Prevalence of the Antarctic Circumpolar Wave over the last two millenia recorded in Dronning Maud Land ice

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[1] The influence of atmospheric circulation patterns on sea salt aerosol deposition in the study area of the new EPICA (European Project for Ice Coring in Antarctica) deep drilling in Dronning Maud Land (DML), Antarctica, has been investigated. Comparison of ice core records with reanalysis data showed that recent sea salt concentrations are strongly influenced by the occurrence of a blocking high pressure ridge over the eastern and enhanced storm activity over the western Atlantic sector of the Southern Ocean (SO) leading to marine intrusions, thus enhanced sea salt export, into DML. These variations occur with periods of 4–5 and 12–14 yr, the prior being associated with the Antarctic Circumpolar Wave (ACW). The prevalence of these periodicities in a 2000 year ice core record from DML shows for the first time that the ACW is a prevalent feature of SO atmosphere dynamics over the last two millennia. *INDEX TERMS:* 0368 Atmospheric Composition and Structure: Troposphere—constituent transport and chemistry; 1620 Global Change: Climate dynamics (3309); 1863 Hydrology: Snow and ice (1827); 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 9310 Information Related to Geographic Region: Antarctica. **Citation:** Fischer, H., F. Traufetter, H. Oerter, R. Weller, and H. Miller (2004), Prevalence of the Antarctic Circumpolar Wave over the last two millenia recorded in Dronning Maud Land ice, *Geophys. Res. Lett.*, *31*, L08202, doi:10.1029/2003GL019186.

1. Introduction

[2] Identification of teleconnection patterns in the Southern Hemisphere has only been possible since the compilation of meteorological data sets of global coverage. One extraordinary example is the ACW which has been identified in observational data from 1985–94 AD [*White and Peterson*, 1996]. During this interval band-pass filtered data on sea level pressure (SLP), sea surface temperature (SST) and sea ice extent (SIE) were characterized by wave number-two anomaly patterns over the SO propagating around Antarctica in about eight years. Cold (warm) SST connected to large (small) SIE anomalies lead (trail) high SLP by approximately one year (equivalent to 45° in longitude). In addition, *Simmonds* [2003] reports an association of ACW anomalies with cyclonic activity. While various modeling studies support the existence of ACW-like patterns in the SO, its persistence and propagation in extended meteorological data sets remains ambiguous [*Bonekamp et al.*, 1999; *Christoph et al.*, 1998; *Connolley*, 2002].

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[3] Here, we aim at extending the temporal perspective of SO atmosphere dynamics using ice core records of sea salt concentrations from the high plateau region of DML. We perform an upscaling study of the ice core archives using spatially resolved reanalysis data. Because sea salt aerosol in DML has its sources predominantly in the Atlantic sector of the SO and is generated and exported efficiently by cyclonic activity it is especially suited for this purpose.

2. Methods

[4] High resolution (4–10 samples/yr) records of four ice cores and snow pits at the sites DML03 (74°30′S, 1°58′E, 2843 m above sea level (a.s.l.)), DML05 (75°00′S, 0°00′E, 2882 m a.s.l.), DML07 (75°35′S, 3°26′W, 2669 m a.s.l.) and DML17 (75°10′S, 6°30′E, 3160 m a.s.l.)) have been analysed by ion chromatography for the concentrations of methanesulfonate, Cl^-, NO_3^-, SO_4^{2-}, Na^+, NH_4^+, Mg^{2+}, and Ca^{2+} [*Göktas et al.*, 2002]. High-resolution measurements are available from 1950–97 AD (1957–84 AD in all three cores), a time span covered by NCEP/NCAR reanalysis data. In addition, long-term anion records in annual resolution have been measured at DML05 covering the time span after 173 AD. The uncertainty of the Na^+ and Cl^- concentrations is less than 5%. Na^+ and Cl^- are equally used as indicators for sea salt aerosol in this study. Because we are mainly interested in interannual variations and periodicities in the sea salt record, the occurrence of a constant chloride excess in DML snow does not affect our conclusions.

