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A 700-year record of atmospheric circulation developed from the Law Dome ice core, East Antarctica

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[1] A 700-year, high-resolution, multivariate ice core record from Dome Summit South (DSS) (66°46′S, 112°48′E; 1370 m), Law Dome, is used to investigate sea level pressure (SLP) variability in the region of East Antarctica. Empirical orthogonal function (EOF) analysis reveals that the first EOF (LDEOF1) of the combined glaciochemical, oxygen isotope ratio, and accumulation rate record from DSS represents most of the variability in sea salt seen in the record. LDEOF1 is positively correlated (at least 95% confidence level) to instrumental June mean SLP across most of East Antarctica. Over the last 700 years, LDEOF1 levels at Law Dome were the highest during the nineteenth century, suggesting an increase in intensification of winter circulation during this period. The Law Dome DSS oxygen isotope ratio series also indicates that the nineteenth century had the coldest winters of any century in the record. In contrast, LDEOF1 levels were the lowest at Law Dome during the eighteenth century, suggesting a significant shift in the patterns and/or intensity of East Antarctic atmospheric circulation between the eighteenth and the nineteenth centuries. The LDEOF1 sea salt record is characterized by significant decadal-scale variability with a strong 25-year periodic structure. *INDEX TERMS:* 1610 Global Change: Atmosphere (0315, 0325); 1620 Global Change: Climate dynamics (3309); 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 4215 Oceanography: General: Climate and interannual variability (3309)

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1. Introduction

[2] The Antarctic climate system plays a critical role in the global climate system through heat exchange, albedo and sea ice dynamics, deep water production and global oceanic circulation, marine biological productivity, and atmospheric circulation forcing [*Tomczak and Godfrey*, 1994; *King and Turner*, 1997; *Villalba et al.*, 1997]. However, our knowledge of the spatial and temporal variability of the Antarctic climate system is limited due to the short period and limited number of observational and instrumental data available from the continent. To improve our understanding of how the Antarctic climate system operates, and what sort of variability has existed within the system, researchers are focusing on the information that is contained within the ice sheet itself through the study of ice cores.

[3] Ice cores provide a high-resolution archive of the past composition and behavior of the atmosphere. Time series of major ion concentrations from ice cores provide information about changes in aerosol source area, transport pathways, and production rates [e.g., *Legrand and Mayewski*, 1997]. Correlations between Greenland and Antarctic ice core stable isotope ratio, accumulation rate and glaciochemical time series with instrumental temperature and pressure records demonstrate that statistically calibrated proxy records can be developed from ice cores [e.g., *van Ommen and Morgan*, 1997; *White et al.*, 1997; *Appenzeller et al.*, 1998; *Rogers et al.*, 1998; *Kreutz et al.*, 2000]. In this paper we investigate the environmental implications of changes in glaciochemical concentrations at Law Dome, East Antarctica. This study will assist in the interpretation of a continuous Holocene record of glaciochemistry currently being developed from the 1200 m surface-to-bedrock ice core [*Morgan et al.*, 1997] drilled from Dome Summit South (DSS), Law Dome.

2. Data and Methodology

[4] The glaciochemical (Ca^{2+}, K^+, Mg^{2+}, Na^+, Cl^-, NO_3^-, and SO_4^{2-}), accumulation rate, and oxygen isotope ratio

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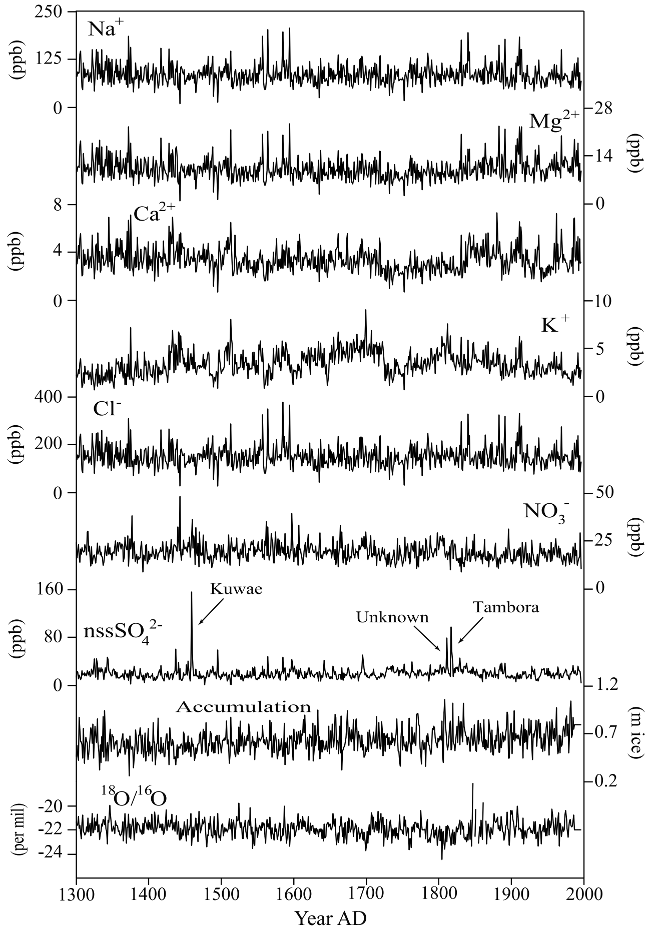

Figure 1. Glaciochemical (Ca^{2+}, K^+, Mg^{2+}, Na^+, Cl^-, NO_3^-, and SO_4^{2-}), accumulation rate, and oxygen isotope ($^{18}O/^{16}O$) annual time series from the Law Dome composite DSS ice core record.

