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Sea level pressure variability in the Amundsen Sea region inferred from a West Antarctic glaciochemical record

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Abstract. Using European Center for Medium-Range Weather Forecasts (ECMWF) numerical operational analyses, sea ice extent records, and station pressure data, we investigate the influence of sea level pressure variability in the Amundsen Sea region on a West Antarctic (Siple Dome) glaciochemical record. Empirical orthogonal function analysis of the high-resolution Siple Dome multivariate ice core chemical time series record (SDEOF1) documents lower tropospheric transport of sea-salt aerosols to the site. During 1985–1994 the SDEOF1 record of high (low) aerosol transport corresponds to anomalously low (high) sea level pressure (SLP) in the Amundsen Sea region. Spatial correlation patterns between ECMWF monthly SLP fields and the annual SDEOF1 record suggest that a majority of sea-salt aerosol is transported to Siple Dome during spring (September, October, and November). Analysis of zonal and meridional wind fields supports the SLP/SDEOF1 correlation and suggests the SDEOF1 record is sensitive to changes in regional circulation strength. No relationship is found between sea ice extent and the SDEOF1 record for the period 1973–1994. To investigate the SDEOF1 record prior to ECMWF coverage, a spring transpolar index (STPI) is created, using normalized SLP records from the New Zealand and South America/Antarctic Peninsula sectors, and is significantly correlated (at least 95% c.l.) with the SDEOF1 record on an annual (r = 0.32, $p < 0.001$) and interannual (3 years; $r = 0.51$, $p < 0.001$) basis. Dominant periodicities (3.3 and 7.1 years) in the annual SDEOF1 record (1890–1994 A.D.) suggest that a portion of the recorded interannual variability may be related tropical/extratropical ENSO teleconnections. Changes in the periodic structure of the full (850–1994 A.D.) Siple Dome record suggests a shift in SLP forcing during the Little Ice Age (~1400–1900 A.D.) interval.

1. Introduction

The Antarctic continent is increasingly recognized as an important and dynamic component of the Earth's climate system, because of the critical role the region plays in coupling several climate subsystems (atmosphere, cryosphere, hydrosphere, and biosphere). Understanding interannual climatic variability in the Antarctic region takes on considerable importance when potential regional- to hemispheric-scale interactions are considered, acting both on and from the continent. For example, changes in Southern Hemisphere albedo (through ice sheet and sea ice extent) can potentially alter equator-to-pole temperature gradients and hence influence atmospheric and ocean dynamics. The unique geography of the high-latitude Southern Hemisphere allows transport of ocean temperature and salinity anomalies among the three major oceans (Atlantic, Pacific, and Indian), in addition to potential impacts on ocean basin conditions through deep-water formation. Finally, heat transport between the ocean and atmosphere, particularly near the sea ice margin, can have a significant impact on atmospheric and oceanic circulation.

The Antarctic Circumpolar Wave (ACW) in sea ice extent, sea surface temperature, surface wind speed, and sea level pressure [*White and Peterson*, 1996], which propagates around the continent with a period of 4–5 years is an important example of the significant interannual variability that exists in the southern polar region. On the basis of the frequency of ACW variability and correlation of several other Antarctic instrumental records (such as temperature and precipitation), a potential link exists between interannual Antarctic climate variability and the El Niño-Southern Oscillation (ENSO) [*Smith and Stearns*, 1993; *Cullather et al.*, 1996; *White and Peterson*, 1996]. Mechanisms to explain the propagation of tropical signals to higher latitudes through both the ocean and the atmosphere have been proposed, and mainly focus on the strength of the split polar jet [*Chen et al.*, 1996; *Cullather et al.*, 1996]. Although the exact dynamics of this teleconnection are not yet fully understood, such mechanisms probably exist and need to be understood both in a local and in a regional context.

West Antarctica and the offshore Amundsen Sea region (taken broadly to include the Ross, Amundsen, and Bellingshausen Seas (Figure 1)) exhibit the greatest degree of interannual climatic variability in Antarctica [*Bromwich*, 1988; *Cul-*

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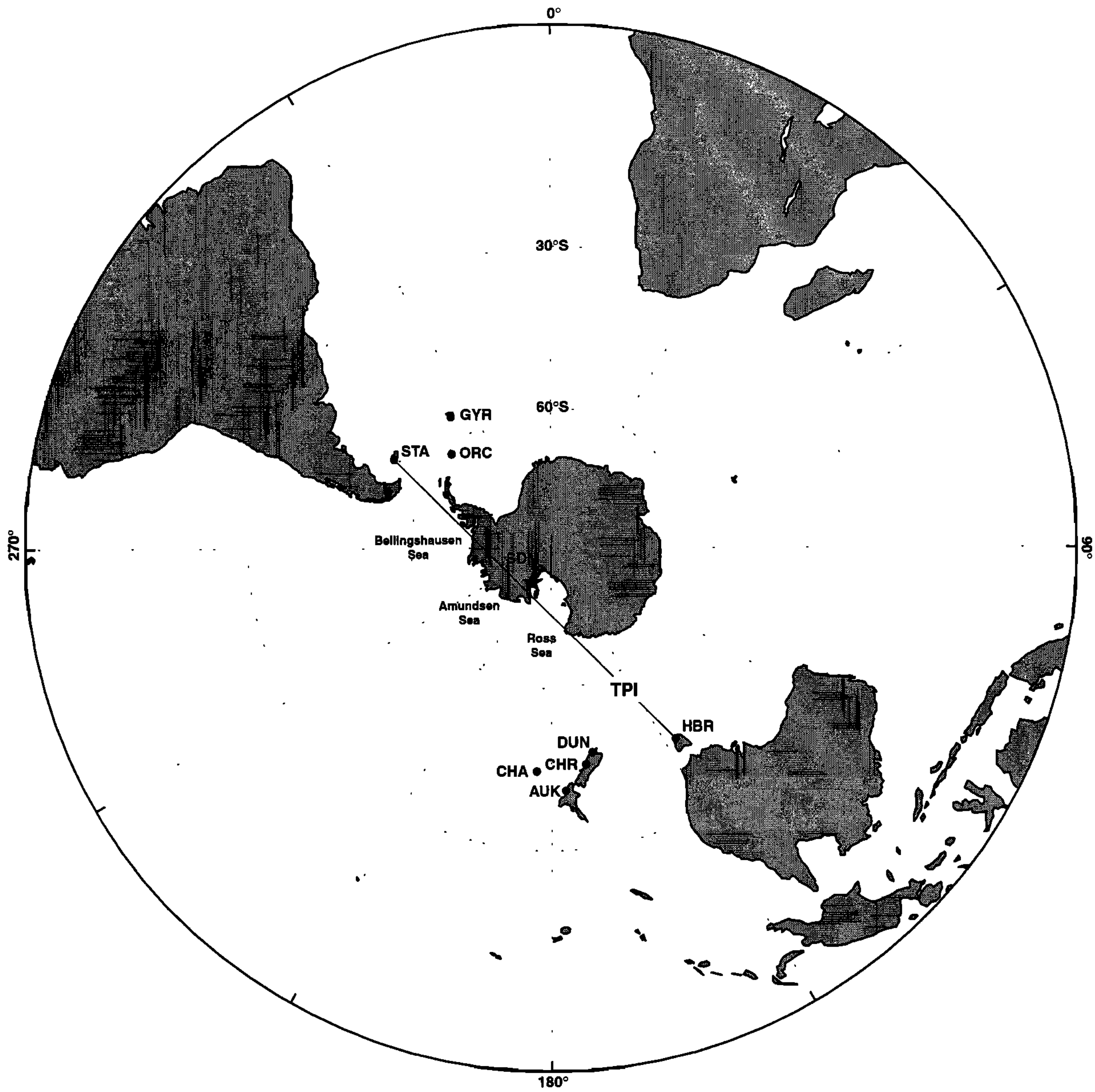

Figure 1. Location map for Southern Hemisphere meteorological sites (abbreviations defined in Table 1, except Hobart (HBR)), and the 1994 Siple Dome (SDM) ice core. TPI represents the transpolar index of *Pittock* [1980].