[5] For stratigraphic dating of the core at DML05 we used the pronounced seasonal signal in high-resolution continuous flow analysis Na^+ data [*Sommer et al.*, 2000]. The dating error is between 1–5 yr down to 1259 AD dependent on the occurrence of volcanic time markers and increases to ±24 yr around 170 AD [*Traufetter et al.*, 2004]. Since counting errors are distributed stochastically along the record, the dating accuracy is sufficient to resolve a 4 yr ACW cycle. For the interval 1950–1997 AD the seasonality of all chemical tracers has been taken into account. In addition, fix points defined by the year of drilling and by sulfate peaks in 1992, 1968 and 1956 AD attributed to the eruption of Pinatubo/Cerro Hudson, Deception Island and Bristol Island, respectively, limit the dating error for the shallow cores to zero to maximum one year. Only at DML17, where the accumulation rate was 30% lower, no unambiguous dating could be accomplished. Accordingly, this record was excluded from further analyses.

[6] Ice core data were compared to NCEP/NCAR reanalysis data for SLP, geopotential height at the 500 hPa level (z500) and 2 m air temperatures (SAT). To quantify cyclonic

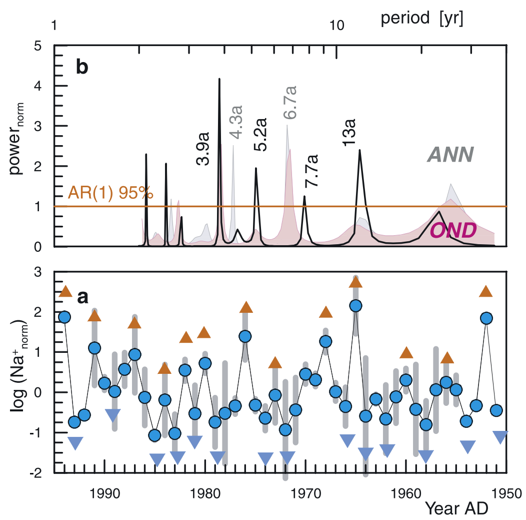

Figure 1. a) Na^+ stack from shallow ice cores in DML: The interval 1957–84 AD is covered by three and 1955–91 AD by at least two cores. Grey error bars indicate the standard deviation, orange triangles mark years of high, blue triangles of low normalized logarithmic Na^+ concentrations used in Figure 2, b) MC-MESA (MESA order M = 22, number of red noise realisations n = 1000) of the Na^+ stack for the time interval 1957–84 AD (black line) and for detrended annual (grey) and OND (pink) SLP data at 55°S, 0°E in the time interval 1948–99 AD. All power spectra are normalized to the red noise 95% significance level.

activity we calculated seasonal and annual means of the variance of band-pass filtered (1–10 days) SLP reflecting the variations induced by passing cyclones. In view of the sparse meteorological data available for the Antarctic ice sheet and its pronounced surface topography, the reliability of reanalysis data for the interior of Antarctica may be questioned. Because we restrict our interpretation to regions along the transport route of the aerosol over the open SO, this problem does not affect our study. Also spurious trends had been reported in reanalysis data for the SO. Comparison with coastal Antarctic station data showed that the interannual variability is sufficiently preserved in the reanalysis after 1968 AD [*Hines et al.*, 2000]. Previous time intervals showed progressive degradation of correlation with meteorological station data which is most pronounced prior to 1958 AD [*Marshall and Harangozo*, 2000]. Because our stacked Na^+ record (see below) covers years after 1957 AD only and because we used detrended pressure data, we considered reanalysis data over the complete time span covered but interpretation of our results will rely mainly on years after 1968 AD.