series used in this study (Figure 1) is the composite 700-year long (1300–1996 A.D.) DSS record developed from the DSS (1300–1841 A.D.), DSS99 (1841–1888 A.D.), and DSS97 (1888–1996 A.D.) ice cores recovered from the summit of Law Dome, East Antarctica [*Morgan et al.*, 1997; *Palmer et al.*, 2001]. Ultraclean procedures were used to continuously sample the ice cores at 5–10 cm intervals [*Buck et al.*, 1992]. The DSS ice core was sampled and analyzed via suppressed ion chromatography at the University of New Hampshire. Cations were analyzed with a Dionex™ CS12A column, 500 μL loop, and 20 mM MSA eluent and anions were analyzed with a Dionex™ AS11 column, 500 μL loop, and 6 mM NaOH eluent. The DSS99 and DSS97 ice cores were sampled and analyzed via suppressed ion chromatography at the Antarctic Cooperative Research Center, Hobart, Tasmania. Cations were analyzed with a CS12A column, either a 200 or 250 μL loop, and isocratic H_2SO_4 eluent and anions were analyzed with a AS14 column, and either a 450 μL loop and isocratic $Na_2B_40_7$ eluent or a concentrator column and a gradient $Na_2B_40_7$ eluent [*Curran and Palmer*, 2001]. All samples were melted at room temperature in sealed polyethylene containers immediately prior to analysis. Interlaboratory comparisons and calibrations were conducted to ensure that the glaciochemical analyses from each institution were equivalent and intercomparable.

[5] The depth-age scale developed for the DSS ice cores is based on the seasonal signature of the oxygen isotope ratio, glaciochemical, hydrogen peroxide, and electrical-conductivity profiles measured in the cores [*van Ommen and Morgan*, 1996, 1997; *Morgan et al.*, 1997; *Curran et al.*, 1998; *Palmer et al.*, 2001]. In addition, independent depth-age control is provided by volcanic SO_4^{2-} reference horizons (Figure 1) of known age (e.g., Kuwae; Tambora) [*Hammer*, 1977; *Zielinski et al.*, 1994; *Palmer et al.*, 2001]. The DSS multivariate ice core record dating is unambiguous at the annual level from A.D. 1807 to 1996 and has an uncertainty of ±1 year at A.D. 1301 [*Palmer et al.*, 2001]. Based on the depth-age scale developed for the DSS cores, the sampling resolution for the 700-year-long glaciochemical record used in this study is 6–20 samples per year. For the purposes of our investigation, the Law Dome glaciochemical, accumulation rate, and oxygen isotope ratio series are uniformly resampled at annual resolution using the depth-age relationships developed for the DSS ice cores.

[6] Instrumental Antarctic station pressure data used in this research are from the compilations of the British Antarctic Survey (BAS) [*BAS*, 2002]. The data were assessed for quality and long-term homogeneity and suspect values either verified or corrected [*Jones and Limbert*, 1987, and updates]. Automatic weather station surface pressure data from Law Dome are from I. Allison (Program Leader, Glaciology, Australian Antarctic Division and Antarctic CRC, Hobart, Tasmania, Australia, personal communication, 2000). Sea ice extent data covers the period 1973–1997 and are from the compilations of *Jacka* [1983, and updates] and *Simmonds and Jacka* [1995]. The sea ice data consists of monthly means on the latitude of maximum Antarctic sea ice extent averaged for each 10° of longitude and are from the U.S. Navy/National Oceanic and Atmospheric Administration (NOAA) Joint Ice Facility weekly maps. Monthly sea ice anomalies are developed for each 10° of longitude by subtracting long-term (1973–1997) monthly means from monthly values for each year.

3. Empirical Orthogonal Function (EOF) Analysis

[7] To begin to investigate the relative importance of accumulation rate, sea ice extent and sea level pressure (SLP) variability in determining glaciochemical concentrations at Law Dome, we perform EOF analysis on the combined annually resolved glaciochemical, oxygen isotope ratio, and accumulation rate time series from the DSS ice cores to identify relationships among the various ice core time series which can be associated with climatic variables [e.g., *Mayewski et al.*, 1994; *Meeker et al.*, 1995]. In EOF analysis, the combined time series are factored into a series of statistically uncorrelated (orthogonal) principle components referred to as EOFs (or eigenmodes). Each EOF represents a different mode of the temporal variability in the data set, such that, when ordered, each successive EOF explains the maximum amount possible of the remaining

Table 1. EOF Analysis of the Annual Law Dome Glaciochemical, Oxygen Isotope ($^{18}O/^{16}O$), and Accumulation Rate (H_2O) Time Series for the Period 1300–1996 A.D.

				Eigenvector components					
Species	EOF1	EOF2	EOF3	EOF4	EOF5	EOF6	EOF7	EOF8	EOF9
Ca^{2+}	0.78	−0.05	0.13	−0.15	0.34	0.10	0.48	−0.05	0.01
K^+	0.56	0.24	−0.19	−0.05	0.67	−0.31	−0.22	0.03	0
Mg^{2+}	0.94	−0.11	0.11	−0.02	−0.16	0.16	−0.02	0.22	−0.01
Na^+	0.96	−0.01	0.05	−0.04	−0.16	0.09	−0.16	−0.12	−0.08
Cl^-	0.95	0.01	0.04	0	−0.17	0.12	−0.18	−0.08	0.09
SO_4^{2-}	0.44	0.48	−0.05	0.55	−0.29	−0.40	0.17	0	0
NO_3^-	−0.24	0.75	0.16	0.29	0.20	0.49	−0.04	0	0
$^{18}O/^{16}O$	−0.08	−0.42	0.77	0.41	0.21	−0.10	−0.08	−0.01	0
H_2O	0.11	−0.52	−0.56	0.58	0.17	0.22	0.01	−0.01	0
				Percent variance explained					
Species	EOF1	EOF2	EOF3	EOF4	EOF5	EOF6	EOF7	EOF8	EOF9
Ca^{2+}	60.3	0.2	1.6	2.3	11.4	1.0	23.0	0.2	0
K^+	31.5	5.8	3.4	0.3	44.5	9.4	5.0	0.1	0
Mg^{2+}	87.6	1.2	1.3	0	2.5	2.6	0	4.9	0
Na^+	91.5	0	0.3	0.2	2.5	0.9	2.6	1.4	0.7
Cl^-	90.8	0	0.2	0	2.9	1.5	3.1	0.6	0.8
SO_4^{2-}	19.6	23.0	0.2	29.8	8.5	16.1	2.8	0	0
NO_3^-	5.9	55.5	2.6	8.2	4.1	23.6	0.2	0	0
$^{18}O/^{16}O$	0.7	17.7	59.4	16.5	4.3	0.9	0.7	0	0
H_2O	1.3	30.8	30.8	33.2	2.7	4.7	0	0	0
				Percent of total variance explained					
	EOF1	EOF2	EOF3	EOF4	EOF5	EOF6	EOF7	EOF8	EOF9
	43.2	14.5	11.1	10.0	9.3	6.7	4.1	0.8	0.2

