340 years of atmospheric circulation characteristics reconstructed from an eastern Antarctic Peninsula ice core

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[1] Precipitation delivery mechanisms for Dolleman Island (DI), located off the east coast of the Antarctic Peninsula, are investigated using reanalysis and back trajectory data. The Southern Annular Mode (SAM) and ENSO are both shown to influence precipitation delivery and event size. Precipitation delivery variability is compared against the interannual variation of chemical data from two DI ice cores. Nitrate concentration in the cores is strongly linked with the ratio of easterly to westerly back trajectories arriving at DI, as described by a Cross-Peninsula Index (CPI) defined in this paper. This CPI is used subsequently to reconstruct the atmospheric circulation characteristics for the 340-year ice core record. The analysis highlights a period of increased easterlies during 1720–1780 and an increase in westerlies for 1950–1980, the latter concomitant with a positive SAM trend and western Peninsula warming. The reconstruction also reveals periods when polynyas may have been present in the Weddell Sea. **Citation:** Russell, A., G. R. McGregor, and G. J. Marshall (2006), 340 years of atmospheric circulation characteristics reconstructed from an eastern Antarctic Peninsula ice core, *Geophys. Res. Lett.*, *33*, L08702, doi:10.1029/2006GL025899.

1. Introduction

[2] The record of in situ meteorological measurements from the Antarctic Peninsula (AP) has highlighted a warming trend that is both large and rapid [*Vaughan et al.*, 2001]. This change is statistically significant in the annual and seasonal (except spring) observations from both Rothera and Faraday on the western AP and in the summer observations from Esperanza on the eastern AP [*Vaughan et al.*, 2001]. Although the connection between these warming trends and concurrent changes in the high latitude Southern Hemisphere atmospheric circulation has been investigated at some length [e.g., *Thompson and Solomon*, 2002; *Marshall et al.*, 2006] the longer term significance of these studies is hampered by the brevity and sparseness of Antarctic observations. In an effort to overcome these limitations, some workers have reconstructed aspects of atmospheric circulation by investigating transfer functions between glaciochemical [e.g., *Goodwin et al.*, 2004] or accumulation [e.g., *Appenzeller et al.*, 1998] data from ice cores and atmospheric circulation. To date, no such reconstructions have been performed for the AP despite the fact that there is an urgent need to understand the climate forcing mechanisms associated with the observed rapid warming over the AP and associated impacts such as the collapse of the Larsen B ice shelf.

[3] Given these facts the aim of this paper is twofold. Firstly to derive transfer functions describing the link between atmospheric circulation and annual ice core chemistry at Dolleman Island (DI), an ice core site from the eastern AP, and secondly to perform a reconstruction of atmospheric circulation by applying the transfer functions in reverse to the full 340 years of available ice core data.

2. Data and Methods

[4] All precipitation events that occurred at DI between 1979 and 1992 were defined using the European Centre for Medium Range Weather Forecasting (ECMWF) re-analysis (ERA-40). The reasons for employing this temporal range of ERA-40 were: 1992 is the last year of the DI ice core accumulation record; and 1979 is the point at which the ERA-40 skill dramatically increases in the southern high latitudes [*Bromwich and Fogt*, 2004]. Furthermore, *Russell et al.* [2004] have demonstrated that the annual ERA-40 precipitation minus evaporation ($P - E \approx$ accumulation) data for the local ERA-40 grid cell is reasonably well correlated with the DI ice core accumulation after 1979 ($r = 0.59$, $p < 0.01$) and that the precipitation climatology of DI is driven by an unusually wide range of both westerlies and easterlies when compared to other Antarctic sites, making it an ideal location for such work. They also reported very high correlations between the ERA-40 temperature and pressure data and that recorded by an automatic weather station located on DI in the 1980s - confirming that ERA-40 is of sufficient quality to represent the climatological conditions at DI with confidence. *Turner et al.* [2006] have shown, by comparing the timing of western AP precipitation events from observations and from ERA-40, that the modeled precipitation data is of reasonable quality in the AP region, especially after 1985.

[5] 5-day back trajectories (BTs) for the dates associated with the precipitation events were run to identify the source of the precipitation bearing air masses. The BT analysis was run using the British Atmospheric Data Centre trajectory model, which derives 3-D air parcel paths from ERA-40 pressure driven winds. The BTs were initiated at 850hPa, 1200hrs and 70.3°S, 60.5°W (the ice core location). The initial level of 850hPa exceeds the elevation of DI (398m) but is still low enough for air parcels to be influenced by the smoothed AP topography in the model and to interact with the sea surface over the 5 days [*Russell*, 2005]. As a wide