3. Results and Discussion

[7] For the interpretation of the sea salt aerosol record in terms of atmospheric transport patterns the meteorological and glaciological setting for DML and the surrounding ocean is important. The ice core sites are located in the western plateau region of DML. The altitude is approximately 2800 m altitude and the distance to the coast is about 550 km along the Greenwich meridian, i.e., the sites are well outside the marine boundary layer. The annual snow accumulation is in general very low (4 to 8 cm water equivalent/yr) but varies by a factor of two between sites. Four day back trajectory analyses [*Reijmer and van den Broeke*, 2000] show that about 60% of the air masses reaching DML originate in the Atlantic sector of the SO between 50 and 70°S and enter DML following a cyclonically curved pathway. The strong cyclonic influence on the Atlantic sector of the SO is also reflected in the deepest Subantarctic cyclones found at 0–30°W and 60°S [*Simmonds and Keay*, 2000]. Longest back trajectories are encountered in austral spring in phase with the seasonal maximum of sea salt in DML snow [*Göktas et al.*, 2002]. Automatic snow gauges deployed in DML show that in 1997–98 AD about 80% of the annual snow accumulation was derived from only 4–5 major snow fall events per year [*Noone et al.*, 1999; *Reijmer and van den Broeke*, 2000]. Evaluation of heavy snowfall events indicated that they are usually connected to a blocking high-pressure ridge over the eastern part of the Atlantic sector of the SO, which diverts Subantarctic cyclones onto the plateau region of DML.

[8] The connection between atmospheric circulation changes and sea salt aerosol transport onto DML is quantified by comparing interannual variations in Na^+ snow concentrations with changes in SLP and z500. The outcome of our study is highly dependent on the dating accuracy of the cores which is zero to maximum one year for the last 40 years. To further reduce depositional noise or dating ambiguities we averaged the normalized records of logarithmic annual concentrations of the three cores as shown in Figure 1a. Performing Monte Carlo maximum entropy spectrum analysis (MC-MESA) on the stacked Na^+ record for the time span 1957–84 AD covered by all three cores (Figure 1b) reveals prominent periodicities (significantly different from red noise on the 95% level) at periods of 3.9 and 5.2 yr. The first is in line with an ACW induced periodicity in SLP found in the eastern part of the Atlantic sector of the SO (Figure 1b) and in previous ACW analyses [*White and Peterson*, 1996]. While the splitting into a 3.9 and a 5.2 yr cycle is not clearly represented in the SLP data, a prominent 6.7 yr cycle found in SLP throughout the SO cannot be found in the Na^+ record. Clearly, longer records are needed to better quantify the exact periodicities.

[9] To identify the circulation pattern connected to the strong interannual sea salt variability we performed a correlation analysis between the stacked Na^+ record and detrended SLP data in the dominant source region of air masses affecting DML [*Reijmer and van den Broeke*, 2000]. This revealed positive correlations of annual Na^+ concentrations (r up to 0.48, significant on the 99% level) with annual SLP data over the Atlantic sector of the SO north of our drill sites and generally lower SLP east of Patagonia. The correlation is stronger (r up to 0.73; Figure 2a) for October through December (OND) averages in SLP, reflecting the spring maximum in sea salt concentration. The same anomaly pattern is found for z500 implying that this blocking high-pressure ridge extends through the free troposphere, where long-range transport of aerosol predominantly occurs. Pattern regression analysis shows that the SLP and z500 patterns for OND explain about 40% of the variance in annual Na^+ concentrations. Regression analyses on the individual cores showed essentially the same corre-

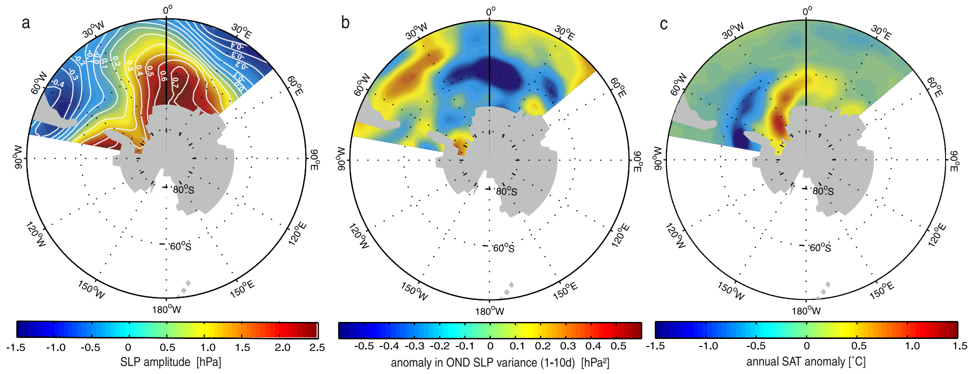

Figure 2. a) Pattern regression analysis of the Na^+ stack for the years 1957–84 AD with gridded SLP for OND over the Atlantic sector of the SO. Correlation coefficients are given by white isolines. The colorscale indicates the SLP amplitude connected to the regression between Na^+ and SLP, b) composite anomaly map for storm activity during years of high Na^+ concentrations minus low Na^+ concentrations, c) same as b) for SAT.