variance in the data set [*Peixoto and Oort*, 1992]. Results from our EOF analysis for the period 1300–1996 A.D. are presented in Table 1. The first EOF (LDEOF1) explains a considerable (>43%) portion of the overall variance in the multivariate ice core record and is loaded primarily (>85%) by the major components of sea salt aerosols (e.g., Na^+, Cl^-, and Mg^{2+}). Components of an EOF that explain a significant portion of the overall variance in a multivariate data set are likely to represent some underlying physical linkages among the variates [*Peixoto and Oort*, 1992]. Given the coastal location of Law Dome and the fact that the DSS site is mainly affected by marine air masses [*Curran et al.*, 1998; *Delmotte et al.*, 2000], we interpret LDEOF1 to be a record of marine aerosol deposition to Law Dome.

4. LDEOF1/Accumulation Rate Relationship

[8] Previous work by *Wolff et al.* [1998] indicates that for coastal Antarctic sites characterized by high annual snow accumulation, such as Law Dome [*Morgan et al.*, 1997], wet deposition by falling snow is the dominant depositional process for aerosol species and that dry deposition is only a minor contributor to chemical fluxes. If dry deposition is significant at Law Dome, however, past changes in the accumulation rate could lead to a variable dilution of the dry chemical flux to the ice sheet and thus modulate the chemical concentrations preserved in the snow and ice [*Legrand and Mayewski*, 1997]. Results presented in Table 1 indicate that no significant percentage of the variance in the accumulation rate time series is explained by LDEOF1. This indicates that the LDEOF1 record is independent of accumulation rate and implies that the interannual variability exhibited in the LDEOF1 record is not a function of changes in accumulation rate (i.e., moisture flux and/or precipitation) at Law Dome.

5. LDEOF1/Sea Ice Extent Relationship

[9] It has been suggested by several authors that sea salt aerosol production and transport to a given core site may be controlled by changes in local sea ice extent and concentration [*Peel and Mulvaney*, 1992; *Hall and Wolff*, 1998; *Wagenbach et al.*, 1998]. Accordingly, we attempt to determine if there is any statistically meaningful relationship between the LDEOF1 sea salt record and monthly changes in meridional sea ice extent off the coast of Law Dome. Specifically, we use linear regression to investigate the correlation between the LDEOF1 record and monthly changes in meridional sea ice extent over every 10° of longitude between 70°E and 120°E for the period 1973–1996. The rationale to include 70°–120°E in our sea ice analysis, rather than just 110°E (i.e., the longitude of DSS), stems from the work of *Cavalieri and Parkinson* [1981] and *Parkinson and Cavalieri* [1982] who suggest that Antarctic sea ice extent and concentration are strongly influenced by quasi-stationary atmospheric systems. A quasi-stationary longwave trough, the Davis Sea Low (DSL), is located northwest of Law Dome near 100°–110°E in the circumpolar trough [*Bromwich*, 1988; *Goodwin*, 1990; *Morgan et al.*, 1991]. Climatological charts of monthly mean SLP generally resolve the DSL as extending from 70°E to 120°E longitude in the circumpolar trough [*Schwerdtfeger*, 1984; *King and Turner*, 1997; *Bromwich and Parish*, 1998]. We therefore speculate that this sector of sea ice (70°–120°E) may be a potentially important and dynamic region of local sea salt aerosol production and transport to Law Dome. If a robust, physically significant relationship exists

Table 2. Correlation (R)[a] Between the Annual LDEOF1 Sea Salt Record and Antarctic Sea Ice Extent for the Period 1973–1996

Sector	January	February	March	April	May	June	July	August	September	October	November	December	Annual
70°E[b]	0.06	0.09	−0.16	0	0.09	−0.09	0.09	0.06	−0.13	−0.05	−0.05	0.11	0
80°E	−0.23	0.06	**−0.44**	−0.02	−0.08	0.32	0.28	−0.33	0.03	−0.23	−0.13	0.03	−0.12
90°E	**0.58**	0.32	0.14	0.08	0.04	0.26	0.33	−0.08	−0.25	−0.09	0.19	−0.22	0.16
100°E	0.22	0.39	−0.08	0.24	−0.08	0.26	**0.54**	−0.02	−0.25	−0.13	−0.27	0.13	0.13
110°E	0.31	**0.51**	**0.48**	0.14	0.12	0.02	0.30	−0.19	−0.13	−0.24	**−0.49**	0	0
120°E	0.25	0.28	0.28	−0.22	−0.14	−0.20	−0.02	0.11	0.05	−0.03	−0.27	−0.29	−0.09

[a] Correlation coefficients in bold are significant at the 95% (or greater) confidence level.
[b] Sea ice extent averaged from 60°E to 70°E longitude.

between meridional sea ice extent and sea salt aerosol production and transport to Law Dome, we expect to find significant correlations between the LDEOF1 record and sea ice extent for consecutive months at a particular longitude and/or for a single month across multiple longitudes [e.g., *Kreutz et al.*, 2000].

