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The effect of spatial and temporal accumulation rate variability in West Antarctica on soluble ion deposition

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Abstract. Annually-dated snowpit and ice core records from two areas of West Antarctica are used to investigate spatial accumulation patterns and to evaluate temporal accumulation rate/glaciochemical concentration and flux relationships. Mean accumulation rate gradients in Marie Byrd Land (11-23 $gcm^{-2}yr^{-1}$ over 150 km, decreasing to the south) and Siple Dome (10-18 $gcm^{-2}yr^{-1}$ over 60 km, decreasing to the south) are consistent for at least the last several decades, and demonstrate the influence of the offshore quasi-permanent Amundsen Sea low pressure system on moisture flux into the region. Local and regional-scale topography in both regions appears to affect orographic lifting, air mass trajectories, and accumulation distribution. Linear regression of mean annual soluble ion concentration and flux data vs. accumulation rates in both regions indicates that 1) concentrations are independent of and thus not a rescaling of accumulation rate time-series, and 2) chemical flux to the ice sheet surface is mainly via wet deposition, and changes in atmospheric concentration play a significant role. We therefore suggest that, in the absence of detailed air/snow transfer models, ice core chemical concentration and not flux time-series provide a better estimate of past aerosol loading in West Antarctica.

1. Introduction

Records derived from Antarctic snow, firn, and ice cores provide detailed information on ice sheet mass balance through measurement of integrated accumulation rate (total precipitation minus evaporation, sublimation, and drift snow divergence). Temporal variability in such records generally reflects changes in poleward atmospheric moisture transport, while spatial accumulation variability across the ice sheet is related to topography (on various scales) and distance from the predominant moisture source. Determining spatial and temporal accumulation patterns can therefore aid interpretations of moisture transport and atmospheric dynamics [e.g., *Vaughan et al.,* 1999], particularly in regions such as West Antarctica where complex coastal and inland geography exists [*Cullather et al.,* 1996].

Temporal precipitation variability will also affect the transport and deposition of atmospheric aerosols to the surface of the ice sheet. A simple model relating atmospheric concentration, snow accumulation, and snow (or ice) concentration for a particular chemical species is [*Alley et al.,*

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1995]: $f = k_1 C_{air} + k_2 C_{air} b$ and $f = I_c b$, where f is the chemical flux, C_{air} is the atmospheric concentration, k_1 is the dry deposition velocity, k_2 is the dimensionless scavenging ratio, b is the snow accumulation rate, and I_c is the snow concentration. The model implies that $I_c = k_1 C_{air}/b + k_2 C_{air}$. Thus, if k_1 and k_2 are assumed to be constant and wet deposition dominates, I_c provides the best estimate of C_{air}. Conversely, if dry deposition dominates, an inverse relationship between I_c and b exists (i.e., implying a dilution effect; *Legrand,* 1987) and in this case f provides the best estimate of C_{air}. Air/snow transfer processes are undoubtedly more complex; however, in the absence of detailed atmospheric measurements and empirical air/snow transfer models at a particular site, estimating past atmospheric chemical concentrations from ice core records relies upon interpreting either I_c or f time-series. Studies of the spatial relationship between mean I_c and b at sites throughout Antarctica reveal no significant correlations [*Mulvaney and Wolff,* 1994; *Kreutz and Mayewski,* 1999], suggesting that any dilution effects which may exist are offset by other factors such as proximity to aerosol source, contributions of dry and fog deposition [*Bergin et al.,* 1995], variable scavenging ratios, post-depositional transport of snow, and/or post-depositional alteration of ionic species. For a particular site (or region), correlation of ice core I_c, b, and f time-series can yield information on the relative importance of wet and dry deposition [*Alley et al.,* 1995], and thus whether I_c or f provides a better qualitative estimate of past aerosol loading.