lather et al., 1996]. Cyclonic depressions that affect weather over West Antarctica come from middle and even subtropical latitudes in the eastern Indian Ocean and western Pacific [*Schwerdtfeger*, 1984]. The belt of westerlies in the high-latitude Southern Hemisphere includes traveling wave cyclones, which originate in the lower middle latitudes, move poleward and intensify, and then stagnate along the coast of Antarctica in four general locations (Amundsen Sea, Weddell Sea, southeast and southwest Indian Ocean [*Carleton*, 1989]). These wave cyclones carry heat and moisture poleward, contributing to heat redistribution in the Southern Hemisphere [*Rogers*, 1983]. Climatological charts of monthly mean sea level pressure resolve four quasi-stationary lows that are always lower than 988 mbar around the continent (Figure 2). One of these low-pressure cells, the Amundsen Sea low (ASL) (Figure 2), is known to play a large role in the interannual climatic variability observed in the West Antarctica/Amundsen Sea region [*Cullather et al.*, 1996]. Cyclonic systems generated in this oceanic sector are of particular importance to the Antarctic continent, supplying ~40% of the moisture flux to the entire continent through West Antarctica [*Bromwich*, 1990]. Advection of warm, moist air from the Amundsen Sea region through West Antarctica has been noted in automatic weather station (AWS) and other regional weather data [*Hogan*, 1997]. In addition, sea ice extent in the Amundsen Sea region displays significant interannual variability over the instrumental period (1973 to present [*Jacobs and Comiso*, 1997]).

While meteorological and sea ice studies have made significant progress in describing interannual variability in the Amundsen Sea region and potential teleconnections with lower latitudes, they are limited to the short length of the instrumental record in Antarctica (~40 years). Modeling efforts are making progress in simulating several climatic parameters in the high southern latitudes; they too, however, are limited in terms of validation by the short instrumental record. High-resolution proxy records offer the potential to estimate and extend observational data prior to station or instrument installation. Correlations between ice core stable isotope and station temperature records from the Antarctica Peninsula suggest that calibrated temperature proxy records can be derived in Antarctica [*Peel*, 1992]. Ice core glaciochemical records provide proxy information on the general atmospheric circulation [e.g., *Mayewski et al.*, 1997], recording the transport and deposition of species derived from a number of diverse source areas [*Legrand and Mayewski*, 1997]. Here we present a new high-resolution ice core glaciochemical record from West Antarctica which can be used in conjunction with available instrumental data to investigate sea level pressure (SLP) variability in the climatologically dynamic West Antarctic region.

Glaciochemical variability, notably in sea-salt species, in a Siple Dome ice core (Figure 1) was previously linked to the overall intensity of atmospheric circulation in the Amundsen Sea region [*Kreutz et al.*, 1997] and documents, for example, the onset of Little Ice Age conditions in the region. Here we use European Centre for Medium-Range Weather Forecasts (ECMWF) numerical operational analyses, a record of meridional sea ice extent, and instrumental (station pressure) data to investigate the influence of interannual climatic conditions in the Amundsen Sea region on glaciochemical concentrations at Siple Dome. The four overall goals in our study are to (1) identify the main source area(s) and transport pathway(s) for marine aerosol species to Siple Dome; (2) estimate the input timing of marine aerosol species to Siple Dome, so that the time series ice core record can be compared to meteorological records; (3) use a high-resolution ice core time series of marine aerosol transport and deposition to Siple Dome to define and justify a proxy record of interannual SLP variability in the Amundsen Sea region over the past century; and (4) investigate SLP variability in the Amundsen Sea over the past millennium using a 1150-year Siple Dome glaciochemical record.

2. Data

A 150 m core was recovered from Siple Dome, West Antarctica (81.65°S, 148.81°W (Figure 1)), during the 1994/1995 field season [*Mayewski et al.*, 1995]. The upper 24 m of firn were processed at 2 cm intervals by removing all exposed surfaces via scraping with precleaned stainless-steel blades. Below 24 m depth, samples were processed in the same manner at 25 cm intervals. Sample blanks (frozen ultrapure deionized water) were included in processing every meter to verify contamination-free procedures. Samples were melted at room temperature in sealed plastic (polyethylene) containers immediately prior to analysis. Anion (Cl^-, NO_3^-, and SO_4^{2-}) and cation (Na^+, Ca^{2+}, K^+, Mg^{2+}, NH_4^+) analyses were performed via suppressed ion chromatography. Cations were analyzed with a CS12 column, 125 μL loop, and 20 mM MSA eluent. Anions were analyzed with a AS11 column, 75 μL loop, and 6 mM NaOH. Dating of the core was accomplished using annual signals preserved in several chemical species, β-activity profiles, and volcanic horizons [*Kreutz et al.*, 1997, 1999a]. The resulting depth/age scale indicates an age of 1890 A.D. at 24 m,

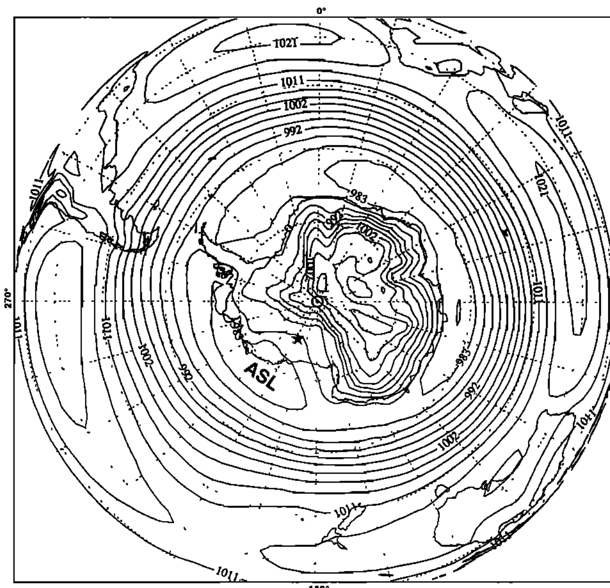

Figure 2. Mean annual sea level pressure (SLP) for the 1985–1995 period from ECMWF numerical operational analysis. ASL refers to the Amundsen Sea low, a semipermanent climatological feature located in the West Antarctic/Amundsen Sea region.

yielding a resolution of 6–12 samples/yr for the past 110 years and biyearly resolution to 850 A.D. (150 m in depth). Raw chemical data time series for the 1994 Siple Dome ice core are shown by *Kreutz and Mayewski* [1999], and 5-year resampled Na^+ and non-sea-salt SO_4^{2-} data are shown by *Kreutz et al.* [1997].

Empirical orthogonal function (EOF) analysis is applied to the multivariate Siple Dome glaciochemical record to examine chemical covariance through time [*Kreutz and Mayewski*, 1999]. In any EOF analysis the first EOF is a single time series that maximizes the variance present in each individual time series and is analogous to a weighted average. EOF results given by *Kreutz and Mayewski* [1999] indicate that the first EOF (SDEOF1) explains a considerable (~50%) portion of the overall chemical variance and is loaded primarily (>90%) by the major components of sea-salt aerosols (Na^+, Cl^-, and Mg^{2+}). Because the EOF loadings for these species are so strong the SDEOF1 time series is indistinguishable from the individual chemical species records in terms of trends and variability. Given the position (adjacent to the Ross Ice Shelf) and elevation (621 m) of Siple Dome, it appears that the site is heavily influenced by marine air masses advected inland from the Amundsen Sea region and is therefore sensitive to changing coastal climatic conditions. The SDEOF1 time series has no significant relationship with annual accumulation rate at Siple Dome [*Kreutz et al.*, 1999b] and therefore provides information on the transport and deposition of marine aerosols which is independent of moisture flux. We interpret the SDEOF1 time series as a record of marine aerosol production, transport, and deposition to Siple Dome and therefore seek to quantify these processes using modeled and instrumental meteorological data. As such, we expect the relevant climatic parameters to be SLP, meridional (v) and zonal (u) wind strength, and sea ice extent.