[10] Following this line of reasoning, the only significant correlation found between the LDEOF1 sea salt record and sea ice extent is a positive correlation with the region 100°–110°E for the months February and March (Table 2). However, satellite passive-microwave observations of sea ice concentration indicate that this region is essentially ice free during February and March [*Gloersen et al.*, 1992], and an increase in sea ice extent off the coast of Law Dome would be expected to contribute to a reduction in sea salt levels at the core site if local ice free water was the major source of the ice core sea salt. Also, the concentration of sea salt in the Law Dome ice core is at a minimum during February and March (i.e., during the austral summer) when the extent of local ice free water is expected to be at a maximum. We conclude therefore, that while statistically significant, there is no statistically meaningful physical relationship between sea ice extent and glaciochemical sea salt concentrations at DSS. This conclusion is supported by the fact that Law Dome lies in the Western Pacific Ocean sector (90°–160°E) of the Southern Ocean where the Antarctic coastline extends furthest from the South Pole and the Southern Ocean is at its warmest [*Gloersen et al.*, 1992]. As a consequence, sea ice cover in the Law Dome region is the least extensive throughout the year and the seasonal changes in sea ice extent are not as pronounced as in other sectors of the Southern Ocean [*Gloersen et al.*, 1992]. It is reasonable to assume, therefore, that sea ice extent in this region has a reduced impact on the production of sea salt aerosols that are subsequently transported to Law Dome [*Curran et al.*, 1998].

6. LDEOF1/SLP Relationship

[11] Numerous glaciochemical and aerosol studies have documented that sea salt concentrations in Antarctica generally peak during the winter [*Legrand and Delmas*, 1984; *Prospero et al.*, 1991; *Whitlow et al.*, 1992; *Mulvaney and Wolff*, 1994; *Curran et al.*, 1998; *Hall and Wolff*, 1998; *Kreutz et al.*, 1998; *Wagenbach et al.*, 1998]. Because of increased sea ice growth during winter, the observed winter peak in sea salt concentrations is out of phase with fluctuations in the open water fraction of the Southern Ocean. Increased cyclonic activity and intensified meridional transport from ice-free regions of the Southern Ocean has generally been proposed as the source and transport mechanism for the winter sea salt aerosol in Antarctica [*Legrand and Kirchner*, 1988; *Hogan et al.*, 1990; *Savoie et al.*, 1993; *Wagenbach*, 1996]. In addition, previous glaciochemical investigations in both Antarctica and Greenland have generally explained increased sea salt loading as mainly being a result of intensified atmospheric circulation [*Mayewski et al.*, 1993, 1997; *O'Brien et al.*, 1995; *Kreutz et al.*, 1997, 2000].

[12] To investigate the influence of atmospheric circulation on the production and transport of sea salt aerosols to Law Dome, the LDEOF1 sea salt record is compared to monthly SLP at Casey station, located 110 km from DSS [see *Morgan et al.*, 1997, Figure 1]. Results of linear regression indicate that the annual LDEOF1 sea salt record is significantly correlated to June SLP at Casey for the period 1957–1996 (r = 0.37, n = 40, p < 0.02) (Figure 2a). In addition, automatic weather station monthly surface pressure observations from DSS are positively correlated to Casey monthly SLP for the period 1992–1999 (r = 0.93, n = 76, p < 0.001) (Figure 2b). We assume therefore that SLP conditions at Casey are indicative of surface pressure conditions at DSS and, hence, that a positive relationship exists between the LDEOF1 sea salt record and DSS June SLP. We believe that the positive correlation with the June SLP and not other winter months is due to the out-of-phase sea ice annual cycle with the atmospheric circulation. June is an important month because the energetic winter atmospheric circulation pattern is established and sea ice growth lags the circulation pattern with a maximum in sea ice extent occurring later in September. Hence, there is maximum potential for air–sea exchange between an energetic atmospheric circulation and open water in the Southern Ocean. This suggests that while sea salt aerosols are incorporated and transported in the atmosphere at any time of the year, the maximum modulation of the annual sea salt signal at Law Dome is determined by the atmospheric circulation pattern and strength during June. The correlation with June SLP also agrees well with the seasonal signature of the sea salt signal at DSS, which is characterized by a winter peak and summer minimum [*Curran et al.*, 1998].

[13] Although our results suggest a relationship between the LDEOF1 sea salt record and Casey SLP, we recognize that correlation with one station is insufficient to establish the LDEOF1 record as a robust proxy of SLP. We therefore seek to develop a more robust correlation between the LDEOF1 sea salt record and SLP by expanding our region of SLP analysis to include the entire Antarctic continent. Accordingly, we compare monthly mean SLP and surface pressure records from 20 Antarctic stations with the annual