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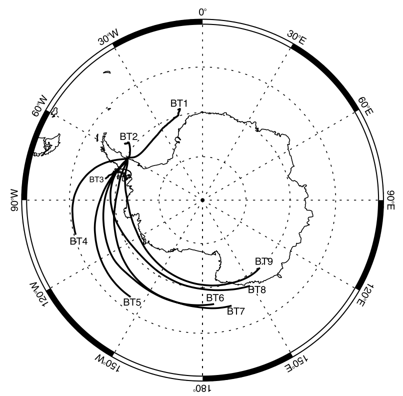

Figure 1. Composite BT patterns for the DI BTs associated with precipitation events. The BT patterns have been numbered so that BT1 has the most eastern origin and BT9 has the most western origin.

variety of BTs were found, individual BTs were grouped using hierarchical cluster analysis, based on Ward's solution [*Ward*, 1963], in order to identify the major BT patterns. The link between these BT patterns and the major modes of atmospheric circulation were investigated. *Russell* [2005] has shown that other phenomena, such as, for example, variations in sea ice extent and the Interdecadal Pacific Oscillation, are only of secondary importance when compared to the influence of atmospheric circulation modes on the precipitation delivery to DI. These other factors will, therefore, be considered in the future but are deemed beyond the remit of this work.

[6] BT clustering facilitates an objective method to compare the precipitation delivery mechanisms with the DI ice core data: a correlation analysis can be performed between the frequencies of the BT patterns and the concentration of species analyzed for the full length of the two cores: nitrate (NO_3), chloride (Cl), methane sulphonic acid (MSA) and sulphate (SO_4). It is assumed that the BT–chemistry relationships are stationary over the analysis period. It is considered methodologically sound to apply the transfer functions calculated from the most recent DI core (drilled in 1993) to the older, longer core (1985) as the data from the overlapping periods are significantly correlated [*Russell et al.*, 2004]. This analysis was performed on the annual timescale because of the irregular sub-annual sampling of the DI ice core data. This, and other aspects of the DI cores, are discussed by *Pasteur et al.* [1995] and references therein.

3. Results

[7] Composite trajectories for the BT patterns are plotted in Figure 1; Table 1 shows how many of the 4663 precipitation trajectories fell into each of these BT patterns. In order to identify the synoptic states related to these BT patterns, we look to *Russell et al.* [2004], who have discussed how the southward migration of the South Pacific convergence zone (SPCZ) during El Niño events leads to blocking near to the AP, thus allowing easterlies (i.e., BT1 and BT2) to dominate - see, in particular, the MSLP anomalies plotted in their Figure 11. They also showed that westerlies (BT3 and above) were prevalent under conditions of a deep circumpolar trough, which relates to a positive SAM index, corroborating the findings of *Marshall et al.* [2006].

[8] The results of the correlation analysis between the BT patterns and the ice core data are presented in Table 2. The most striking relationship in these results is the switch from negative to positive correlations between nitrate and the BT patterns as they progress from easterlies (BT1 and BT2) to westerlies (BT3–BT9). Indeed, the correlation co-efficient between the combined annual frequency of BT1 and BT2 and nitrate is −0.75 ($p < 0.01$). An equally strong, but positive, relationship is seen between nitrate and the combined frequency of westerly BT patterns. This highly significant correlation highlights a linkage but does not provide any mechanism connecting the atmospheric circulation and the ice core chemistry. Important factors in justifying such a link are that the easterly trajectories originate further south than the westerlies and that the Weddell Sea generally has a more northerly sea ice extent than to the west of the AP. Therefore, the easterly trajectories are much less likely to have tracked over open sea water, which is one of the sources of nitrate in precipitation [*Liss et al.*, 2004]. The opposite is true for the westerlies and the link is compounded by the fact that the other major source of nitrate - transported from the stratosphere via the polar vortex [*Legrand and Mayewski*, 1997] - will also deliver nitrate from the west. There are no such clear links for the other species though. It should be noted that there are remarkable similarities between the MSLP anomalies presented by *Goodwin et al.* [2003] and those from *Russell et al.* [2004] associated with westerlies, thus indicating that similar mechanisms led to the entrainment of nitrate to DI and Wilkes Land - the site studied by *Goodwin et al.* [2003]. Chlorine is principally derived from sea salt (i.e., open sea water, generally to the west of the peninsula) and the negative to positive switch is evident in Table 2, albeit with

Table 1. Number of Days Clustered Into the BT Patterns[a]

BT1[b]	BT2[b]	BT3[c]	BT4[c]	BT5[c]	BT6[c]	BT7[c]	BT8[c]	BT9[c]
685	1317	717	1040	746	44	40	34	40
14.7%	28.2%	15.4%	22.3%	16.0%	0.9%	0.9%	0.7%	0.9%

[a]These numbers of days are also expressed as a percentage of all the days that DI received precipitation. The BT patterns are also divided into those that come from the east and from the west of DI.
[b]Easterly BT group. Total easterlies = 42.9%.
[c]Westerly BT group. Total westerlies = 57.1%.