Numerical analyses have played an important role in a va-

Table 1. New Zealand and South American/Antarctic Peninsula Meteorological Stations Used to Create Regional Records of Monthly Mean Sea Level Pressure (SLP)

Station Name	Latitude	Longitude	First Year	Abbreviation
South American/Antarctic Peninsula Stations				
Grytviken, South Georgia	54.3°S	36.5°W	1905	GYR
Orcadas, South Orkneys	60.7°S	44.7°W	1903	ORC
Stanley	51.4°S	57.9°W	1841	STA
New Zealand Stations				
Auckland	37.0°S	174.5°E	1853	AUK
Christchurch	43.5°S	172.6°E	1864	CHR
Dunedin	45.9°S	170.5°E	1864	DUN
Chatham Island	44.0°S	176.6°E	1930	CHA

riety of atmospheric studies in high southern latitudes [e.g., *Trenberth and Solomon*, 1994; *Bromwich et al.*, 1995; *Budd et al.*, 1995]. Validation studies of such analyses produced by ECMWF, the National Centers for Environmental Prediction (NCEP), and the Australian Bureau of Meteorology found that the ECMWF analyses were superior in depicting high-latitude Southern Hemisphere meteorological conditions, based on comparisons with rawinsonde and glaciological data [*Bromwich et al.*, 1995]. The ECMWF analyses are generally found to offer a reasonable depiction of the broadscale atmospheric circulation, pressure level fields, and surface winds when compared to Antarctic AWS units and ship observations [*Cullather et al.*, 1997]. The ECMWF archive we employ here was obtained from the National Center for Atmospheric Research (NCAR) and contains monthly averaged analyses (reported at 0000 and 1200 UTC) on a 2.5° latitude-longitude grid, at 14 standard pressure levels as well as surface and boundary level variables for the period 1985–1995.

Instrumental data used to further investigate the link between climatic conditions in the Amundsen Sea region and EOF1 include time series of sea ice extent and station pressure data. The sea ice extent data we use covers 1973–1995 and represents one of the longest Southern Hemisphere sea ice data sets available. The monthly data (averaged over each 10° of longitude) on the latitude of the sea ice edge is derived from the U.S. Navy-National Oceanic and Atmospheric Administration (NOAA) Joint Ice Facility weekly maps in the compilations of *Jacka* [1983] and *Simmonds and Jacka* [1995]. Although there are several automatic weather stations in the vicinity of Siple Dome, the short record length (1-5 years) and substantial data gaps make the records unsuitable for use in this study. Continuous monthly sea level pressure (SLP) data were obtained from seven stations in the Southern Ocean thought to reflect conditions in the Amundsen Sea region (Table 1 and Figure 1).

3. Results and Discussion

3.1. Investigation of Siple Dome EOF1 Time Series Using ECMWF Analyses (1985–1994)

To begin to investigate the relationship between SLP in the Amundsen Sea region and Siple Dome glaciochemistry, we define years of high and low marine aerosol transport as being at least $\pm 1\sigma$ from the 1985 to 1994 SDEOF1 mean. Accordingly, low years are 1994 and 1991, and high years are 1992 and 1989. Subtracting low-year mean annual SLP fields (derived from the ECMWF data set) from high-year fields results in the spatial patterns presented in Figure 3a. The influence of SLP conditions in the Amundsen and Bellingshausen Seas on aerosol transport to Siple Dome is apparent, with the highest negative difference occurring at ~225°–270°W. The significant negative difference suggests that at least on an annual basis, when transport of marine aerosol to Siple Dome is enhanced, Amundsen Sea SLP is relatively low (~8 mbar anomaly). A test performed by differencing SLP from random years during 1985–1994 does not reveal a similar pattern in the Amundsen Sea region.

The SLP difference field presented in Figure 3a is very similar to the mean position of the Amundsen Sea low (ASL), a climatological feature (Figure 2) associated with cyclonic activity propagating into the region. Variability in both the position and the intensity of the ASL is known to occur on interannual timescales, with shifts in mean annual position occurring between the Ross Sea and close to the Antarctic Peninsula [*Cullather et al.*, 1996]. Modeled moisture flux into a portion of West Antarctica, including Siple Dome, demonstrates the influence of the ASL, with normal net precipitation conditions occurring when the ASL occupies a position near the eastern Ross Ice Shelf [*Cullather et al.*, 1996]. Under these conditions, moisture flux into the region (and likely to Siple Dome) occurs from almost due north. Under low net precipitation conditions, the ASL is significantly farther east and closer to the Antarctic Peninsula. Fluctuations in modeled moisture flux into the region, and hence the position of the ASL, have been linked to ENSO warm events (i.e., low precipitation and the ASL positioned near the Antarctic Peninsula during 1982 and 1987 [*Cullather et al.*, 1996]). Results presented in Figure 2 are consistent with the relationship previously noted between the ASL and the moisture flux and suggest that the ASL influences aerosol transport in the region as well.

Previous studies suggest that the majority of sea-salt deposition occurs at Siple Dome in winter (broadly defined as April to November [*Kreutz et al.*, 1998, 1999a]). These results are based on linear interpolation of the depth/age scale between known summer peaks in other chemical species. In an attempt to better define sea-salt input timing, as well as investigate the influence of the ASL on SDEOF1, we correlate monthly gridded SLP values for the entire Southern Hemisphere with mean annual SDEOF1 values. By doing so, we avoid any assumption regarding chemical input timing on a seasonal basis. The spatial distribution of the correlation coefficients was examined for each month. We sought correlations significant (at the 95% c.l.) over large areas (i.e., at least several hundred square kilometers) which persisted through at least 2 months, indicating a dominant dynamical process that may be linked to SDEOF1. Results of these monthly correlations reveal significant correlation in the Amundsen and Bellingshausen Seas during the months of September, October, and November (SON) (Figures 4a–4c). Correlations are negative during these months, consistent with our finding of decreased Amundsen Sea SLP and increased SDEOF1. SLP difference analysis (Figure 3b), using only the SON pressure fields, indicates a similar region of SLP influence (~235°–260°) as in the annual analysis (Figure 3a). While the size of the region of negative correlation remains roughly constant during the 3-month period, the position migrates ~30° longitude to the west (Figures 4a–4c). In addition, a region of positive correlation seen in the midlatitudes (20°–60°S) displays variability in both size and position in