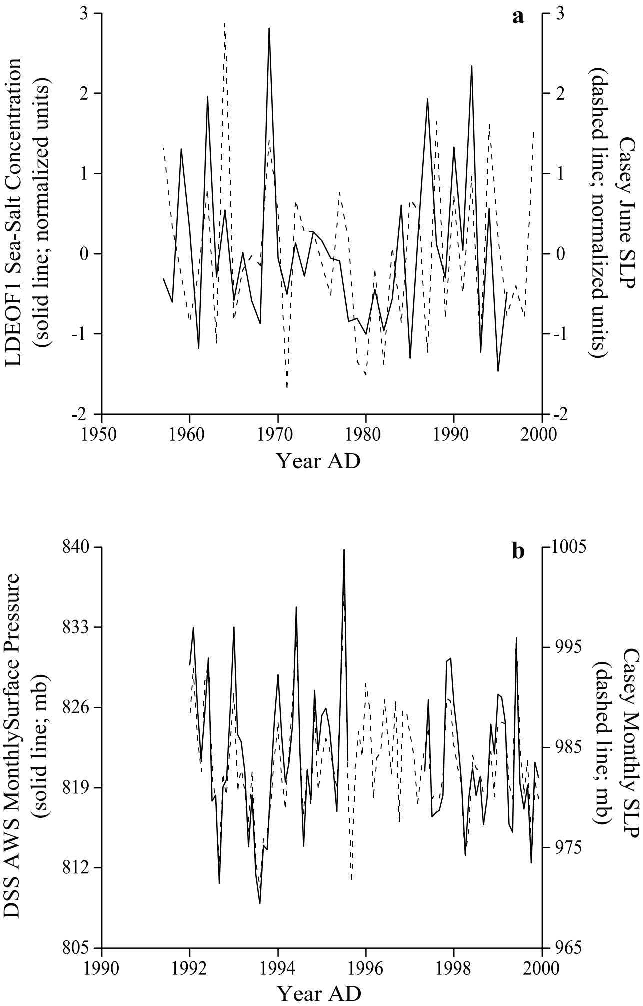

Figure 2. (a) Correlation of the annual LDEOF1 record (solid line; normalized units) and Casey June SLP (dashed line; normalized units) for the period 1957–1996. (b) Correlation of DSS automatic weather station (AWS) monthly surface pressure observations (solid line) and Casey monthly SLP (dashed line) for the period January 1992 to December 1999.

LDEOF1 sea salt record (Table 3 and Figure 3). If a robust, physically meaningful relationship exists between SLP and sea salt aerosol production and transport to Law Dome we expect to find significant correlations between the LDEOF1 sea salt record and SLP. Results of linear regression indicate significant positive correlations (at least 95% confidence level) between the annual LDEOF1 sea salt record and June SLP for 12 Antarctic stations (Table 4). The significant correlation to SLP over such a broad area of East Antarctica (Figure 3) suggests that sea salt aerosol production and transport to Law Dome is related to the large-scale atmospheric circulation system over the continent during winter, the Antarctic High.

[14] While this is diagnostic information we next investigated the mechanism that controls the sea salt inclusion in the air mass and its transport to DSS. Possible mechanisms may be related to (1) the latitudinal SLP gradient across the circumpolar trough, (2) the latitude of the center of the lowest SLP in the circumpolar trough and its time-dependent relationship with the limit of monthly sea ice extent, and (3) the longitude of the center of the lowest SLP in the circumpolar trough and the atmospheric transport distance to Law Dome. An analysis of the June and June, July, and August (JJA) SLP gradients between 60°S and 65°S at longitudes 90°E, 100°E, and 110°E was made. While these SLP gradients explain some of the variance in the LDEOF1 record for some years they are not reliable indices. The JJA SLP gradient between Casey and the center of the circumpolar trough at 60°S, 110°E has been intensifying

Table 3. Names and Locations of Stations Numbered in Figure 3 and the Span of Years for Which SLP, or Surface Pressure (*), was Used

Station	Location	Data years
1. Amundsen-Scott*	90°S	1957–1993
2. Novolazarevskaya	71°S, 12°E	1961–1996
3. Syowa	69°S, 31°E	1957–1991
4. Molodezhnaya	68°S, 46°E	1963–1996
5. Mawson	68°S, 63°E	1954–1996
6. Davis	69°S, 78°E	1957–1996
7. Mirny	67°S, 93°E	1956–1996
8. Vostok*	79°S, 107°E	1958–1996
9. Casey	66°S, 111°E	1957–1996
10. Dumont d'Urville	67°S, 140°E	1956–1993
11. Leningradskaya	69°S, 159°E	1971–1991
12. McMurdo	77°S, 167°E	1956–1992
13. Scott Base	78°S, 167°E	1957–1986
14. Byrd*	80°S, 120°W	1957–1970
15. Argentine Is.	65°S, 64°W	1944–1991
16. Bellingshausen	62°S, 59°W	1944–1996
17. General Belgrano	78°S, 48°W	1955–1979
18. Halley	76°S, 27°W	1956–1996
19. Neumayer	71°S, 08°W	1981–1996
20. SANAE	70°S, 03°W	1957–1992

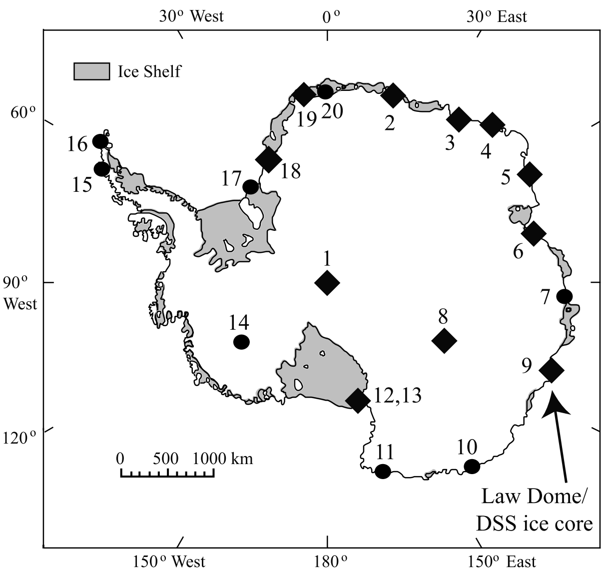

Figure 3. Location map of Antarctic stations whose SLP or surface pressure data are used in this study. Additional information on each numbered station appears in Table 3. Stations whose June SLPs are significantly correlated (at least 95% confidence level) to the annual LDEOF1 sea salt record are shown as diamonds. Correlation coefficients for all stations are shown in Table 4.

