites B and C, a distance of only 70 km and an elevation gain of less than 400 m, average concentrations for the sea-salt-dominated species Na and Cl drop by approximately 60% (Figure 6b). The values are approximately the same at Sites A and B and at Sites C and D. The sea-salt fraction, ssNa,

Table 3. Summary of Major Ion Chemistry Concentrations (ppb) for 1954-1994

	Na	K	Mg	Ca	Cl	NO$_3$	SO$_4$
Site A (n=408)	55.2 (53.5)	3.3 (2.7)	7.5 (6.4)	4.7 (4.1)	113.9 (100.1)	37.9 (18.0)	55.6 (35.1)
variability[a] (%)	45	35	44	44	44	29	34
precision[b] (%)	2.3	4.2	4.0	5.3	3.0	0.8	1.3
Site B (n=539)	52.7 (69.7)	2.7 (3.1)	6.9 (8.0)	2.6 (3.0)	106.7 (121.1)	38.9 (18.6)	59.1 (40.2)
variability (%)	73	67	64	62	65	24	32
precision (%)	2.8	3.4	5.6	8.8	1 0	1.2	1.8
Site C (n=331)[c]	24.6 (22.3)	1.8 (1.4)	3.4 (3.0)	2.7 (1.7)	50.4 (40.3)	40.9 (16.2)	50.5 (32.1)
variability (%)	46	27	46	36	42	23	39
Site D (n=533)	21.6 (25.6)	1.4 (1.7)	2.8 (2.9)	1.9 (2.4)	44.3 (45.5)	44.8 (16.6)	37.2 (22.2)
variability (%)	59	61	51	48	54	22	28
South Pole[d]						113 (22.8)	54.6 (19)
variability (%)						20	35
RIDS95C[e]						39.9 (12.8)	53.2 (34.8)
variability (%)						32	65
Siple Dome[f]						35 (18.9)	114 (105)
variability (%)						54	92

One standard deviation shown in parentheses; n is the number of samples analyzed. Selected data for other West Antarctic sites presented are for comparison.
[a] Refers to interannual variability and is the coefficient of variation of annually resampled time series.
[b] Precision is the average coefficient of variation of duplicate analyses (24 for Site A, 34 for Site B).
[c] Site C record starts in 1955.
[d] South Pole data from E. Meyerson (personal communication, University of New Hampshire, 1997).
[e] RIDS95C is near Byrd Station at 80 °S, 119 °W. Data from Kreutz et al. [1998].
[f] Siple Dome data from Kreutz and Mayewski [1998].

behaves similarly (Figure 6c). These data suggest that a stronger (weaker) marine sea-salt influence regime is found at Sites A and B (Sites C and D). Hogan's synthesis of observational data [1997] indicates that all of the CWA sites lie in the warmest region of interior West Antarctica (see Hogan [1997], Figure 5). Because the warm air is typically associated with higher sea-salt concentrations, the drop in concentration from Site B to C may reflect a boundary between the region of warm air and its surroundings. Such a boundary does not appear in European Center for Medium Range Weather Forecasts (ECMWF) meteorology data (700 mbar winds, 1985-1995 seasonal averages), but this may be due to its relatively low spatial resolution. Intersite EOF analyses of ssNa support the existence of a relationship or common (unknown) process between Sites C and D. Using annually resampled data, EOF1 accounts for 76% and 81% of the variance for Sites C and D, respectively, and 43% of the total variance in the combined ssNa data set. However, the EOF analyses do not help in explaining the high values at Sites A and B since these sites are partitioned into separate EOF modes.

A space-time plot of ssNa (Plate 1) clearly shows both the existence of temporal variability in the sea-salt concentrations and that Sites A and B typically have the highest values (red and yellow shades) as expected from the averages. Plate 1 also shows that there are some years where Sites C and D have values comparable to or exceeding the levels at Sites A and B (for example, 1959). This may represent variability in the path of the warm air advection, and its higher sea-salt levels, or a higher number of intrusions of marine sea-salt air from the Weddell Sea.

Average SO$_4$ shows similar behavior to the sea-salt species from Site B to C but with only a 15% decrease (Figure 6b). Unlike the sea-salt species, SO$_4$ continues to drop from Site C to D with a 27% decrease. This is likely related to the stronger influence of the non-sea-salt component on this species since this fraction makes up 77-88% of the average total SO$_4$. Average concentrations for nssSO$_4$ are approximately the same for Sites

A, B, and C but decrease by nearly 30% between Sites C and D (Figure 6d). When annual averages are examined, Site D is significantly higher than Site C during only four years. This pattern in nssSO$_4$ may reflect seasonal differences in the sea-salt-dominated and nssSO$_4$-dominated circulations as well as differences in aerosol removal processes.

The exception to these spatial trends is NO$_3$ which shows no significant changes between individual sites and only a small overall increase from Site A to D (~7 ppb, Figure 6b). The lack of a strong gradient suggests that the source area is roughly equidistant from each site, that transport from multiple source areas at different distances is offset by different strengths of transport to each site, or that NO$_3$ is well mixed in the atmosphere over this region. It is also possible that NO$_3$ concentrations are reduced by reemission to the atmosphere after deposition which would tend to smooth spatial variability [Mayewski and Legrand, 1990]. The relatively small distances between sites (~200 km) both support a well mixed atmosphere for NO$_3$ and argue against different transport strengths and multiple source areas. Equidistant sources are generally supported by what is known about NO$_3$ transport in Antarctica, namely that the primary transport path is through the polar stratosphere [Mayewski and Legrand, 1990; Mulvaney and Wolff, 1993]. Multisite EOFs for NO$_3$ provide little additional information about site relationships showing little spatial structure and supporting NO$_3$ being fairly well mixed by the time it arrives at the CWA sites.