2. Methods

A total of 17 snowpits and cores were sampled at Siple Dome and on the West Antarctic plateau (within the Ross ice drainage system [RIDS] region of Marie Byrd Land; Figure 1 and Table 1). Snowpit sampling and core processing was performed by workers wearing non-particulating suits, polyethylene gloves, and particle masks. Samples were collected into precleaned polyethylene containers and stored below -15°C until melting immediately prior to chemical analysis. Analysis of major cations (Na^+, K^+, NH_4^+, Mg^{2+}, Ca^{2+}), anions (Cl^-, NO_3^-, SO_4^{2-}), and methyl sulfonate (CH_3QO^-; MS) was performed via suppressed ion chromatography. Partitioning of SO_4^{2-} into seasalt (ss) and nonseasalt (nss) fractions was done using standard Na^+/SO_4^{2-} seawater ratios. Gross β-activity was measured on 20 cm samples from 5 cores using a gas-flow proportional counter. Maxima in each β-activity profile (Figure 2) are assumed to represent the global peak reached prior to the 1963 Atmospheric Test Ban Treaty, which due to atmospheric transport times reached Antarctica during the austral summer 1964/65. In each core, it is possible to accurately count back to the 1964/65 chronostratigraphic horizon using summer
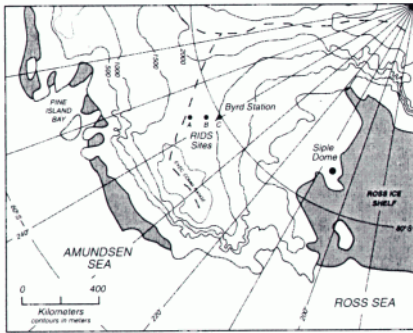
Figure 1. Location map for West Antarctic sites. Elevation contours are every 500m.

nssSO$_4$$^{2-}$ peaks. Annual layer thickness in both snowpits and cores are therefore calculated based on seasonal nssSO$_4$$^{2-}$ cycles, and converted to accumulation rates (b, in gcm^{-2}yr^{-1}) using density profiles (data every 3 cm in snowpits and 1 m in cores).

3. Results and Discussion

3.1 Accumulation Rate Spatial Variability

Results from both regions display gradients in mean b (Table 1). In Marie Byrd Land, b decreases by a factor of ~2.5 along the 160 km traverse (Figure 2), with the relative change between sites RIDSA and RIDSB (60% increase) larger than that between sites C and B (33% increase). Our estimate at RIDSC, ~3 km NE of Byrd Station, is consistent with previous estimates surrounding Byrd [*Whillans*, 1978, and references therein]. In addition, *Whillans* [1978] noted a steep b gradient in the same vicinity as RIDSA that is consistent over different time periods (1964-67 and 1968-
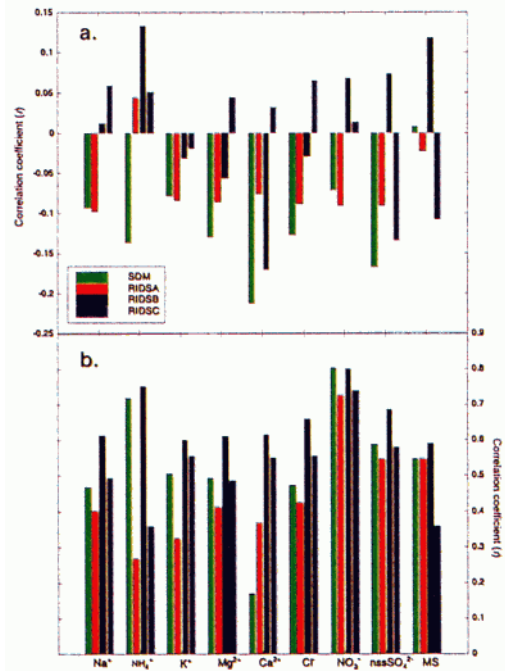
Figure 3. Correlation coefficients (r) of **a)** mean annual soluble ion I_c vs. b, and **b)** mean annual soluble ion f vs. b for the Siple Dome (SDM), RIDSA, RIDSB, and RIDSC cores Time periods used for each core are given in Table 1.