Table 4. Correlation (R)[a] Between the LDEOF1 Sea Salt Record and Instrumental Antarctic SLP or Surface Pressure (*)

Station	January	February	March	April	May	June	July	August	September	October	November	December	Annual
1. Amundsen-Scott*	0.03	0.04	−0.04	0.08	0.17	**0.52**	0.14	−0.16	−0.03	0.07	−0.02	0.02	0.07
2. Novolazarevskaya	0.07	−0.01	−0.05	0.19	0.15	**0.41**	0.17	0.20	0.12	0.12	−0.13	0.11	**0.50**
3. Syowa	0.01	−0.09	−0.14	0.10	0.16	**0.36**	0.19	−0.08	0.01	0.03	−0.25	0.02	0.15
4. Molodezhnaya	0.14	0.06	0.02	0.19	0.23	**0.48**	0.17	−0.18	−0.04	0.04	−0.24	−0.07	0.20
5. Mawson	0.12	−0.09	−0.03	0.15	0.25	**0.59**	0.07	−0.23	−0.10	−0.03	−0.05	−0.06	0.06
6. Davis	0.02	0.01	0.16	0.11	0.32	**0.54**	0.08	−0.11	−0.16	0.07	0.08	0.06	0.09
7. Mirny	0.11	−0.07	0.17	0.02	0.15	0.28	0.11	−0.03	−0.19	0.03	−0.06	0.02	0.06
8. Vostok*	0.29	0	−0.08	−0.03	−0.06	**0.39**	−0.04	−0.18	**−0.45**	0.09	−0.04	0.18	−0.02
9. Casey	0.09	−0.06	0.03	0.18	0.12	**0.37**	0.01	−0.06	−0.19	0.05	−0.15	−0.05	0.08
10. Dumont d'Urville	−0.03	−0.03	0.16	0.01	−0.01	0.21	−0.11	−0.10	−0.22	**0.36**	0.02	0.11	−0.05
11. Leningradskaya	0.26	−0.21	0.11	0.17	0.06	0.27	0.19	−0.30	0.06	0.16	0.06	0.11	0.25
12. McMurdo	**0.41**	0.16	0.06	0.07	−0.04	**0.42**	0	0	0.01	0.10	0.14	0.07	**0.38**
13. Scott Base	0.20	−0.13	−0.08	−0.01	−0.19	**0.51**	−0.06	0.01	−0.05	0.08	−0.04	0.01	−0.21
14. Byrd*	0.04	**−0.46**	−0.10	−0.19	−0.19	0.30	0	−0.15	0.05	−0.08	−0.27	0.08	−0.19
15. Argentine Is.	0.04	−0.14	−0.24	0.07	0.09	−0.02	0.01	0.07	−0.06	−0.08	−0.30	−0.18	−0.13
16. Bellingshausen	−0.09	−0.11	−0.12	0.10	0.10	0.03	0	0.07	−0.06	−0.04	−0.08	−0.03	−0.12
17. General Belgrano	0.21	−0.11	−0.14	−0.09	−0.24	0.24	−0.01	0.04	−0.18	−0.01	−0.18	−0.04	−0.14
18. Halley	0.09	0	−0.09	0.02	0.24	**0.40**	0.04	−0.04	0.04	0.05	−0.22	0.11	0.19
19. Neumayer	0.06	0.27	−0.26	0.21	**0.57**	**0.53**	0.20	−0.32	0.23	−0.04	−0.20	0.21	**0.33**
20. SANAE	−0.22	−0.14	−0.29	0.01	0.11	0.25	0.09	−0.12	−0.02	0	−0.22	0.07	−0.07

Station locations are shown in Figure 3 and additional station details are given in Table 3.
[a] Correlation coefficients in bold are significant at the 95% (or greater) confidence level.

since 1957 and there is no apparent corresponding trend in the LDEOF1 sea salt record. Therefore, SLP fluctuations in the circumpolar trough to the north of Law Dome are not the cause of the observed sea salt variability at DSS.

[15] Analysis of the National Centers for Environmental Prediction (NCEP) reanalysis June SLP data set between 70°E and 140°E suggests that the key to understanding the atmospheric controls on sea salt inclusion into the airstream and transport to DSS is the location of the deepest low pressure within the circumpolar trough, and hence, the location of the center of the DSL. The latitude of the central core of the DSL for June is plotted against the LDEOF1 sea salt concentration in Figure 4a and the longitude of the central core of the DSL for June is plotted against the LDEOF1 sea salt concentration in Figure 4b. There is reasonable agreement between LDEOF1 and the latitude of the central June SLP in the trough with a correlation coefficient of $r = -0.43$ ($n = 40$, $p < 0.01$) (Figure 4a). This relationship would be improved if SLP data for May, June, and July were included for some years. The correlation between the data sets is also remarkably good given that the