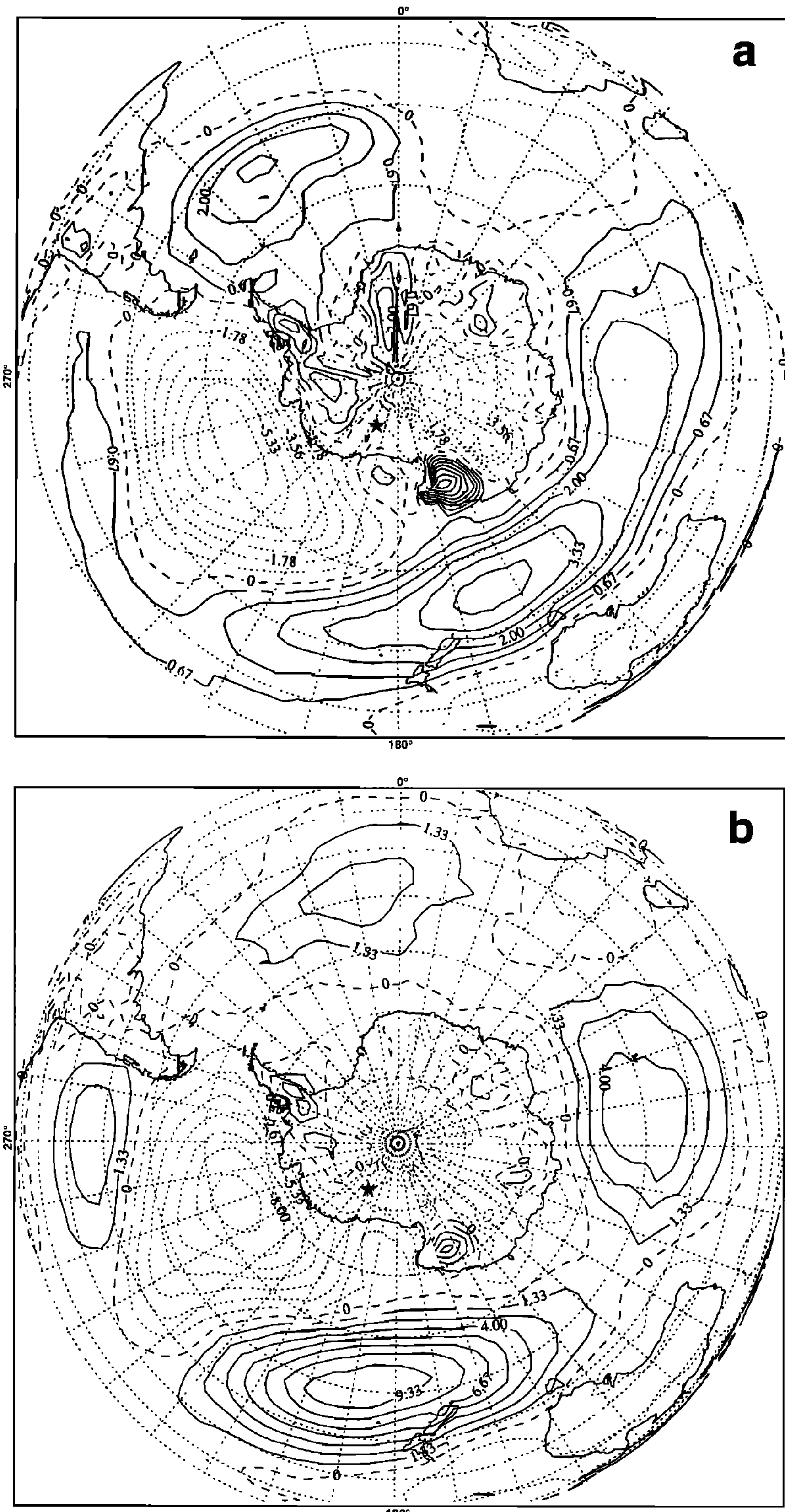

Figure 3. (a) Mean annual SLP differences derived from ECMWF numerical analyses. Method used to select years based on the Siple Dome EOF1 record is described in the text. Values plotted are SLP differences in millibars, with positive values contoured every 0.67 mbar (solid lines), and negative values contoured every 0.89 mbar (dashed lines). (b) Mean September to November (SON) SLP differences derived from ECMWF numerical analyses. The same years were used in the SON analysis as in Figure 3a. Values plotted are SLP differences in millibars, contoured every 1.33 mbar.

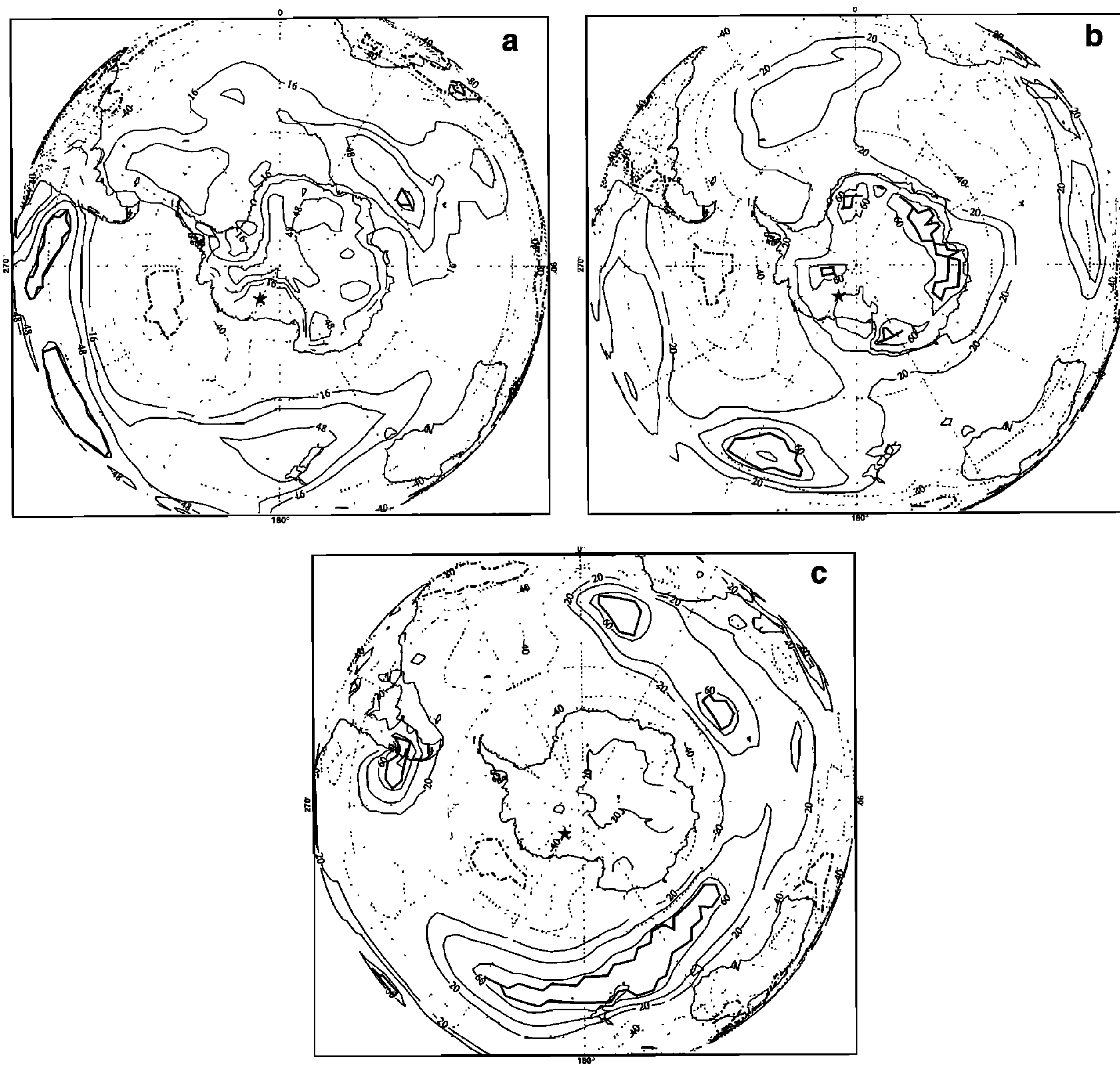

Figure 4. Spatial correlation patterns for the period 1985–1994 between monthly SLP and the mean annual SDEOF1 record for (a) September, (b) October, and (c) November. Plotted values are correlation coefficients (r) × 100, with positive values contoured at an interval of 20 (except for Figure 4a at 16) and negative values at an interval of 40. Bold broken lines indicate significant (95% c.l.) negative correlations, and bold solid lines represent significant (95% c.l.) positive correlations.

the SON period. The reason behind the observed migrations in spatial correlation patterns is unclear but may have to do with high-latitude blocking (formation of persistent high-pressure systems near Australia) on a seasonal scale [*Sinclair*, 1996]. On a mean annual basis, *Cullather et al.* [1996] demonstrated that the position of the ASL migrates ~1400 km, apparently in response to changes in the split tropospheric jet. While these fluctuations probably affect the SDEOF1 record on an annual basis, it is unclear how such changes would affect the monthly correlation patterns. Regardless, it appears that SON is the period of maximum sea-salt input to Siple Dome.

Previous glaciochemical investigations have explained increased sea-salt loadings as mainly being a result of increased zonal and meridional wind stress [e.g., *Mayewski et al.*, 1993, 1997; *O'Brien et al.*, 1995]. The ECMWF data set allows for an examination of the u and v (at 10 m) wind components and SDEOF1. Difference fields for the u wind component in SON indicate increased (by 2.7–3.9 m/s) westerly flow in the South Pacific 35°–65°S region and increased (by 2.2–2.8 m/s) easterly flow in the 65°–80°S region. Corresponding fields for the v wind component demonstrate increased (by 1.8–2.7 m/s) northerly flow from 195° to 240°W and increased (by 2.2–2.7 m/s) southerly flow from 240° to 270°W. In terms of mean synoptic conditions these wind patterns suggest enhanced cyclonic activity associated with the ASL (i.e., increased cyclonic airflow around the mean low-pressure location). Correlations between monthly u and v wind stress and annual SDEOF1 values reveal similar wind strength patterns (correlations above the 95% c.l. in the Amundsen Sea region suggesting increased ASL intensity) during the SON season.