1973*)*. Our data from 1965-1995 (period of β-profile constraint), and for the longer periods with annual I_c data in each core (Table 1), also indicate that this gradient has remained relatively constant over the past several decades. The 60 km transect of snowpits and cores at Siple Dome (Table 1) displays a factor of ~2 decrease in b going south
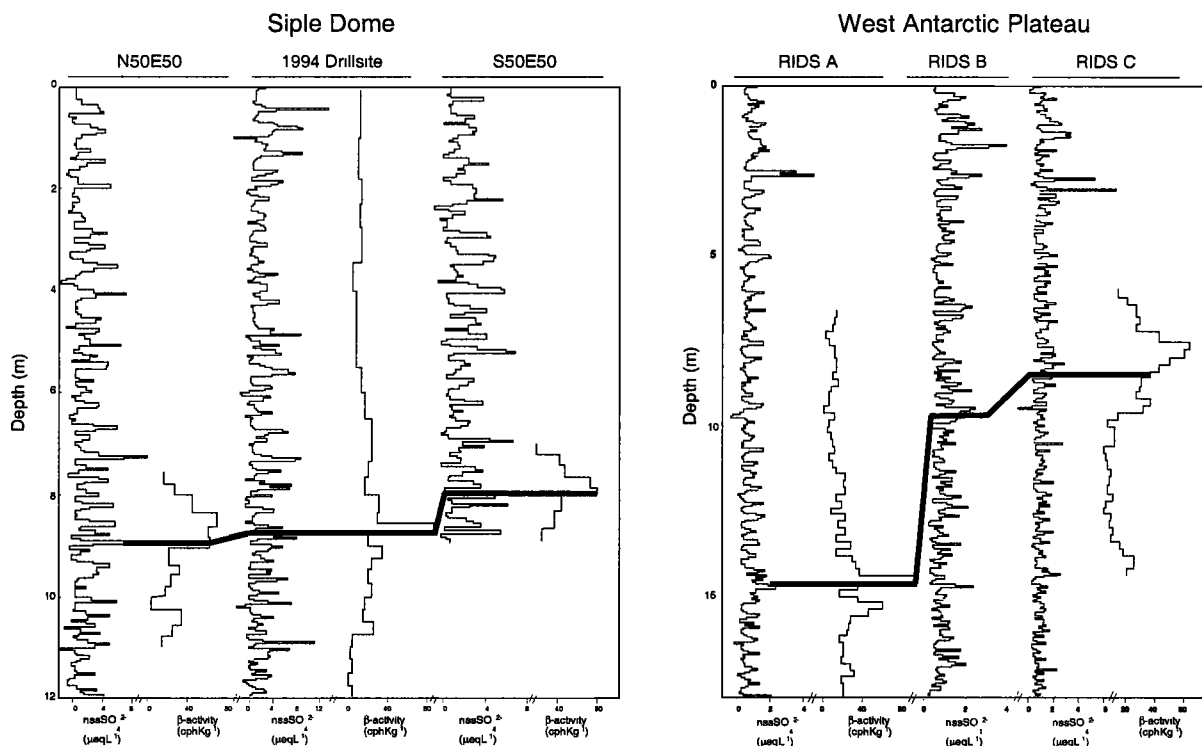
Figure 2. Beta (β) activity and nssSO$_4$$^{2-}$ profiles from Siple Dome and Inland West Antarctic cores. The thick black lines correspond to the 1964/65 time horizon, based on β-activity peaks and layer counting of annual chemical signals.

Table 1. Siple Dome and West Antarctic plateau site information. The divide position for Siple Dome refers to the local east-west trending divide on Siple Dome [*Nereson et al.*, 1999], while the divide position for the West Antarctic plateau sites refers to the regional ice divide dividing the Ross embayment from the Amundsen Sea (Figure 1). For the ice cores, time periods and mean accumulation rates in parentheses refer to the portion of the core with annually-resolved chemical data.

| Location	Elev. (m)	Depth (m)	Position	Time Period (Year AD)	Mean Acc Rate (gcm^{-2} yr^{-1})
Siple Dome					
N50E50 Core	602.9	10	5 km NE	1964-1994	14.5
1994 Core	620.1	150	0.7 km N	(1890) 1964 -1994	(11.7) 12.1
S50E50 Core	601.9	10	5 km SE	1964-1994	11.6
Snowpits					
1996-E	395.7	2	30 km N	1992-1996	18.2
1996-G	580.1	2	10 km N	1992-1996	17.3
1994-2	602.2	2	5 km NW	1990-1994	12.7
1994-4	602.9	2	5 km NE	1990-1994	11.5
1994-6	619.8	1	0.8 km N	1991-1994	10.9
1994-1	620.1	4	0.7 km N	1982-1994	11.5
1996-B	620.5	4	0.5 km S	1984-1996	12.2
1994-3	600.7	2	5 km SW	1989-1994	13.7
1994-5	601.9	2	5 km SE	1989-1994	8.6
1996-H	582.4	2	10 km S	1989-1996	11.4
1996-F	436.4	2	30 km S	1987-1996	9.5
West Antarctic Plateau					
RIDSA Core	1740	150	20 km S	(1831) 1964-1995	(23.5) 23.7
RIDSB Core	1603	60	110 km S	(1925) 1964-1995	(15.1) 14.8
RIDSC Core	1530	60	180 km S	(1905) 1964-1995	(11.2) 11.1

across the roughly east-west trending local ice divide. Accumulation rate estimates from shallow cores suggest that this gradient (within ±5 km of the ice divide) has persisted for at least the last 30 years (Table 1).