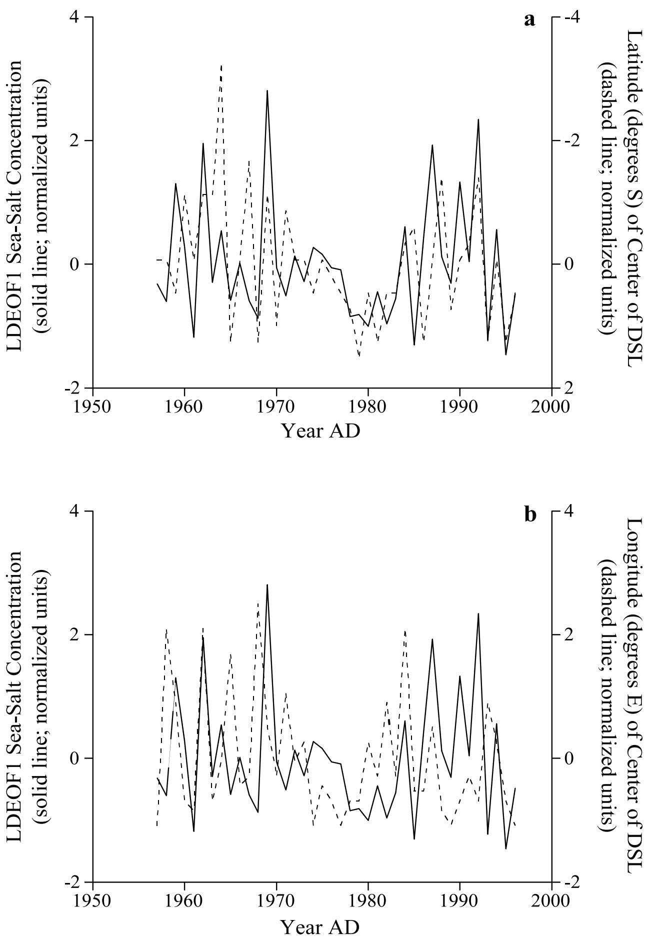

Figure 4. (a) Correlation of the annual LDEOF1 record (solid line; normalized units) and the latitude (°S) of the central core of the DSL during June (dashed line; normalized units). (b) Correlation of the annual LDEOF1 record (solid line; normalized units) and the longitude (°E) of the central core of the DSL during June (dashed line; normalized units).

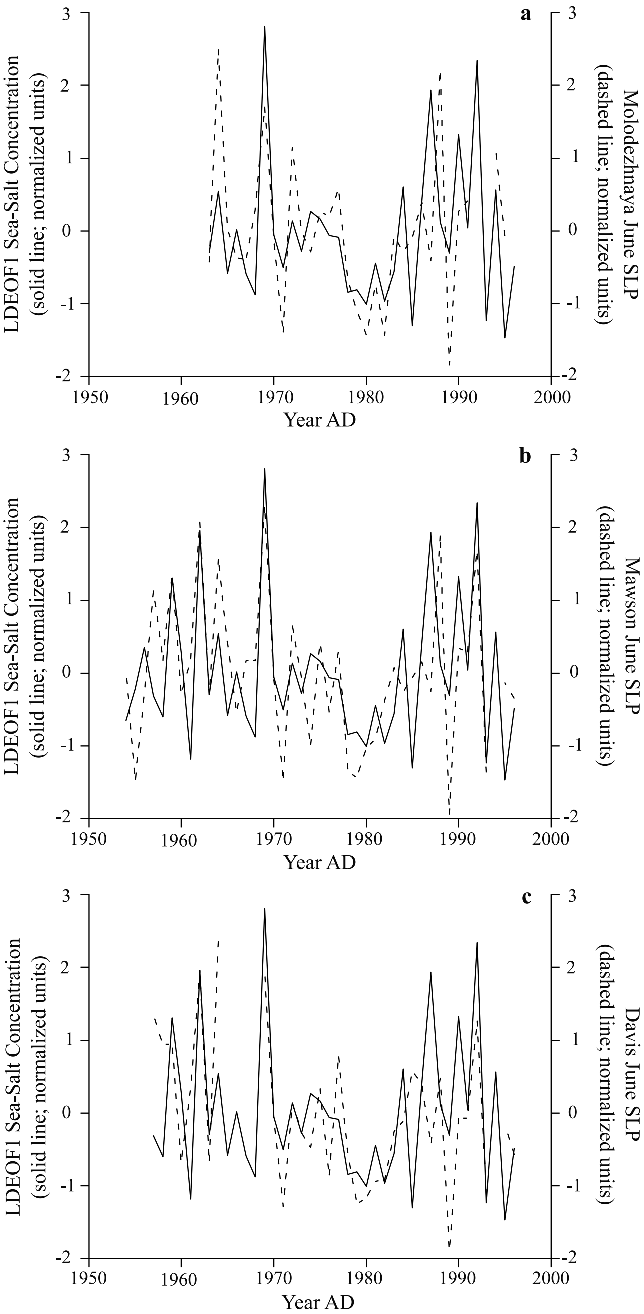

Figure 5. (a) Correlation of the annual LDEOF1 record (solid line; normalized units) and Molodezhnaya June SLP (dashed line; normalized units). (b) Correlation of the annual LDEOF1 record (solid line; normalized units) and Mawson June SLP (dashed line; normalized units). (c) Correlation of the annual LDEOF1 record (solid line; normalized units) and Davis June SLP (dashed line; normalized units).

NCEP reanalyses are numerical simulations of the SLP field. In overview, the higher LDEOF1 concentrations are related to years where the center of the DSL is displaced further offshore by the northward expanding Antarctic High, causing cyclones to track north of the sea ice edge and hence over more open water. The sea ice edge at 100°E fluctuates between 60°S and 63°S over the 1973–1996 period. Therefore, central SLP locations north of 60°S are over open water. This explains why we did not find a significant correlation with simply winter sea ice extent. It is the location of the DSL (and more broadly the circumpolar trough) relative to the sea ice edge that controls the entrainment of sea salt to Law Dome.

[16] Figure 4b shows that there is some agreement between the longitude of the DSL central core and the LDEOF1 sea salt concentration. A general comment can be made that sea salt concentrations are lowest when the DSL central core is located furthest west at around 80°–90°E near Davis station. During these periods the central core extends around to 60°E, offshore from Molodezhnaya and Mawson stations. This is consistent with the regression analysis of the June SLP and LDEOF1 (Table 3) where the highest correlations with June SLP at Antarctic coastal stations occurs for locations to the west of Casey/Law Dome, particularly Molodezhnaya, Mawson, and Davis (Figure 5). These analyses indicate that sea salt concentrations at Law Dome are intrinsically linked to the strength of the Antarctic High and its influence on the latitudinal belt occupied by the circumpolar trough. Maximum sea salt concentrations occur during periods of high SLP anomalies over the Antarctic continent, contemporaneous with the central locus of cyclone activity displaced further northwards over open water and/or thinner sea ice.