Katabatic winds from both East Antarctica and from more northerly (but still inland) portions of West Antarctica may also be affecting CWA NO$_3$ and nssSO$_4$ since the study area is either within or on the fringe of the confluence zone of these winds [Carrasco et al., 1997; Parish and Bromwich, 1997]. Winds from East Antarctica may transport NO$_3$ and nssSO$_4$ with stratospheric (and lower latitude) origins from the polar plateau to the CWA region. West Antarctic katabatic winds may
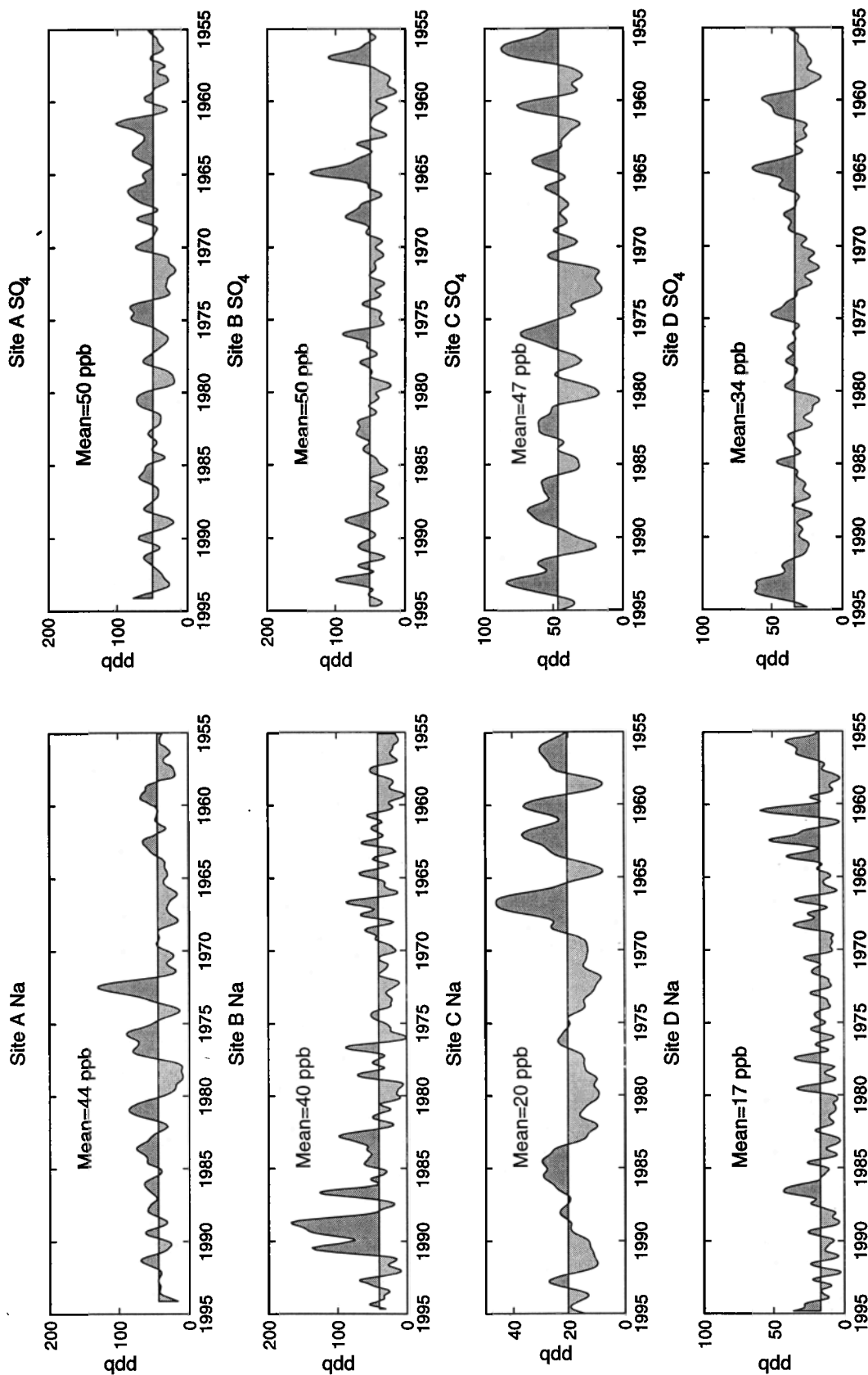
Figure 5. Smoothed Na and SO$_4$ at all sites with values in ppb (ng/g). Original data for both species was smoothed using robust splines, approximately 84% (λ = -0.05 to -0.13) for Na and 76% (λ = -0.07 to -0.1) for SO$_4$. Mean concentration of the smoothed data is shown in each plot and also used to show periods of above or below average concentration.
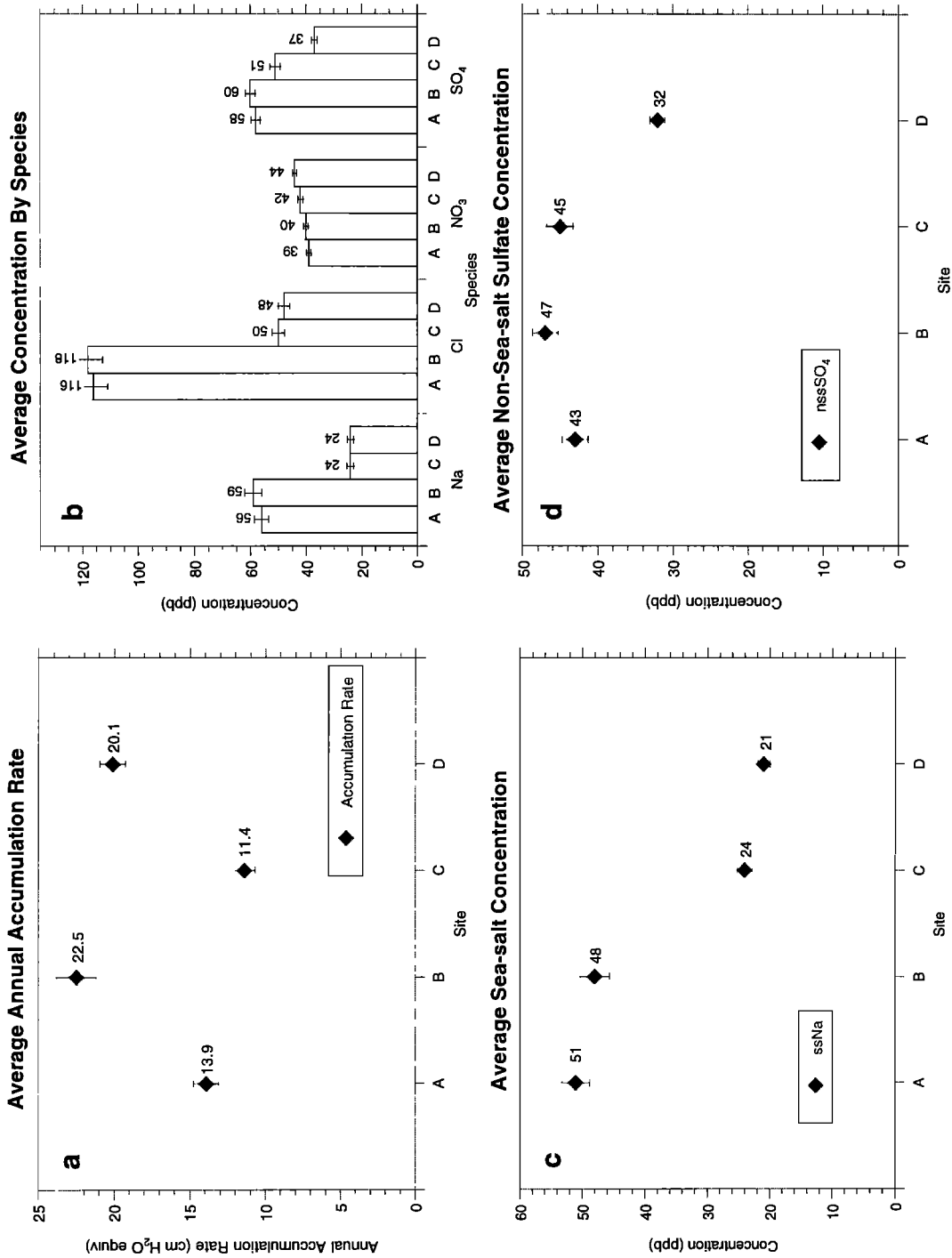