Unlike several other regions in Antarctica, there are no coastal stations in West Antarctica from which aerosol measurements are available for comparison with the Siple Dome EOF1 results. An analysis of back trajectories to South Pole for the period 1985–1989 suggests, however, that a majority of the marine aerosol that reached South Pole is advected through West Antarctica and originates in the Amundsen Sea region [*Harris*, 1992]. Most input of particle-laden air to the South Pole region occurs as discrete cyclonic events resulting in widespread warming [*Hogan*, 1997]. Aerosol measurements made during these warmings indicate the predominance of sea-salt species [*Parungo et al.*, 1979; *Bodhaine et al.*, 1986]. The annual cycle in sea-salt aerosol at South Pole, estimated from nephelometer aerosol-scattering extinction coefficients, shows a peak in SON [*Bodhaine et al.*, 1986]. Timing of this peak is consistent with the yearly breakdown of the Antarctic vortex (decline of inland high-pressure systems) and associated increase in vertical mixing [*Hogan and Gow*, 1993]. In a study of seasonal changes in surface pressure using ECMWF data, *Parish and Bromwich* [1997] found that the most pronounced changes occur during transitional periods (SON) when thermal adjustment in the lower atmosphere alters the vertical distribution of pressure. *Rogers* [1983] noted the relationship between higher spring temperature variability and increased meridional circulation in Antarctic station data. While our SON sea-salt input estimate from Siple Dome is consistent with South Pole measurements, air masses reaching South Pole across the West Antarctic polar plateau probably do not affect Siple Dome directly. Therefore we also compare our results to those from the Ross Ice Shelf [*Warburton et al.*, 1981; *Herron and Langway*, 1979]. Chemical measurements in snowpit and core samples from the Ross Ice Shelf were shown to peak in winter/spring based on comparison with oxygen isotope profiles [*Warburton et al.*, 1981; *Herron and Langway*, 1979], and thus sea-salt deposition at Siple Dome during SON appears to be consistent with regions both to the east and to the west.

3.2. Sea Ice Extent/Glaciochemical Relationships 1973–1994

The influence of sea ice extent and concentration on determining sea-salt production and transport to a given core site has been addressed by several authors [e.g., *Peel and Mulvaney*, 1992; *Mayewski et al.*, 1994; *Wagenbach*, 1996]. Two views are (1) source argument: decreased sea ice extent and increased open lead areas result in increased sea-salt production and hence increased ice core sea-salt concentration and (2) circulation strength argument: sea-salt aerosol and snow concentrations display maxima during cold periods of enhanced meridional flow (i.e., winter, Little Ice Age, Last Glacial Maximum), which are also the times of maximum sea ice extent. These two views need not be mutually exclusive, and if so, it may be difficult to separate their individual effect on an ice core record.

Statistical (EOF) analysis of the entire sea ice anomaly data set (thirty-six 10° longitude bands × 288 months) indicates that the greatest degree of ice-edge variability occurs in the 170°–250° region, consistent with observations of *Simmonds and Jacka* [1995]. Comparison of seasonal (DJF, MAM, JJA, and SON) mean sea ice extent time series for this region with SDEOF1 reveals no significant correlations. A comparison of mean SON sea ice anomalies during high and low SDEOF1 years (Figure 5) (years used are given in section 3.1) suggests that a large portion of the Amundsen Sea region is out of phase with adjoining regions. These results suggest that during years of increased aerosol transport, sea ice extent in the Amundsen Sea region may be anomalously high. This would contradict source arguments and support circulation strength arguments which indicate cold periods are times of increased sea-salt flux [*Mayewski et al.*, 1994; *O'Brien et al.*, 1995]. To further investigate the sea ice/SDEOF1 relationship, monthly time series of sea ice extent in each 10°-wide longitude slice was correlated with the SDEOF1 mean annual time series for 1973–1994. Results indicate significant correlations only in three months (January, April, and November) and in no more than two 10°-wide regions. During months previously identified as having increased aerosol transport (SON), there is no coherent correlation pattern between monthly sea ice extent (by 10° region) and SDEOF1 (Figure 6). If a strong physical link exists between sea ice extent and aerosol transport to Siple Dome, we would expect to see significant correlations over a larger region and in consecutive months.

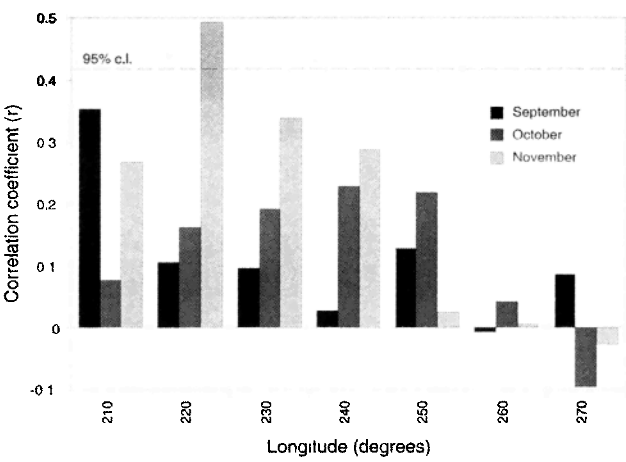

Figure 6. Correlation coefficients (r) of monthly sea ice extent (September to November) and annual EOF1 values for the period 1973–1994. Sea ice extent data are averaged over each 10°-wide longitude slice. Longitudes correspond to 90°–150°W.

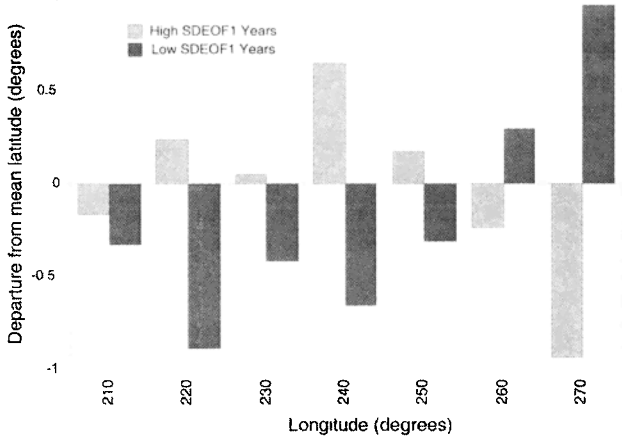

Figure 5. Average sea ice extent anomalies for September to November during years of high and low SDEOF1. Longitudes correspond to 90°–150°W. Positive (negative) latitude departures represent northward (southward) sea ice extent.

Because we cannot identify a quantitative relationship between sea ice extent and SDEOF1, transport of marine aerosols during SON is likely driven by SLP changes and enhanced air mass advection. In a detailed study of the Amundsen and Bellingshausen Sea regions, *Jacobs and Comiso* [1996] noted significant interannual variability in sea ice extent over the past two decades, with an overall 20% decline during that period. The decrease in sea ice extent was negatively correlated with surface air temperatures on the west side of the Antarctic Peninsula, which has increased ~0.5° per decade since the mid-1940s. No relationship was found, however, between mean wind stress or direction during the same interval. *Carleton* [1989] investigated relationships between the SLP and the sea ice extent in the Ross Sea and found that stronger midlatitude westerlies were associated with more extensive sea ice coverage in the region, consistent with observations by *Streten and Pike* [1980] and a modeling study by *Mitchell and Hills* [1986]. SON is the period of maximum sea ice extent in the Amundsen Sea region [*Gloerson et al.*, 1992], which perhaps explains in part the insensitivity of the Siple Dome EOF1 record to interannual changes in sea ice extent.