Topographically forced moisture transport convergence is known to be responsible for the meridional precipitation

distribution in the Antarctic, with large amounts over the marginal ice slopes and small values in the continental interior [*Vaughan et al.*, 1999]. The topography of coastal and inland West Antarctica appears to play a major role in channeling incoming moisture into fairly well defined pathways, and also affecting more local precipitation regimes. In particular, the trough between the Executive Committee Range (~3000 m elevation) and Pine Island Bay (Figure 1) provides a pathway for frontal systems to migrate onto the polar plateau. Potential temperature isotherms [*Hogan*, 1997] support this view, showing maximum values in a narrow band well inland from the coast. In Marie Byrd Land, the observed b gradient near the Siple/Amundsen coast ice divide (Figure 1) suggests that orographic lifting of air masses and channeling along the topographic boundary occurs. Results from Siple Dome suggest a similar effect of local topography on controlling moisture transport and precipitation [*Nereson et al.*, 1999]. Time-series b changes from the Siple Dome and West Antarctic plateau sites studied here have been compared to modeled moisture flux into West Antarctica, and were shown to be in close agreement [*Bromwich et al.*, 2000]. Because the modeled moisture flux is primarily driven by changes in the strength and position of the Amundsen Sea low (ASL) pressure system, the similarity of the two records suggests that the main moisture source region for Siple Dome and Marie Byrd Land is the Ross and Amundsen Seas.

3.2 Ion Concentration and Flux vs. Accumulation Rate

Sources of water soluble ions in Antarctic snow and ice have previously been summarized by *Mulvaney and Wolff* [1994]; the two aerosol types responsible for a majority of the ionic load in coastal and near-coastal regions are sea-salt and biogenic sulfur oxidation products. To investigate the spatial and temporal relationship between b and I_c in West
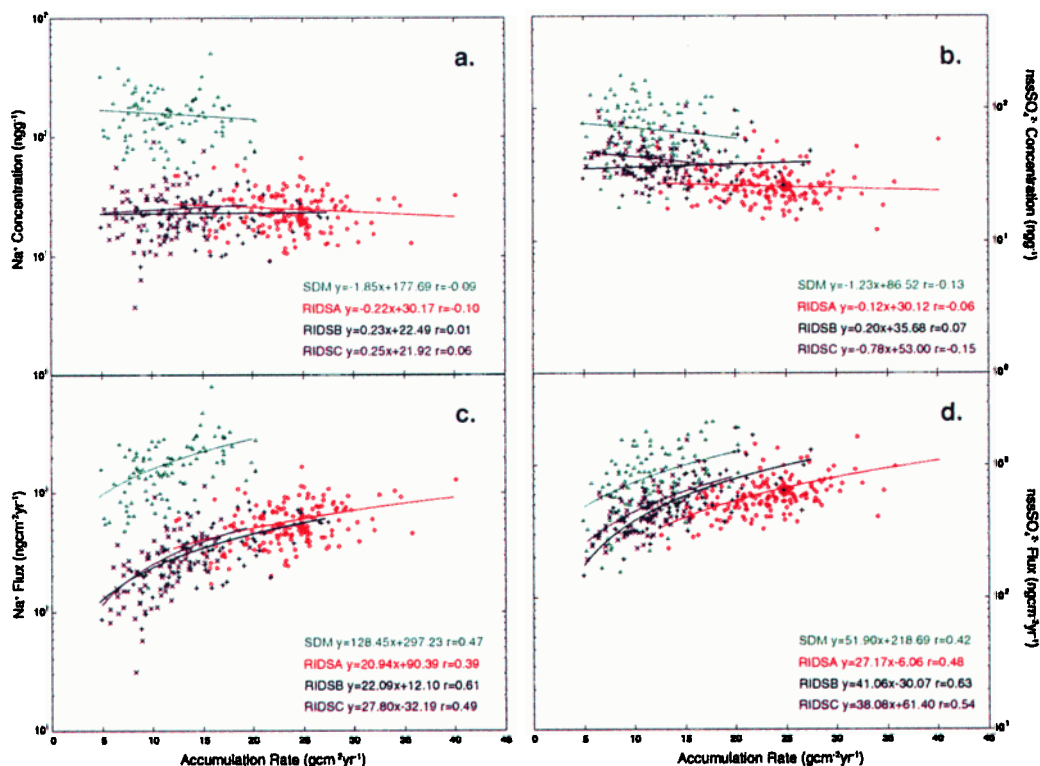
Figure 4. Linear regression results of Na$^+$, nssSO$_4^{2-}$, and accumulation rate data from the four West Antarctic sites. Time periods used for each core are given in Table 1. **a.** Na$^+$ concentration vs. accumulation rate, **b.** nssSO$_4^{2-}$ concentration vs. accumulation rate, **c.** Na$^+$ flux vs. accumulation rate, and **d.** nssSO$_4^{2-}$ flux vs. accumulation rate.