Figure 6. Full record averages (1954-1994 A.D.): (a) Annual accumulation rates. (b) Na, Cl, NO_3, and SO_4. Na and Cl are shown as representative of the sea-salt dominated species. (c) Sea-salt Na representing the sea-salt fraction of each sample. (d) Non-sea-salt SO_4 showing the drop from Site C to D. Error bars show the standard error of the mean.
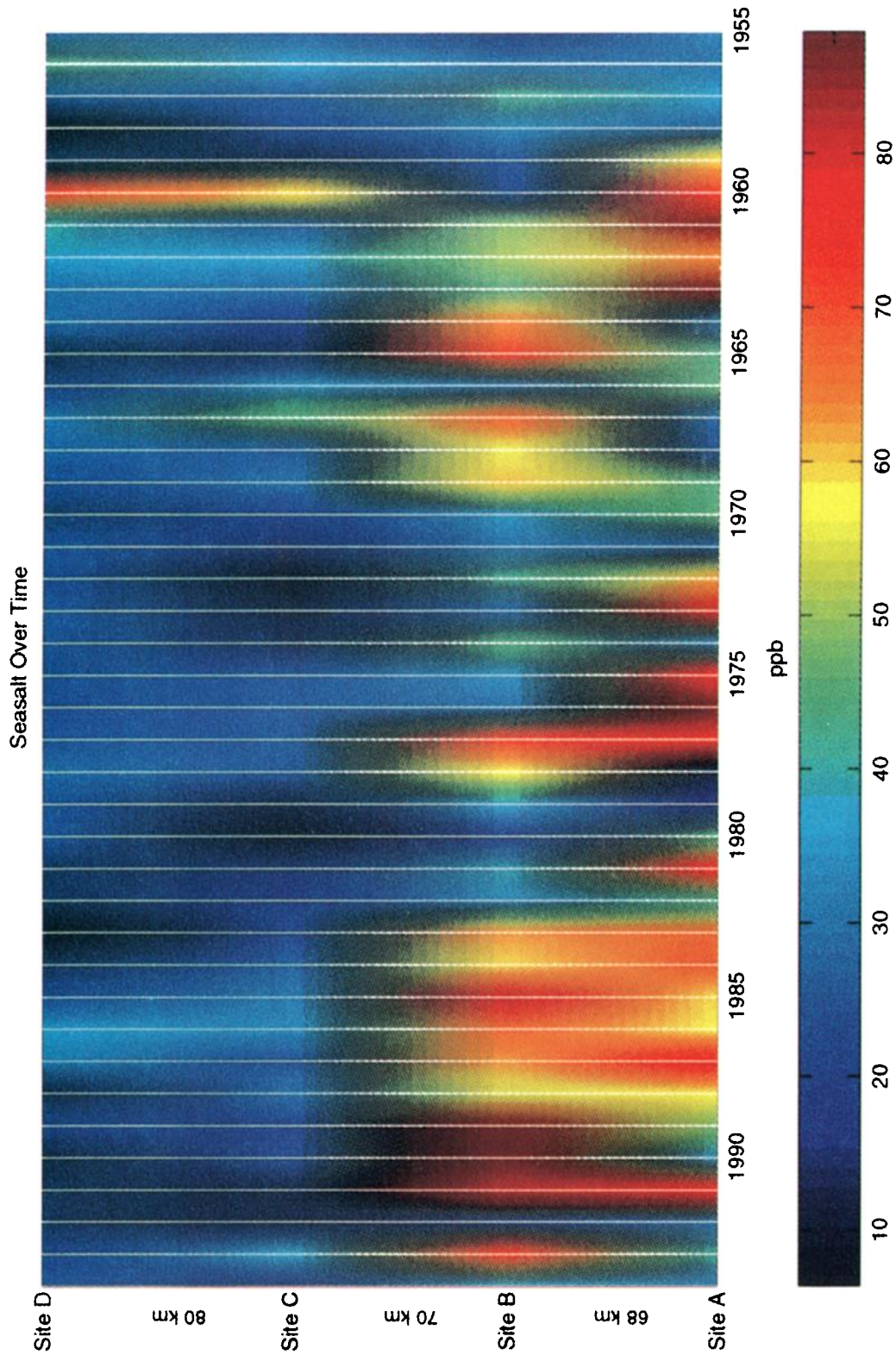
Plate 1. Sea-salt Na over time and space with values in ppb (ng/g). The consistently higher concentrations at Sites A and B validate the 40 year averages. There are also occasional years of higher levels at Sites C and D. Note that five values for annual ssNa concentrations have been omitted from this figure. Each value was more than two standard deviations above the mean. Removing these values decreased the range of values to be represented by the color scale which provides a better representation of the remaining data.