lation pattern with lower significance levels. Splitting the stacked record in two halves revealed the same regression pattern (r up to 0.8), implying that this pattern is a temporally robust feature, given that the reanalysis data are correct for the first half of the record. A composite anomaly map of cyclonic activity (Figure 2b) indicates that spring seasons in years of high Na^+ concentrations show substantially lower storm activity in the high pressure ridge compared to years of low Na^+ concentrations, while potential aerosol source regions east of Patagonia [*Reijmer and van den Broeke*, 2000] exhibit higher storm activity.

[10] To check whether the pressure anomalies are in phase with the ACW a time/longitude diagram of band-pass (3–7 yr) filtered SLP anomalies at 55°S is shown in Figure 3 over the time span 1948–1999 AD, equivalent to the study by *White and Peterson* [1996]. As expected from the spatial correlation in Figure 2a, years of high Na^+ concentration are generally in phase with higher SLP in the SO north of our drill sites, where 10 out of 13 years with high Na^+ concentrations can be associated to positive ACW anomalies. Note, however, that propagation of these patterns is not unambiguous especially in the first half of the record. In summary, we conclude that sea salt export onto DML is significantly influenced by large-scale changes in average pressure patterns as well as cyclonic activity over the Atlantic sector of the SO, with a significant part of this variability being induced by the ACW.

[11] While our interpretation implies a variation of sea salt export from the open ocean, the formation of sea ice has recently been discussed as another sea salt aerosol source for coastal Antarctica [*Rankin et al.*, 2000; *Wagenbach et al.*, 1998]. Because modulation of SIE is also a feature of the ACW, this source may provide another potential explanation for increased sea salt concentrations in DML. However, ACW induced positive SIE anomalies lead SLP by 45° longitude, thus have already passed DML at the time of the ACW induced sea salt maxima. Indeed, the composite anomaly map in Figure 2c shows 1°C warmer annual SAT in the coastal regions off DML in the years of high Na^+ concentrations. Accordingly, it is difficult to reconcile areas of increased sea ice formation with aerosol transport onto the DML plateau region [*Reijmer and van den Broeke*, 2000]. In addition, the seasonal sea salt maximum in DML during spring [*Göktas et al.*, 2002] is out of phase with sea ice formation, which is expected to be maximum in fall.

[12] One of the open questions related to the occurrence of the ACW is its persistence over longer time scales. Having shown that sea salt records in DML ice cores are significantly affected by the ACW over the last decades, they can be used to investigate whether the ACW has been active for previous times as well. MC-MESA performed on the long-term chloride record of the core at DML05 covering the time span 173–1948 AD (Figure 4) shows essentially the same significant periodicities in the range 4–5.5 yr as for the last decades. Although we cannot distinguish between a propagating and a standing ACW or identify the wave number of the anomaly patterns by a single ice core, this result indicates that an ACW cycle was a prevalent phenomenon over the SO during the last two millenia. Also prominent in the long-term sea salt record is a period of about 14 yr. A cycle of comparable length (12.1 yr) was also significant for the last 40 years, however, was not discussed due to the rather short record. Spectral analysis on the reanalysis data for longitudinal grid points at 55°S (e.g., in Figure 1b) shows that such a 12–14 yr

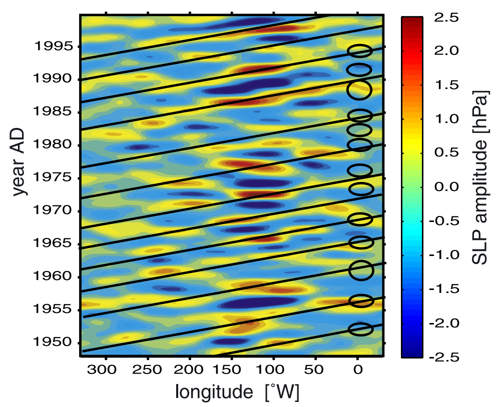

Figure 3. Time longitude diagram of Gaussian band-pass (3–7 yr) filtered SLP data at 55°S corrected for long-term temporal trends by subtracting the zonal mean of each year. Circumpolar propagation of a wave number 2 pattern with a period of 8 yr is suggested by black lines, years of high Na^+ concentrations in DML are marked by circles.