Table 2. Correlation Coefficient Between the Species Analysed From the 1993 DI Ice Core and the Annual Frequency of the BT Patterns

	Cl	NO_3	SO_4	MSA
BT1	−0.20	**−0.64**[a]	−0.10	0.05
BT2	−0.40	**−0.66**[a]	−0.34	−0.29
BT3	0.42	**0.65**[a]	0.27	0.15
BT4	0.13	**0.55**[a]	0.12	0.01
BT5	0.52	**0.61**[a]	0.41	0.33
BT6	−0.23	0.35	−0.14	−0.18
BT7	0.11	0.13	0.10	0.05
BT8	0.21	0.42	0.25	0.22
BT9	−0.01	−0.18	−0.02	0.00
BT1-2	−0.35	**−0.75**[b]	−0.26	−0.15
BT3-9	0.37	**0.74**[b]	0.29	0.16

[a]Significant at below the 0.05 level.
[b]Significant at below the 0.01 level.

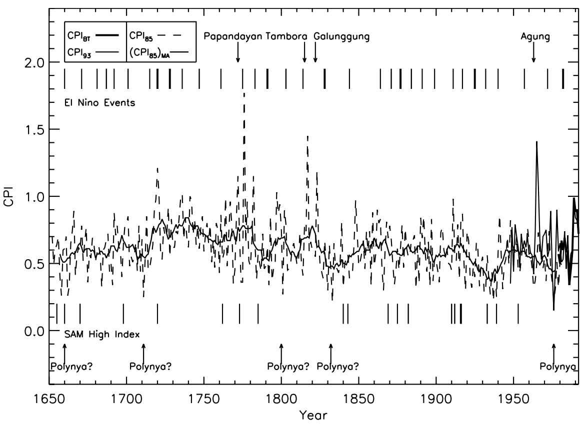

Figure 2. The Cross-Peninsula Index (CPI) calculated from: the frequency of BT patterns (CPI_{BT}; heaviest solid line); a regression of the 1993 ice core chemical species onto the CPI_{BT} (CPI_{93}; thinnest solid line); and the regression equation applied to the chemical species from the 1985 ice core (CPI_{85}; dashed line). The medium solid line shows the 10-point moving average of the CPI_{85}. The bars above and below the plot represent the timings of moderate (thin bar), strong (medium bar) or very strong (thick bar) (top) El Niño events and (bottom) SAM years.

insignificant correlations. However, this link is distorted by the fact that chlorine is also sourced from ''frost flowers'' that form on new sea ice [*Wolff et al.*, 2003], thus also providing a significant eastern source.

[9] These relationships between the chemical species, in particular nitrate, and the BT patterns provide a ''climatological bridge'' by which to reconstruct the atmospheric circulation of the AP region. Firstly, a Cross-Peninsula Index (CPI) has been created and is defined as the ratio of precipitation delivering easterlies to westerlies (i.e., the combined frequency of BT1 and BT2 divided by the combined frequency of BT3 to BT9). The CPI derived from BTs, or CPI_{BT}, is presented in Figure 2. Secondly, the concentrations of the chemical species analyzed in the 1993 core for the period 1979–1992 were linearly regressed onto the CPI_{BT}, which resulted in the following equation:

$$CPI = 1.13[NO_3] + 0.013[Cl] - 0.31[MSA] - 0.023[SO_4] - 0.18 \quad (1)$$

Finally, given the high correlation between the two ice cores, this equation was applied to all the ice core data to give indices reconstructed from the 1993 and 1985 cores (CPI_{93} and CPI_{85}, respectively; Figure 2).

[10] Equation (1) shows that the regression is weighted most strongly on the nitrate data, for which the largest and most significant correlations were found with the BT patterns that had the largest number of members (i.e., BT1–BT5). The index, therefore can be assumed to be a good representation of the precipitation delivery mechanisms for DI, as discussed in more detail below.

4. Discussion

[11] We shall first assess the reliability of the CPI as a reconstruction of atmospheric circulation by discussing its characteristics in relation to recorded atmospheric and environmental factors. By definition, the peaks in the CPI, such as those at 1965, 1989 and before and after the 1976 trough, should represent periods of frequent easterly BTs. Indeed, there was a moderately strong El Niño event in 1965 and a very low SAM index score, which would imply a dominance of easterlies. Further, without the erroneous influence of the 1976 Weddell Sea polynya (see below), and by examining the CPI_{93} variation before and after this feature, it is likely that there would have otherwise been a peak in 1976, a year which also saw a strong El Niño event.