transport marine-origin nssSO$_4$ farther inland after advection by storm systems.

4.1.3. Intersite correlation coefficients. Calculation of correlation coefficients of the chemistry at different sites provides a simple means for quantifying spatial variability and tests the apparent lack of similarity seen in multisite graphs of the same species. Intersite correlations are sensitive to differences in dating between cores which tend to add noise to the preexisting spatial variability. Added noise may reduce correlations or introduce false similarities. Statistical significance of the correlation coefficients was tested by comparing calculated Z-values (using a "normal approximation for testing the significance of correlation coefficients" [*Mendenhall et al.*, 1981]) to the critical t-value for the $\alpha=0.05$ significance level (1.960).

Correlations of annually resampled chemistry data yielded only 10 statistically significant Z-values out of a possible 42 (Table 4). The $\alpha=0.05$ significance level implies that two of the 10 significant correlations could be by chance. R^2 values of the significant correlations imply that the variance attributable to these correlations is generally no more than 20% (only three R^2 values are greater than 0.2). The two highest correlations occur between Sites C and D for Na and Mg ($R=0.63$ and 0.69, $R^2=0.40$ and 0.48, respectively). These results (32 nonsignificant correlations out of 42) mean that more than 75% of the intersite species-to-species comparisons have no predictive power; that is, the record of concentration at one site provides no information about that species at other sites, at least for annual averages. This quantitatively confirms the qualitative lack of intersite similarity seen in the smoothed data (for example, Figure 5).

The small amounts of variance seen in the sparse number of significant linear correlations suggest at least two possible explanations for the high spatial variability. First, there is very little similarity between sites at this spatial scale (50 to 200 km). This is reasonable since significant variability at this scale has

Table 4. Calculated Z-Values and Correlation Coefficients for Intersite Correlations

Value	Na	K	Mg	Ca	Cl	NO₃	SO₄
			Site A versus B				
Z	-0.20	-0.23	-0.34	-0.18	-0.16	0.35	-0.59
R							
			Site A versus C				
Z	0.74	1.44	0.78	-0.62	0.64	2.11	-0.36
R						0.33	
			Site A versus D				
Z	1.26	1.79	1.61	-0.45	1.25	0.59	0.81
R							
			Site B versus C				
Z	0.05	0.29	0.00	0.19	0.13	3.03	2.06
R						0.46	0.33
			Site B versus D				
Z	-0.94	-0.20	-0.79	2.67	-1.10	0.06	2.01
R				0.41			0.32
			Site C versus D				
Z	4.46	2.60	5.18	0.76	3.84	0.44	
R	0.63	0.40	0.69		0.56		0.32

Each intersite comparison uses two rows with row 1 the Z-value and row 2 the correlation coefficient for statistically significant correlations ($\alpha=0.05$ significance level, $t > 1.96$).