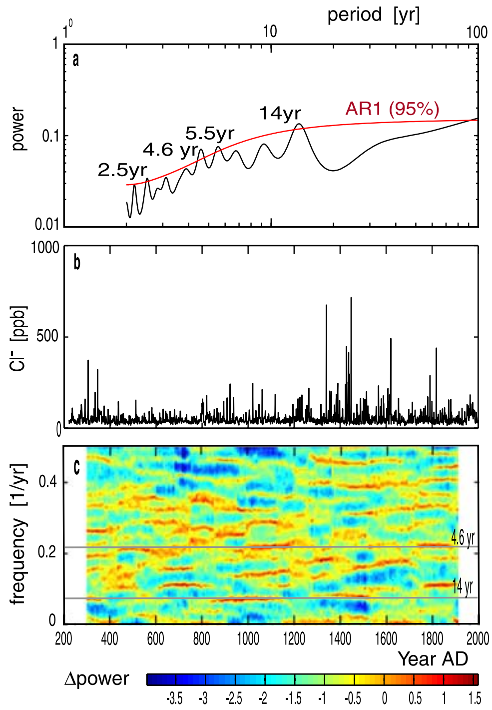

Figure 4. Long-term variations in sea salt concentration at DML05: a) MC-MESA (M = 30, n = 1000) of logarithmic Cl^- concentrations from 173–1948 AD, b) annual Cl^- concentration, c) evolutionary MC-MESA (AR(30), n = 100, window width 160 yr): Printed is the difference of the power spectrum of the logarithmic Cl^- record and the 95% significance level for red noise data, i.e., periods, where power is significantly different from red noise on the 95% level, are larger than zero. Also indicated are the major frequencies (grey lines) as indicated in Figure 4a.

periodicity is indicated by SLP data in nearly all regions around Antarctica. However, a 6.7 yr cycle in SLP (which happens to be about half of the 12–14 yr cycle) is not significantly documented in the long-term sea salt record from DML.

4. Conclusions

[13] While this study supports the prevalence of a 4–5 yr ACW and a longer 12–14 yr cycle over the last two millennia based on sea salt records from DML, an ACW signal should be detectable in ice cores from most regions of the Antarctic ice sheet. In fact, SLP variability is highest at 100 to 150°W (Figure 3). Investigation of spatially distributed Antarctic ice core records may allow to distinguish between a propagating and a standing ACW.

[14] Evolutionary MC-MESA in Figure 4c shows periods of absence or fading of an ACW cycle. Those may be partly due to the dating error but may also point to a weakening of the ACW during those times. Occurring tendencies to somewhat longer or shorter cycles may indicate climate-induced shifts in wind stress or the strength of the Antarctic Circumpolar Current which drive the circumpolar progression of SLP and SST anomalies. Accordingly, the long-term aerosol record which will be available after completion of the EPICA deep drilling in DML will provide an important archive of the atmosphere and ocean dynamics in the SO region over the complete Holocene up to the last glacial cycle.

[15] **Acknowledgments.** NCEP/NCAR reanalysis data were kindly provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA (at http://www.cdc.noaa.gov/). Helpful comments on the manuscript by M. van den Broeke are greatly appreciated. This work is a contribution to the "European Project for Ice Coring in Antarctica" (EPICA), a joint ESF (European Science Foundation)/EC scientific programme, funded by the European Commission and by national contributions from Belgium, Denmark, France, Germany, Italy, the Netherlands, Norway, Sweden, Switzerland and the United Kingdom. This is EPICA publication no. 94.

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