Previous comparisons of SLP and glaciochemical concentrations on the Antarctic Peninsula [*Peel and Mulvaney*, 1992] have suggested that sea-salt concentrations in the ice core record are also primarily a result of SLP fluctuations and not necessarily sea ice conditions. Major Cl^- peaks tend to occur when the Orcadas-Halley pressure index is low, suggesting the circumpolar trough is shifted northward. Under these conditions, cyclones will track more frequently across open ocean areas to the north of the ice edge, which favors the generation and inclusion of sea-salt aerosols [*Peel and Mulvaney*, 1992]. Although not commented upon, the Dolleman Island Cl^- record from 1900 to 1983 appears to be positively correlated with sea ice duration in the South Orkneys [*Peel and Mulvaney*, 1992]. In addition, mean annual Cl^- values at Dolleman Island are negatively correlated with air temperatures at Faraday Station [*Peel et al.*, 1996]. *King* [1994] demonstrated a strong correlation between annual mean temperatures in the peninsula and index of meridional circulation (South Orkney Islands minus Faraday SLP), suggesting that high Cl^- values at Dolleman are related to enhanced southerly flow. It therefore appears that transport of Cl^- to Dolleman Island, as at Siple Dome, is primarily a function of SLP variations and cyclonic tracks and not necessarily sea ice extent. A continuous 2-year aerosol study at Halley Station [*Hall and Wolff*, 1998] demonstrates that maximum sea-salt aerosol concentrations occur during periods of moderate winds and maximum sea ice extent, which may be related to formation of concentrated brine on the surface of local, fresh sea ice. We again note the lack of correlation found between SDEOF1 and sea ice extent in both the SON and the prior JJA seasons and suggest that other proxy records of sea ice extent in the Amundsen Sea region (e.g., methanesulfonic acid [*Welch et al.*, 1993]) should be sought.

3.3. Extending SDEOF1/Synoptic Meteorological Comparisons Using Station Meteorological Data

Although results suggest a relationship between SDEOF1 and ASL, we acknowledge that 10 years of correlation is insufficient to establish the SDEOF1 record as a robust proxy of the ASL prior to 1985. Given our goal of estimating climatic variability in the Amundsen Sea region over the past millennium using the SDEOF1 time series, we now seek to extend the SDEOF1/instrumental correlation prior to the 10 years represented by ECMWF data. Differences in SLP between pairs of stations have traditionally been used as indices of the large-scale atmospheric circulation, particularly where station density is sparse [e.g., *Trenberth*, 1976; *Lamb*, 1977]. Previous work has defined the TPI (the difference in SLP between Hobart, Tasmania (43°S, 147°E), and Stanley, South Atlantic Ocean (52°S, 58°W) (Figure 1)) to measure the eccentricity of the polar vortex around the South Pole [*Pittock*, 1980].

Although the TPI has proven very diagnostic in analyzing circum-Antarctic mean annual pressure fluctuations, we are interested here mainly in pressure fluctuations in the Amundsen Sea region during the spring (SON) season. We have used the technique of *Villalba et al.* [1997] to derive a STPI using SON SLP data from New Zealand and South America/Antarctic Peninsula stations (Figure 1 and Table 1). To calculate regional pressure records, the annual SON time series for each station was normalized, and then station SLP records within each region were combined using a linear average. Differences in annual regional pressure records (New Zealand minus South America/Antarctic Peninsula) were used to develop the STPI (Figure 7a). Although several of the stations have records extending to the mid-1800s, the STPI has been calculated from 1903 to 1994 for three reasons: (1) inhomogenieties in New Zealand SLP records are known to exist during the nineteenth century [*Villalba et al.*, 1997]; (2) this is the longest common time period of SLP record for available stations (Table 1); and (3) this period covers the length of the subannually sampled portion of the SDEOF1 record (1890–1994).

We assume the STPI index is sensitive to ASL pressure fluctuations and location. On the basis of results presented in Figures 3 and 4, positive STPI values suggest intensification of the ASL and formation of a positive pressure anomaly near New Zealand, while negative STPI values reflect opposite conditions. Examination of mean SON pressure anomalies in the Amundsen Sea region indicates this pattern is consistent through 1985–1995. Therefore we interpret positive STPI values as indicating increased cyclogenesis in the Amundsen Sea and associated deeper low pressure in the ASL. The STPI and EOF1 records are significantly correlated ($r = 0.32$, $p < 0.001$) for the period 1903–1994 (Figure 7a). We note, however, that the correlation statistics, while highly significant, highlight the fact that the SDEOF1 record does not provide an absolute estimate of ASL fluctuations on an annual basis. Possible sources of error in the ice core record include dating error (estimated to be ±1 year in the 1903–1994 time period), snow redistribution on subannual to annual timescales, and local spatial variability in aerosol deposition. To account for these potential errors and to highlight interannual variability, we have applied a 3-year running mean to both series (Figure 7b). At this resolution, correlation statistics increase ($r = 0.51$, $p < 0.001$), and the SDEOF1 series accounts for ~50% of the STPI variance. Correlation results on both timescales suggest that the SDEOF1 record is a viable proxy record of SLP variability in the Amundsen Sea region.

Estimates of ASL variability based on the SDEOF1 record (Figures 7a and 7b) can be compared to other proxy records of the high-latitude Southern Hemisphere over the last century. The only other investigation of SLP variations in the high-latitude Southern Hemisphere was done using tree-ring chronologies from Tierra Del Fuego and New Zealand [*Villalba et al.* 1997]. Summer (November to February) SLP conditions in the two regions, as well as long-term transpolar teleconnections, were reconstructed for the period 1750–1985 A.D. The Siple Dome EOF1 record provides complementary information, recording SLP variability in a region between the two tree-ring locations. Comparison of the SDEOF1 record and TPI reconstructions from *Villalba et al.* [1997] suggests several periods in the 20th century where the two records are correlated. In particular, the largest positive anomaly in the 230-year reconstructed TPI record occurs during the 1930–1935 period. This period corresponds to the largest positive anomaly in the annual SDEOF1 record (Figure 7a), suggesting that the TPI is recording changes in the overall atmospheric circulation of the circumpolar vortex [*Carleton*, 1989]. High-pressure blocking systems off New Zealand are known to have a large influence on steering the westerly system and cyclogenesis toward the Amundsen Sea [*Sinclair*, 1996]. Likewise, a broad increase in the TPI occurs from ~1952 to 1960, which corresponds to a similar increase in EOF1.

3.4. Connections Among the El Niño-Southern Oscillation, Amundsen Sea Low, and the SDEOF1 Record

Despite the relatively short record of conventional Antarctic meteorological data, several studies have demonstrated a link between the El Niño-Southern Oscillation (ENSO) and the high southern latitude meteorology. In particular, variations in SLP and height field anomalies for the Southern Hemisphere, including Antarctica and vicinity, have been examined by *van Loon and Shea* [1987] and *Karoly* [1989] using analyzed fields. As the number of these studies grows, identification of the mechanisms involved in propagation of the ENSO signal has evolved. *Newall et al.* [1981] speculated that possible high-latitude forcing of the Southern Oscillation could be achieved by atmospheric forcing of the Antarctic Circumpolar Current and subsequent sea surface temperature propagation northward via the Peru Current. More recent articles, however, have focused on the role of the South Pacific atmospheric double jet variability in the southward propagation of the ENSO signal [*Smith and Bromwich*, 1994; *Smith et al.*, 1995; *Chen et al.*, 1996]. Tracks of cyclones and anticyclones in this region are strongly influenced by the double jet [*Sinclair*, 1996], and the relative strength of the two components of the double jet varies in conjunction with the SOI [*Chen et al.*, 1996]. Although the nature and role of the double jet oscillation is not well understood, it may be responsible for at least part of the observed variability in both the position and the intensity of the ASL [*Cullather et al.*, 1996]. *Cullather et al.* [1996] have noted that the moisture flux into West Antarctica is strongly controlled by the position of the ASL, which was shown to migrate ~1400 km between years of high and low (1980 and 1982) precipitation. Given the relationship between the split jet and the SO, and the observed variations in ASL position and modeled moisture flux, *Cullather et al.* [1996] speculated that the ASL and SO have a physical connection.