Table 5. Summary of EOF Mode Variance (percent) by Site Using 1954-1994 Data

Site	EOF Mode 1	2	3	4	5
Site A	55.6	21.4	9.4	7.0	5.0
Site B[a]	69.1	20.1	7.6		
Site C[b]	54.2	22.4	8.8	8.2	5.6
Site D	54.1	19.5	10.7	8.5	6.6
Siple Dome[c]	58.1	16.4	11.2	7.5	5.4

Siple Dome data [*Kreutz and Mayewski*, 1998] presented for comparison.

[a] Variance in EOF Modes 4 and 5 was less than 5 percent.

[b] Site C record starts in 1955.

[c] Siple Dome data are for the period 1890-1990.

been seen at other locations in West Antarctica [*Kreutz and Mayewski*, 1998]. Precipitation from mesoscale cyclones may also be spatially patchy enough to result in different histories at each site [*Carrasco et al.*, 1997]. Second, there are strong similarities between sites, but the signature of common events is being lost during subsequent redistribution of snow (perhaps through drifting caused by mesoscale cyclones). Low intersite similarity implies a larger role for climate variability and synoptic-scale processes, whereas lost similarity attributes spatial differences more heavily to topographic and postdepositional effects. The correct explanation likely lies in a combination of these and other processes (for example, synoptic-scale variability in storm tracks). As with accumulation rate, small-to-medium scale topography (for example, long-wavelength drifts in the surface snow) of this region is another likely factor. Overall, large-scale topography is probably not a major factor in the spatial variability pattern since the ice divide upslope from the Siple Coast is too far away, as are the Whitmore and Horlick Mountains.

4.2. EOF Analyses and Circulation Patterns

EOF analyses of the 1954-1994 chemistry records at each site show a dominant EOF mode (EOF1) accounting for 54-69% of the site's variance at all four sites (Table 5). EOF1 has high variance for all the sea-salt-dominated species (Na, K, Mg, Ca, and Cl, Table 6). The time series for EOF1 and the sea-salt fraction of the partitioned chemistry closely resemble each other visually and have high linear correlation coefficients. EOF1 is also the only EOF mode in which Na, Mg, and Cl appear at significant levels. These results suggest that sea-salt-laden marine air masses are the largest single contributor (>50%) to the variability in site chemistry at all sites. Because the sea-salt species peak primarily during the winter [*Wagenbach*, 1996; *Whitlow et al.*, 1992], EOF1 can also be considered a record of winter air masses. However, the multiple peaks that sometimes appear between winter peaks in the ssNa record suggest that sea-salt species also arrive at times outside the "winter season" and therefore a portion of the overall sea-salt variability must come from these events as well.

Nitrate and SO$_4$ have high variance in two distinct EOF modes at all sites which account for over ~90% of their variance and a further ~28% of the total site variance. The stronger mode, EOF2, accounts for 64-80% of the total variance in these two

Table 6. Species Variance (percent) for EOF1 by Site

Site	Species						
	Na	K	Mg	Ca	Cl	NO₃	SO₄
Site A	93.7	67.1	85.9	41.3	94.0	-5.0	1.9
Site B	98.1	92.3	94.4	93.6	98.3	-1.4	5.8
Site Cᵃ	93.6	49.1	90.9	50.3	93.3	-0.5	1.6
Site D	93.7	60.4	93.1	32.3	93.8	-5.3	0.0
Siple Domeᵇ	94.9	92.2	93.3	17.2	92.6	-9.5	28.3

Siple Dome data [*Kreutz and Mayewski*, 1998] presented for comparison. Negative values indicate inverse relationship with other species.
ᵃ Site C record starts in 1955.
ᵇ Siple Dome data are for the period 1890-1990.

species (Table 7) and about 20% of the total site variance (Table 5). Because ssSO₄ is in EOF1, the SO₄ in these two EOF modes represents portions (75% and 15%, respectively) of the nssSO₄ component based on comparison with the partitioned series (the remaining 10% is in other, less significant EOF modes). The EOF2 time series also show a strong annual signal, suggesting that this mode represents the annual signals in these species (marine biogenic nssSO₄ and PSC NO₃). Because NO₃ and SO₄ both peak during the summer [*Mayewski and Legrand*, 1990; *Whitlow et al.*, 1992], EOF2 can also be considered a record of summer air masses.

The secondary NO₃ and nssSO₄ EOF mode accounts for another 15-30% of species variance (Table 7) but less than 10% of the total site variance (Table 5). Unlike EOF2, NO₃ and SO₄ vary inversely in this mode. This EOF mode is likely a combination of background processes and, perhaps, some signal noise. The nssSO₄ background signal probably reflects long-distance, upper tropospheric or stratospheric transport from sporadic events (for example, volcanic eruptions). Similarly, the NO₃ background signal likely represents, in part, long-distance transport from low-level, lower-latitude production sources such as lightning [*Legrand and Delmas*, 1986].