7. 700-Year Glaciochemical Sea Salt Proxy of SLP Variability

[17] Figure 6 is a 50-year smoothed plot of the annual LDEOF1 sea salt record over the last 700 years and highlights the significant decadal-scale to centennial-scale variability that is present throughout the entire record. Over the last 700 years, sea salt concentrations (e.g., LDEOF1) at Law Dome are highest from approximately 1800 to 1900 A.D. suggesting an intensification of the Antarctic High over this period. LDEOF1 is lowest during the mid-1700s suggesting a weakened Antarctic High. The Law Dome DSS oxygen isotope ratio proxy for winter temperature indicates that the 1800s had the coldest winters of any century in the record [*Morgan and van Ommen*, 1997].

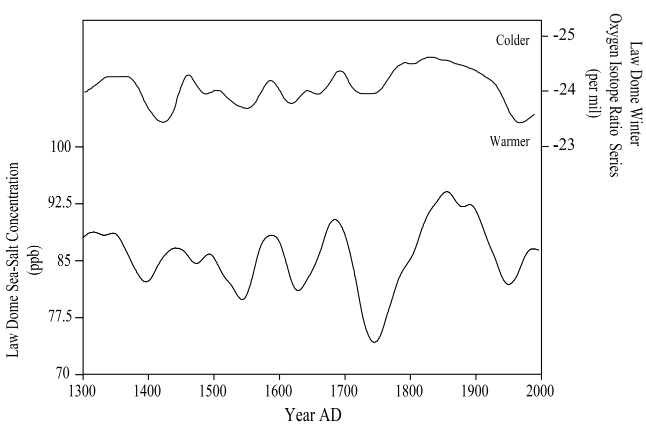

Figure 6. Comparison of the Law Dome sea salt record (LDEOF1) and the winter oxygen isotope ratio profile developed from the DSS ice cores [*Morgan and van Ommen*, 1997].

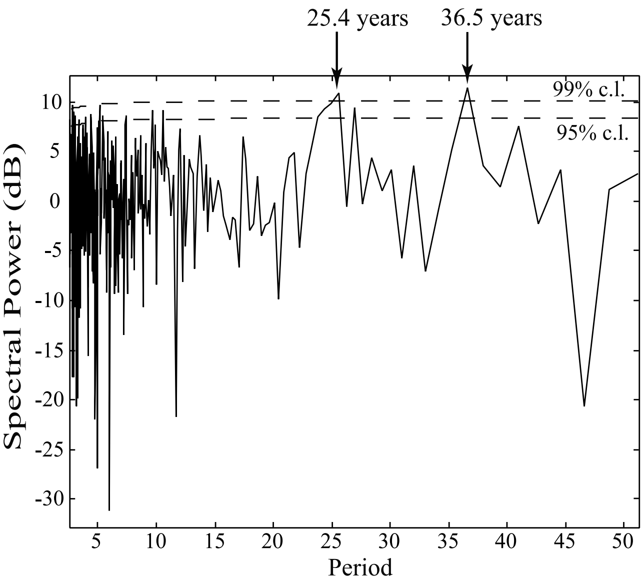

Figure 7. Power spectra for the 1300–1996 A.D. annual LDEOF1 sea salt record. The 95% and 99% confidence levels are based on a first-order Markov model [*Meeker et al.*, 1995]. Period represents years per cycle.

These results are consistent with previous glaciochemical studies that indicate that increased sea salt concentrations are associated with winter-like meteorological conditions (e.g., cooler temperatures and enhanced atmospheric circulation gradients) [*O'Brien et al.*, 1995; *Kreutz et al.*, 1997]. The pattern of intensified atmospheric circulation during winter over Law Dome and lower temperatures is maintained throughout the 700 years of record.

[18] To investigate the dominant periodicities in the annual LDEOF1 sea salt record we utilized spectral analysis [*Bloomfield*, 1976; *Meeker et al.*, 1995]. The 90%, 95%, and 99% red noise critical values were estimated from fifteen simulation runs of a Markov process with lag-1 autocorrelation of the annual LDEOF1 sea salt time series. Peaks that exceed the 99% confidence level occur at 25.4 and 36.5 years (Figure 7). Interestingly, a 20–30-year oscillation in July instrumental SLP between 40°S and 50°S has been identified by *Enomoto* [1991] and attributed to fluctuations in the overall strength of midlatitude zonal circulation associated with symmetric, wave number zero flow around Antarctica. The results of our spectral analysis agree with the findings of *Enomoto* [1991] (i.e., a 20–30-year oscillation in SLP) and further validate the use of the LDEOF1 sea salt record as a proxy for winter SLP conditions and atmospheric circulation patterns over East Antarctica and the Southern Indian Ocean.

8. Conclusions

[19] EOF analysis of the annual DSS glaciochemical, oxygen isotope ratio, and accumulation rate time series indicates that EOF1 (LDEOF1) is a record of marine aerosol (i.e., sea salt) deposition to Law Dome that is not dependent on annual accumulation rate. No significant physically meaningful relationship between the LDEOF1 sea salt record and meridional sea ice extent is found for the period 1973–1996. Analyses of instrumental Antarctic station pressure and NCEP reanalysis SLP data suggest that sea salt concentrations at Law Dome are intrinsically linked to the strength of the winter Antarctic High and its influence on the latitudinal belt occupied by the circumpolar trough. As such, the results presented here provide a 700-year proxy record of multidecadal-scale behavior of the Antarctic High. Comparison of the 700-year LDEOF1 sea salt record with the DSS oxygen isotope ratio winter temperature proxy suggests that cold winters over Law Dome were associated with an intensified wintertime Antarctic High and increased sea salt deposition to DSS.

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