In a study of several observational data sets, *White and Peterson* [1996] noted interannual circum-Antarctic variability in SLP, SST, sea ice extent (SIE), and meridional wind stress (MWS). In particular, coupled anomalies in the studied parameters propagate eastward, taking 8–10 years to fully encircle the continent and were hence named the Antarctic Circumpolar Wave (ACW). Variability at a given location can be expected with a 4 to 5-year periodicity. In the Amundsen Sea region, SLP and MWS variability during the 1985–1994 period are in phase (decreased (increased) SLP corresponding to southward (northward) MWS) and are consistent with our findings based on correlations with the SDEOF1 record. On the basis of the observed periodicity, *White and Peterson* [1996] speculate that initiation of the ACW is associated with ENSO activity in the equatorial Pacific, possibly through an atmospheric teleconnection with higher southern latitudes. In addition, feedbacks probably exist to maintain the ACW as it travels around Antarctica, which may alter the propagation itself [*White and Peterson*, 1996].

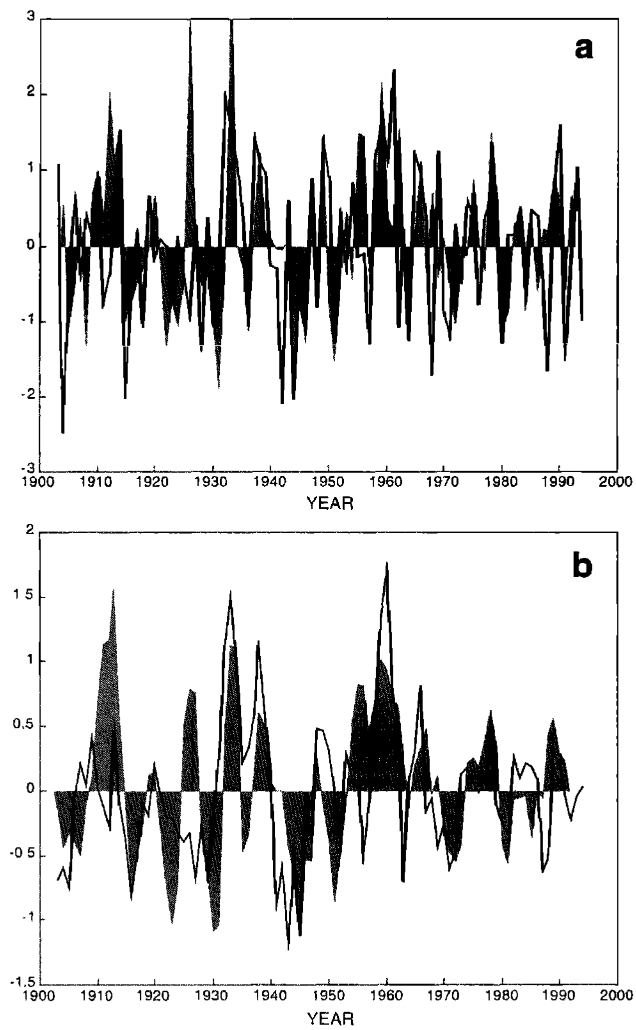

Figure 7. Correlation of (a) annual mean and (b) 3-year running mean SDEOF1 (solid line) and spring transpolar index (STPI) index (shaded line) records (both in normalized units) for the period 1903–1994.

Having demonstrated the relationship between the ASL and the SDEOF1 record, we now investigate the SDEOF1 record for a potential ENSO signal. To determine the dominant periodicities in the annual-resolution SDEOF1 record, we employ the spectral analysis technique using modified discrete Daniel smoothing [*Bloomfield*, 1976; *Meeker et al.*, 1995]. Fifteen simulation runs of a Markov process with lag-1 autocorrelation of the time series estimate the 95% red noise critical values. Peaks that exceed the 95% confidence level occur at 3.3 and 7.1 years (Figure 8). Because these periods are less than 10 times the sample interval, we tested for significance using a

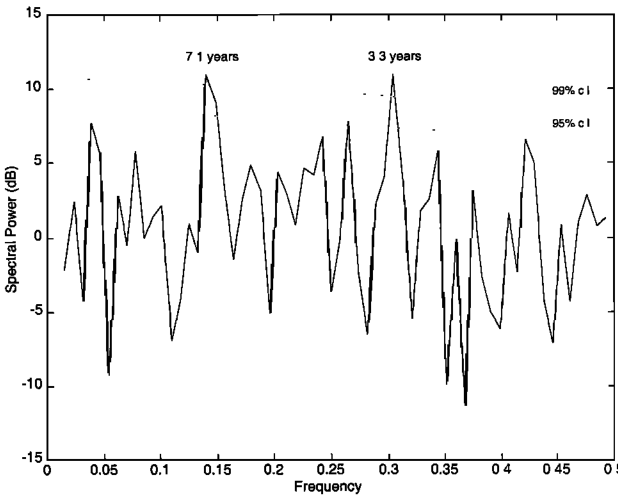

Figure 8. Power spectra for the 1890–1994 SDEOF1 record. The 95% confidence level is based on a first-order Markov model [*Meeker et al.*, 1995]. Frequency represents cycles/year.

Fisher's test of the un-padded spectrum. Again, peaks at 3.3 and 7.1 years are significant at the 95% confidence level. As a further test, identical analyses were performed on a 12 sample/year SDEOF1 time series (close to the original core sampling interval) and yielded identical 3.3- and 7.1-year components. The 3.3-year oscillation in the SDEOF1 record is similar to the 3.4-year oscillation present in the Southern Oscillation Index (SOI) [*Mann and Park*, 1994] and is consistent with the dominant periodicity noted in tree-ring reconstructions of Southern Ocean summer SLP [*Villalba et al.*, 1997]. There is no significant variability at 7.1 years associated with ENSO [*Mann and Park*, 1994]; however, coherency was noted between reconstructed summer SLP in New Zealand and South America and the SOI [*Villalba et al.*, 1997]. The ubiquitous nature of these oscillations in high southern latitude SLP and precipitation [*Bromwich et al.*, 1999] reconstructions provides further evidence of a teleconnection with tropical processes and suggests that an ENSO influence on the ASL may have persisted for at least the last century.

3.5. SLP Variability in the Amundsen Sea Region Over the Past 1150 Years

The term Little Ice Age (LIA) represents a late Holocene (nominally ~1400–1900 A.D.) climatic cooling and period of enhanced atmospheric circulation which is well-documented in the Northern Hemisphere, and particularly in the North Atlantic region [e.g., *Lamb*, 1977; *Grove*, 1988; *O'Brien et al.*, 1995; *Keigwin*, 1996]. There is question as to the global extent of this event, in part because the number of continuous high-resolution paleoclimatic records spanning the LIA in the Southern Hemisphere is limited [e.g., *Cook et al.*, 1996]. Ice core records which do exist from South America [*Thompson et al.*, 1986] and Antarctica [*Mosley-Thompson et al.*, 1990; *Kreutz et al.*, 1997] suggest that there was a shift in oxygen isotope ratios and chemical concentrations related to temperature and atmospheric circulation changes during the LIA. The Siple Dome chemistry record has previously been interpreted in terms of changing meridional circulation strength over the past millennium [*Kreutz et al.*, 1997], with an increase in sea-salt aerosol transport at the onset of the LIA (~1400 A.D.) which persists into the present century. On the basis of the correlation of the high-resolution 110-year portion of the Siple Dome record with instrumental data presented above, we interpret these changes in ice core chemistry as reflecting an overall deepening of the ASL during the LIA period. In addition, there is pronounced decadal-scale variability throughout the record, which is enhanced during the LIA period. It therefore appears that SLP gradients in the Amundsen Sea region during the LIA were both enhanced and more variable than the preceding half of the millennium.