Results from short-term, high-resolution, single-site EOF analyses show that there are three consistent atmospheric circulation processes active at all four sites which account for approximately 80% of the total variance: marine sea-

Table 7. Species Variance (percent) for NO₃ and SO₄ EOF Modes by Site

	Primary		Secondary		Total	
	NO₃	SO₄	NO₃	SO₄	NO₃	SO₄
Site A	72.9	75.9	-15.8	18.0	88.7	93.9
Site B	73.7	67.0	-24.8	27.2	98.5	94.2
Site Cᵃ	79.4	75.5	16.9	-14.7	96.3	90.2
Site D	63.4	70.9	28.8	-24.4	92.2	95.3
Siple Domeᵇ	61.5	26.6	25.5	-14.1	87.0	40.7

Total is the sum of the variance in the Primary and Secondary modes. Siple Dome data [*Kreutz and Mayewski*, 1998] presented for comparison. Negative values indicate inverse relationship with other species.
ᵃ Site C record starts in 1955.
ᵇ Siple Dome data are for the period 1890-1990.

Table 8. Summary of EOF Analyses by Site and Atmospheric Process, 1954-1994

Mode	Site A	Site B	Site C	Site D
Marine air (winter)	56	69	54	54
Annual NO₃ and SO₄ (summer)	21	20	22	19.5
Background NO₃ and SO₄	7	7.6	5.6	8.5
Major processes	84	96.6	81.6	82
Minor processesᵃ	14.4		17	17.3
Total	98.4	96.6	98.6	99.3

The first three rows show the percentage of the total variance that the process represents for each site. The last three rows summarize the variance by process group and as the total variance identified by EOF analysis.
ᵃ Minor processes are not significant at Site B.

salt-influenced winter air masses, biogenically and stratospherically influenced summer air masses, and background/stratospheric air (Table 8). Similar EOF analyses of chemistry data at Siple Dome [*Kreutz and Mayewski*, 1998] and at inland sites near Byrd Station (K. J. Kreutz, University of New Hampshire, personal communication, 1997) resemble these results, indicating that these processes are present over much of West Antarctica (Tables 5 and 6). This spatial uniformity, both
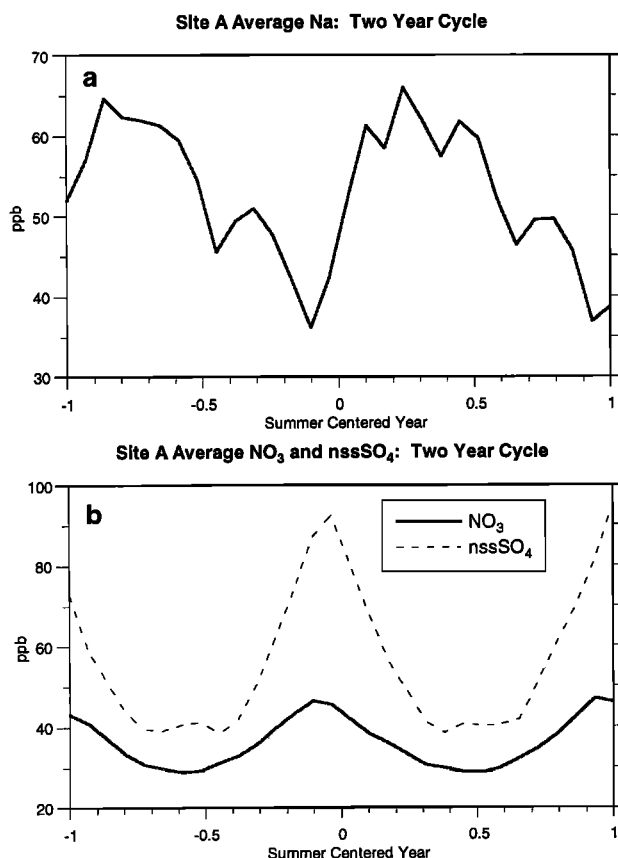
Site A Average Na: Two Year Cycle