Antarctica, linear regression analysis of the two parameters was performed (Figure 3a). With the exception of Ca^{2+} at Siple Dome, there are no significant correlations (at the 95% c.l.) for any species at any site. We therefore conclude that on an annual basis, I_c is independent of b for these sites in West Antarctica.

Distinct large-scale spatial differences in I_c for two chemical species chosen as being representative of sea-salt (Na^+) and sulfur aerosols ($nssSO_4^{2-}$) are shown in Figure 4. Higher Na^+ concentrations at Siple Dome are likely due to more efficient transport of sea-salt aerosol across the Ross Ice Shelf [Kreutz and Mayewski, 1999; Kreutz et al., 2000], rather than accumulation rate effects as the RIDSC and 1994 Siple Dome have similar b values (Table 1). Within the RIDS region, however, there is no appreciable change in Na^+ concentration across the three sites. Results of $nssSO_4^{2-}$ regressions are similar, yet the relative difference in $nssSO_4^{2-}$ concentration between Siple Dome and the RIDS sites is not as great. At South Pole, sulfate aerosols have been shown to exist mainly in the Aitken mode ($r < 0.1\ \mu m$), while sea-salt aerosols generally are much larger ($r \sim 0.4\ \mu m$; Shaw, 1979). Therefore, the spatial differences in I_c observed between the two regions may be related to the efficiency of aerosol transport, with smaller sulfate aerosols more easily advected to inland sites.

Plots of mean annual Na^+ and $nssSO_4^{2-}$ flux vs. b at each site (Figure 4) display positive slopes, and therefore are consistent with concentration results implying no significant dilution effect. As noted by Alley et al. [1995], such a result is expected at sites dominated by wet deposition, whereby years with increased b will bring an increased amount of aerosol. Correlation coefficients (Figure 3b) of f vs. b for all chemical species range between 0.17 and 0.80 and average 0.54, suggesting that significant variability is not accounted for in the flux model. Deviations from the regression slope would occur if significant changes in atmospheric chemical concentration occur in addition to b variability, which is expected to be the case. Recent studies in Antarctica, where aerosol, snowfall, and snowpack chemistry were compared at several coastal sites [Wolff et al., 1998], have found a reasonable agreement between aerosol concentration and I_c. It appears that in West Antarctica, as at the coastal sites, wet deposition is dominant and thus I_c can be expected to provide a better qualitative time-series estimate of aerosol loading. It has been suggested that the intercept on f vs. b plots provides an estimate of the dry deposition rate [Legrand, 1987; Alley et al., 1995]. As we have no data at very low accumulation rates ($<5\ gcm^{-2}yr^{-1}$) at any of the sites, it is difficult to assess how well the plot intercepts (Figure 4) reflect dry deposition, particularly at the RIDS sites where negative intercepts are observed in some cases. Such information, however, would be useful for comparing deposition processes in West Antarctica with those occurring at ice core sites dominated by wet deposition (i.e., GISP2; Alley et al. [1995]) and with significant dry deposition (i.e., Vostok; Legrand [1987]).

4. Conclusions

The b gradients shown here highlight the complexity of moisture transport into West Antarctica, and suggest that both local and regional-scale topographic features play a role in determining mean b at a particular site. Given the additional variability imposed by temporal changes in moisture flux (related to changes in the size and/or position of the ASL), a greater number of detailed ice core and surface geophysical observations are clearly needed to understand recent and past West Antarctic mass balance dynamics. The linear regression results presented here indicate that there is no significant temporal relationship between I_c and b, and that f time-series, while indicating that wet deposition is dominant, are controlled by factors in addition to b. Therefore, until detailed air/snow transfer data and models [e.g., Bergin et al., 1995] are available for specific West Antarctic ice core sites, we suggest that I_c time-series are more appropriate for qualitative estimates of past atmospheric aerosol concentrations.

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