To investigate whether changes in the periodic structure of the full Siple Dome record coincide with the LIA interval, we performed evolutionary spectral analysis on the 1150-year resampled (to a 3-year interval) SDEOF1 record (Plate 1). On the basis of empirical studies, a window length of 600 years and time step of 25 years was found to provide reliable results in the spectral analyses. The strongest periodicity observed in the Siple Dome record is 40–45 years (ending ~300 years before present (BP) (2000 A.D.)), with a weaker 20- to 30-year periodicity throughout most of the 1150-year record. This is consistent with the results of *Enomoto* [1991] who noted a similar 20–30 periodicity in the instrumental SLP record for July and 40°–50°S latitudes. Although not commented on, tree-ring reconstructions of Southern Hemisphere summer SLP [*Villalba et al.*, 1997] appear to display a similar 20- to 30-year periodicity. During the LIA interval (~600–100 years B.P.), there is a shift from 60 to 80 years to longer (80–140 years) periodicities. It therefore appears that the periodic behavior of SLP in the Amundsen Sea region over the past millennium has changed significantly, particularly during the last ~600 years. Given the length of the SDEOF1 record, however, it is difficult to interpret the longer periodicities that are confined to the latter portion of the record. Unfortunately, other proxy records of Southern Hemisphere SLP of similar length and resolution do not currently exist with which we can compare our findings. Tree-ring records from Tasmania contain pronounced periodicities similar to the SDEOF1 record (30, 57, 77, 200 years); however, these records are interpreted as temperature and not as SLP proxies [*Cook et al.*, 1996]. New paleoclimate records recovered as part of an international effort to improve the spatial coverage of ice cores in Antarctica (International Trans-Antarctic Scientific Expedition [*Mayewski and Goodwin*, 1996]) as well as deep ice-coring efforts of U.S., European, and Japanese programs should provide a much more comprehensive view of Late Holocene climate in the Southern Hemisphere.

4. Conclusions

Results presented here represent the first meteorological/glaciochemical correlations in West Antarctica and provide a means for reconstructing SLP in the Amundsen Sea region prior to instrumental coverage. By using ECMWF fields for the period 1985–1994, we are able to show that the ice core record of lower tropospheric marine aerosol transport to Siple Dome (SDEOF1) is sensitive to SLP conditions in the Amundsen Sea region. By performing spatial correlation analyses between the monthly ECMWF SLP fields and the annual average SDEOF1 record, the seasonal time period of maximum aerosol input is estimated to be September to November. This result is consistent with aerosol measurements made at Antarctic stations, particularly at South Pole. The significant correlations found among SDEOF1, SLP, and wind stress, but not sea ice extent, highlight the complex interaction of various climate compo-

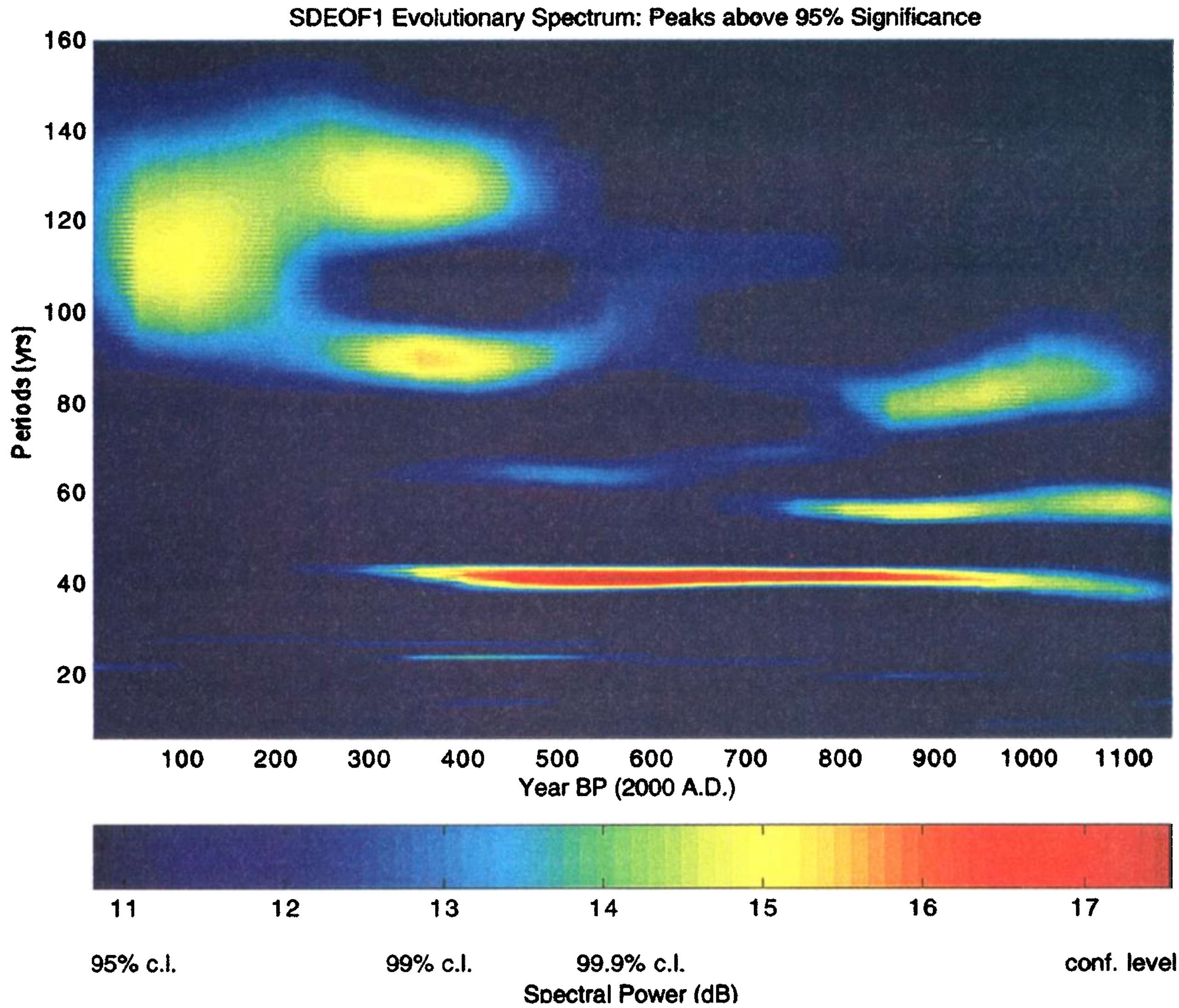

Plate 1. Evolutionary spectrum of the 1150-year SDEOF1 record (3-year resampled data set [*Kreutz et al.*, 1997]). Peaks above the 95% confidence level are denoted as those colored other than the dark blue background. The window length in the analysis is 600 years, with a 25-year step interval.

nents in the region. As there is no apparent connection between the SDEOF1 record and the sea ice extent, other chemical records (e.g., methanesulfonic acid [*Welch et al.*, 1993]) should be investigated for possible relationships with sea ice extent. To calibrate the SDEOF1 record over longer timescales than represented by the ECMWF fields, we have constructed a normalized pressure index using station SLP records (SON) from the New Zealand and Antarctic Peninsula regions. There is a significant correlation between this index and the SDEOF1 record during the 1903–1994 period, providing further confidence that the SDEOF1 record provides a proxy record of SLP conditions in the Amundsen Sea region. Longer records of marine aerosol transport to Siple Dome, on interannual or longer timescales, can therefore be interpreted in terms of regional pressure conditions. On annual timescales the SDEOF1 record probably represents a combination of the overall strength (as evidenced by correlation with TASL) and position of the ASL. A relationship between the ASL and tropical ocean forcing (ENSO) has previously been noted [*Cullather et al.* 1996], and this forcing is recorded in the SDEOF1 record based on results of spectral analysis (3.3- and 7.1-year periodicities). Evolutionary spectral analysis of the full 1150-year SDEOF1 record indicates that significant changes in the periodic structure of this SLP proxy occurred during the Little Ice Age. It is expected that a more diverse array of records, both in terms of the number of parameters measured and the spatial distribution, will provide a more accurate representation of tropical forcing in West Antarctica, as well as a more robust interpretation of decadal-scale SLP variability [*Karoly et al.*, 1996] prior to the instrumental period.

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