Site A Average NO₃ and nssSO₄: Two Year Cycle

Figure 7. Fifty three year composites of chemistry data from Site A. Data from each year was averaged with the other years after interpolation to the same timescale. The x axis shows two annual cycles centered on austral summer but should not be interpreted below annual resolution. (a) ssNa. (b) nssSO₄ and NO₃.
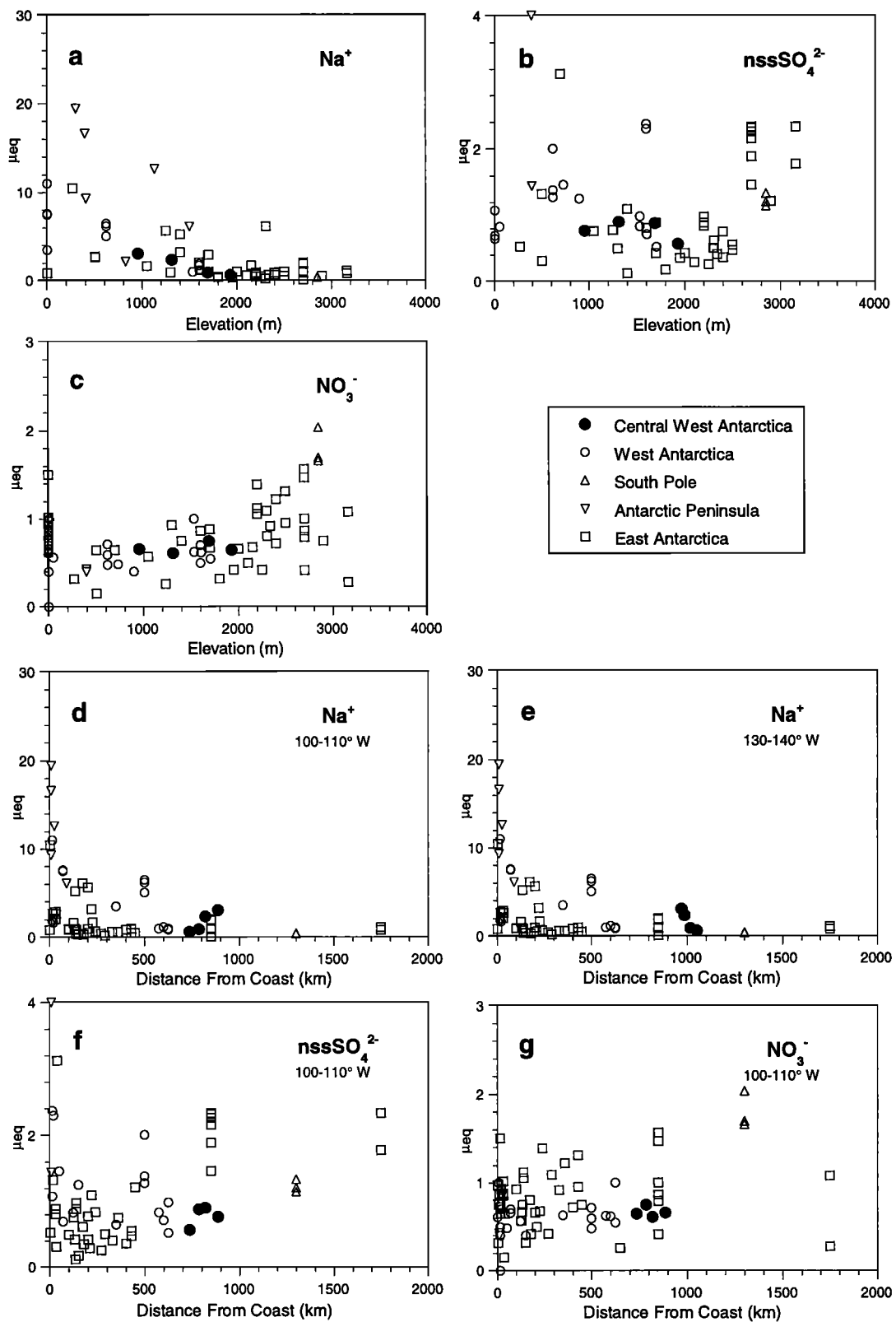
Figure 8. (a-c) Average species concentrations (in µeq) plotted versus elevation and (d-g) distance inland from nearest coast. "Central West Antarctica" identifies sites of this study. Remaining sites distributed throughout Antarctica. Numbers under species name in Figures 8d-8g indicate longitude range of nearest coast used to calculate distance inland for the figure.

in the study region and in comparisons to Siple Dome, 600-700 km away, contrasts with the spatial variability seen in average concentrations and accumulation rates. It also suggests a large-scale uniformity of atmospheric circulation superimposed on high spatial variability at synoptic and smaller scales.

4.3. Species Timing

4.3.1. Sea-salt. Stacking individual years from a site's ssNa record provides some insight into the multiple annual peaks present in some years which make this record less useful than the SO_4 or NO_3 records for dating. The stacked record for Site A (Figure 7a, based on 53 individual years) shows that on average there tend to be two separate peaks each year. The subannual dating of the CWA records is not accurate enough to assign these peaks to specific months or seasons of the year. Given that ssNa arrives primarily during the winter [Whitlow et al., 1992], the double peak in ssNa at Site A probably reflects seasonal changes in the intensity of cyclogenesis and associated intrusions of marine air. Comparisons with composite ssNa records from the other sites show that the secondary peak is strongest at Site A and weakens moving upslope until it is absent at Site D.

4.3.2. Nitrate and nssSO₄. A comparison of time series shows that NO_3 either leads or arrives at approximately the same time as $nssSO_4$ about 80% of the time. A composite of 53 years of data from Site A demonstrates the near-synchronous timing of these two species (Figure 7b). One explanation for this synchroneity is simply transport via the same air masses. Since the primary means of transport to Antarctica for NO_3 produced in lower latitudes is held to be stratospheric subsidence over the polar plateau (for example, [Mayewski and Legrand, 1990]), $nssSO_4$ would also have to travel this path.

However, it is unlikely that this is true for the bulk of the $nssSO_4$ due to the pattern of $nssSO_4$ concentrations and variability at other West Antarctic sites (Table 3). Sites closer to the Ross, Amundsen, and Bellingshausen Seas (for example, [Kreutz and Mayewski, 1998; Kreutz et al., 1998]) have both higher concentrations and variability due to closer source proximity and stronger transport. Concentrations and variability at South Pole are lower due to increased distance and weaker long-range transport from the western Southern Ocean during the summer (from back trajectory analysis [Harris, 1992]) when biogenic sources are strongest. Thus even though average $nssSO_4$ concentrations at CWA sites are comparable to South Pole, the higher variability at CWA (more similar to more northerly but still inland sites, for example, RIDS95C at 80° S, 119° W) argues for closer source areas. That makes marine air intrusions from the Ross, Amundsen, and Bellingshausen Seas the likely primary source of $nssSO_4$ for CWA. A small amount of $nssSO_4$ may also be provided by polar plateau katabatic outflow.