[12] The largest of the peaks in the CPI_{85} occur in 1720, 1772, 1775, 1783, 1815 and 1825. Half of these large peaks occur at times when the Pacific basin was in the grip of strong or very strong El Niño events (1720, 1775 and 1783 [*Bradley and Jones*, 1992]). The other three of these peaks relate to signals from Indonesian volcano eruptions, which will upset the usual chemical characteristics of the atmosphere and appears to give the CPI a positive bias. Nearly all of the moderate peaks throughout the CPI can be identified as occurring during moderate or strong El Niño events [*Bradley and Jones*, 1992]. Similarly, many of the periods of low CPI scores (i.e., prevalence of westerlies), in particular 1888, 1919 and throughout the 1930s, correspond to periods of high SAM index scores [*Marshall*, 2003; *Goodwin et al.*, 2004; *Jones and Widmann*, 2004].

[13] The 1976 CPI trough was concurrent with the Weddell Sea polynya of the 1970s and indicates that anomalously low troughs in the CPI are related to polynyas over the Weddell Sea. The new open sea water source to the east of the AP acts as a large chemical source that would not usually interact with the easterly trajectories. Although there is no regional polynya chronology to compare with the CPI_{85}, it is suggested that the negative spikes circa 1660, 1711, 1800 and 1832 are related to polynyas in the Weddell Sea region as they do not relate to any outstanding features of the available circulation indices.

[14] To summarize the factors concerning the reliability of the CPI, there appears to be sufficient evidence of links between the reconstructed CPI and other indicators of mid- to high-latitude atmospheric circulation characteristics to place confidence in its representation of the relative importance of easterlies and westerlies for the DI precipitation delivery mechanisms.

[15] With this in mind, the most interesting features of the CPI reconstruction as a whole are the high values during the 18th Century and the negative trend thereafter. This pattern indicates that precipitation-bearing, warm, maritime westerlies reaching DI have become increasingly more common since around 1700. The implication of this increase in westerlies is that the temperatures on the eastern AP would have also increased due to the warm air arriving from the west. Indeed, to further place the CPI in context, it has previously been calculated that the period of maximum temperature at DI, calculated as c.1850 by *Jones et al.* [1993] from isotope variation, is coincident with one of the longest periods of consistent CPI scores below 0.5. This demonstrates a strong link between the climatic implications of the CPI and the climate at DI as derived from the ice core. With the CPI indicating that the influence of westerlies has become more important for the precipitation regime at DI, this also means that westerlies are increasingly impact-

ing the whole AP as air masses are more frequently passing over the AP. This reconstruction, therefore, represents further evidence for one of the proposed mechanisms driving the observed AP temperature increases [*Vaughan et al.*, 2001] and is consistent with the findings of *Marshall et al.* [2006] who have investigated the effects of increased westerlies on the western AP climate.

[16] It is also of interest that the longest period of consistently high values of the CPI_{85} (i.e., dominance of easterlies) occurs throughout the 18th century. This period is coincident with the "little ice age" (LIA). The LIA is often discussed as being a temporally and spatially irregular phenomenon [*Bradley and Jones*, 1992], however, the AP, as we have shown here, is teleconnected to a much higher degree with the climate of lower latitudes. Indeed, factors associated with a cooler mid-latitude climate would be an increase in the frequency of El Niño events, a much lower SAM index (c.f. Figure 2) and an increased meridional circulation strength variability, particularly around 1700–1800AD [*Kreutz et al.*, 1997; *Goodwin et al.*, 2004]. Therefore, the fact that the response of the CPI_{85} through the 1700s appears to be consistent with the high-latitude LIA interpretation is not only further evidence of AP–mid-latitude teleconnections but also of the effectiveness of the CPI as an atmospheric circulation reconstruction.

5. Conclusions

[17] We have described a strong "cross-Peninsula" relationship linking ice core data and precipitation delivery mechanisms for DI. This manifested itself, in particular, as low (high) nitrate concentrations for easterlies (westerlies) arriving at DI. The circulation regime is influenced most by blocking during El Niño events - allowing easterlies to dominate - and by the prevalence of westerlies during high SAM index years. This allowed us to reconstruct a simple but powerful index of this circulation by regressing the glaciochemical data onto a Cross Peninsula Index derived from back trajectory data.

[18] The results showed that warm periods at DI were dominated by westerlies (e.g., 1950–1980 and 1830–1850) and also exposed cooler periods dominated by easterlies (e.g., 1720–1780). It is of interest that the results presented here are consistent with other SAM reconstructions and also with a chronology of El Niño events and perhaps provide an insight into the timing of past polynyas in the Weddell Sea ice sheet (1660, 1711, 1800 and 1832). It is believed that this type of palaeoatmospheric reconstruction could be applied to longer and/or higher resolution ice cores from this region with similar, or enhanced, results to be uncovered.

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