Therefore the synchroneity of the $nssSO_4$ and NO_3 peaks probably results from a coincidence in the behavior of their sources, not transport by the same air masses. The breakup of the polar vortex, releasing PSC-sequestered NO_3, and increased marine biogenic activity, from ocean warming and sea ice retreat with consequent increased $nssSO_4$, just happen to have similar timing.

4.4. Influence of Distance and Elevation on Concentration

The two main controls on sea-salt-influenced species (Na, Cl, Ca, K, and Mg) concentrations in Antarctic snow are expected to be distance inland and elevation [Kreutz and Mayewski, 1998].

Kreutz constructed an extensive database of average species concentrations from snow pits and firn/ice cores all over the continent to test these relationships and found them to be generally true. Further testing using the new CWA data for the period 1980-1985 (the period with the most sites in the database) confirms the relationship with elevation (Figure 8a).

While the CWA sites collectively fit with the expected decrease in sea-salt as distance inland increases, the individual sites show a distinct increasing trend, opposite to expectations (Figure 8d). Because the nearest coastline is on the Amundsen Sea (~100°-110° W), these sites become closer to the sea moving upslope. The Amundsen Sea coast is the direction (120°-130° W) of prevailing 700 mbar winds based on ECMWF data, so it is probably the most significant direction for marine air masses. However, changing the assumed direction to the nearest coast by only ~30° W, that is, measuring distances from the Hobbs Coast (130°-140° W), restores the sea-salt trend (Figure 8e) to fit with observations from other Antarctic sites [Kreutz and Mayewski, 1998]. There is no explicit meteorological support for this change, so the Hobbs Coast is unlikely to be a significant source region. Nonetheless, this change does demonstrate the sensitivity of the CWA region to this metric (distance inland) and suggests there may be no unique tracers of source direction in this region (in part, because there is no single closest coast). It also makes marine intrusions from the Weddell Sea area appear more viable, though perhaps still not a major influence. A limited (one year) satellite-based analysis shows poleward moisture flux occurring only in the Amundsen and Bellingshausen sectors of West Antarctica [Slonaker, 1997], which supports surface observations of warm, moist air intrusions moving on to the polar plateau [Hogan, 1997]. The satellite data show equatorward moisture flux at all latitudes in the Weddell sector and in the Ross Sea sector south of 72° S. This suggests that marine intrusions from the Weddell Sea into the CWA region may only be contributing marine aerosols without significant accumulation. This is supported in a general sense by the EOF analyses that show concentrations and accumulation rates to be only weakly related.

Of the nonmarine species, the modest increasing trend with elevation found by Kreutz and Mayewski [1998] for NO_3 is confirmed by the CWA data, though the individual sites show no distinct trend (Figure 8c). Nitrate versus distance inland is ambiguous (Figure 8g). Concentrations may be independent of increasing distance or the increasing trend found by Kreutz and Mayewski [1998] may be present. Earlier work has shown NO_3 to be independent of both controls [Herron, 1982; Legrand and Delmas, 1985], and more research on this species remains desirable. The general independence of $nssSO_4$ versus these controls is confirmed by the CWA data (Figure 8b, 8f).

5. Conclusions

The combined results from analyses of glaciochemical and accumulation rate data from the four sites of this study show this region of central West Antarctica to be one of high spatial variability for both atmospheric chemistry and moisture transport. The subjective variability seen in graphs and averages of the data is confirmed by poor results from intersite correlations. There is some evidence for regimes of marine influence in the pairing of Sites A and B and Sites C and D through comparable sea-salt concentrations within the site pairs but significant differences between the pairs. The explanations for the high spatial variability are elusive. Elevation, the path of warm air advection,

variations in storm tracks, and small- to medium-scale topography will all have some influence along with other, larger-scale climate factors.

Yet EOF analysis shows that the same overall circulation processes are operating at all the sites even though the concentrations (and accumulation rates) are uncorrelated. An average of 79% of the variability at the CWA sites can be described using just two atmospheric circulation regimes: winter sea-salt laden air and summer nssSO$_4$- and NO$_3$-laden air. The existence of a marine sea-salt influence on the chemistry of central West Antarctica is expected since it is known that storms regularly track into this region from the Amundsen and Bellingshausen Seas [*Harris*, 1992]. The strength of this influence, 50-70% of site variability, was less predictable and emphasizes the effect these storms have on West Antarctica. While less dramatic, the summer season circulation, with an average of 21% of site variability, also brings a distinct marine signature in the form of biogenic nssSO$_4$. The polar stratosphere also affects the summer season variability by contributing significant NO$_3$ from PSC breakup [*Mulvaney and Wolff*, 1993] and other sources to the region. The signature of these winter and summer air mass patterns is recognizable only with a multiparameter, multisite analysis. This atmospheric chemistry pattern is also seen at other sites in West Antarctica (for example, Siple Dome), suggesting that it is present throughout the region.

These two conclusions, high spatial variability and simple air mass regimes, are not contradictory. It is possible, indeed probable, that the species all arrive in different seasons (though with some overlap) but that incorporation of the chemistry into the snow is highly variable. This pattern may also extend to a much larger portion of West Antarctica based on comparisons with a limited number of other sites. A simpler picture of the patterns of variability in West Antarctica can thus be drawn by using analysis techniques that fully exploit high-resolution, multiparameter, multisite data sets.

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