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INTERANNUAL ANTARCTIC TROPOSPHERIC CIRCULATION AND PRECIPITATION VARIABILITY (AAO, ENSO, ETC.)

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1. INTRODUCTION

Although various authors have previously reported on the southern or Antarctic circulation and climate variability using Empirical Orthogonal Functions (EOFs), the study domain was larger than the Antarctic region stricto sensus. That is, the Antarctic variability was evaluated as embedded within the variability of a larger region, sometimes the full southern hemisphere. Here we restrict the study domain to latitudes higher than 60^{o}S, yet we find that the major modes of variability are those which link the Antarctic region to lower latitudes, either the mid-latitudes in the case of the High-Latitude Mode (HLM), also called Antarctic Oscillation (AAO), or the tropics in the case of the ENSO (El-Nino Southern Oscillation). We also find that the signature of these modes in the Antarctic climate varies through time, the ENSO being particularly present in the 1990s (Genthon et al. 2003).

We evaluate the variability of the atmospheric circulation and of the precipitation in the Antarctic region. The 500 hPa geopotential height (g500) is used as a proxy for tropospheric circulation. A full spatial coverage of g500 is provided by meteorological analyses. However, even reanalyses have deficiencies including temporal inconsistencies which may hamper correct evaluation of variability. Thus, we use and combine various sources of data including climate model results to tentatively minimize biases that could affect one particular source and concentrate on features which different sources have in common. This is even more crucial when analyzing precipitation, which is still poorly known in the Antarctic region and for which different sources significantly disagree. Although precipitation is not (yet) analyzed by meteorological centers, short-term predictions provide observationally-constrained full-coverage datasets, which we complement with model results and satellite data.

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2. DATA AND PROCEDURES

Meteorological analyses, and more particularly reanalyses, are a favorite source of information on the atmospheric circulation and climate. The longest available reanalysis so far is the NCEP/NCAR product (Kalnay et al. 1996), which cover the 1948 to present period and is thus in principle particularly appropriate for studies of interannual variability. This dataset is questionable however, as partially discussed further in the text. To reduce some of the problems, particularly those related to noise in polar precipitation, a reanalysis has been redone for the 1979-present period, known as the NCEP2 reanalysis (Kanamitsu et al. 2002).

Table 1: Datasets and periods used in the present study.

Dataset	g500	Precip
NCEP/NCAR	1958-2002	1958-2002
NCEP2		1979-99
LMDZ nudged	1979-99	1979-99
GPCP		1979-01

The ECMWF 40-year reanalysis (ERA40) is nearing completion at time of writing but is not yet available. The existing reanalysis (ERA15, Gibson et al. 1997) is only 15-year long. Operational analyses are available for more than 20 years at ECMWF but they are strongly affected by temporal inconsistency. To complete 21 years (1979 to1999) of Antarctic climate with some observational control, we run the LMDZ atmospheric general circulation model (AGCM) with high-resolution over Antarctica and lateral nudging by the ECMWF reanalyses (1979-93) and operational analyses (to 1999) (Genthon et al. 2002). This provides an additional dataset, fully independent from NCEP/NCAR, to further analyze and confirm Antarctic variability. Both g500 and precipitation from NCEP/NCAR (24h forecasts) and LMDZ are used. In addition, the precipitation data for 1979-99 from NCEP2 and for 1979-2001 from the GPCP combined satellite/gauge product (Huffman and Bovin 2001) are also evaluated (table 1).

Traditional EOF analysis is performed on these datasets. The covariance matrix is used for g500 while, because precipitation rates are so spatially contrasted in the Antarctic region, the correlation matrix is used for precipitation. To remove intraannual variability, all datasets are subjected to a 25-month Hanning filter in time.

The Antarctic Oscillation Index (AOI) and Southern Oscillation Index (SOI) are used to identify the 2 well-known modes of southern (or global) climate variability in the Antarctic region. The AOI is computed from the NCEP/NCAR sea-level pressure (Gong and Wang 1999) and is thus biased towards this dataset.

3. NCEP/NCAR 1958-2002 CIRCULATION

The quantity of observations available to constrain meteorological analyses in the Antarctic region has evolved thought time, from very few (before IGY, 1957-58), to few at a few sites (up to satellite era, 1970s), to still rather limited (up to now). This is likely to affect the NCEP/NCAR product. We select to restrict use of these data to 1958 (post IGY) to present (2002). Figure 1 shows the 2 main modes of variability which, together accounting for almost 75% of the total, largely dominate the interannual variability of the Antarctic tropospheric circulation.

The time series clearly show that the 1st mode is associated with the HLM/AAO, and the 2nd with ENSO. The spatial patterns show a bulk evolution of the Antarctic troposphere at the AAO pace, and a more spatially contrasted picture at the ENSO pace. However, the 2 modes have their strongest variability in the Amundsen sea area, so that mixed influence of the AAO and ENSO can be expected in this region.

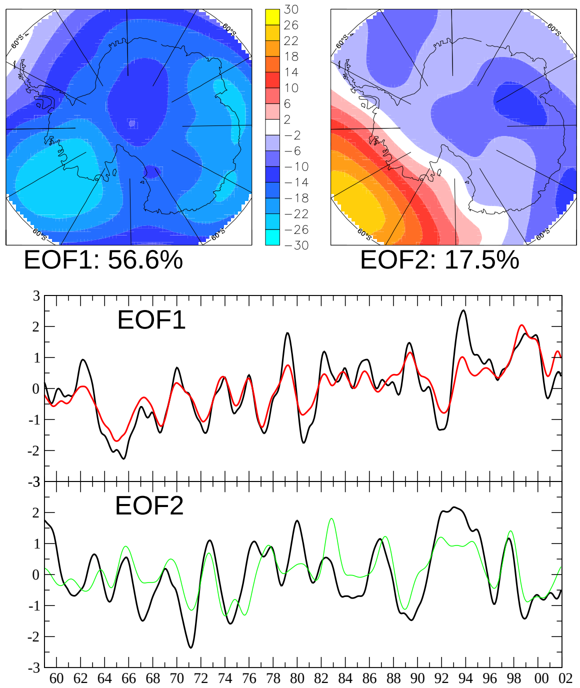

Figure 1: The 2 first EOFs of filtered g500 from NCEP/NCAR, spatial patterns (upper plots, in m) and associated time amplitude functions (lower plots). The filtered AOI (red) and SOI (green, divided by 10) filtered series are also shown.

4. COMMON NCEP/NCAR AND LMDZ 1979-99 CIRCULATION VARIABILITY

When performed over the 1979-1999 period, the EOF analysis of NCEP/NCAR g500 yields results which are very similar to that obtained on a longer period (Genthon et al. 2003), suggesting that the spatial patterns of figure 1 are reasonably stable in time. In addition, the EOF analysis of the LMDZ g500 AGCM results are also very similar. One way to retain the most common part of NCEP/NCAR and (ECMWF nudged) LMDZ is to calculate the combined EOFs, that is the EOFs of the stacked-in-time NCEP/NCAP and LMDZ datasets (Genthon et al 2003). The results are shown on figure 2.

The spatial patterns are forced to be the same for the 2 datasets. They are expectedly very similar to those of figure 1, with similar weights. The fact that the temporal variability (time amplitude functions) associated with each pattern is similar for the 2 datasets (linear correlation = 0.73 and 0.92 for EOF1 and EOF2, respectively) further confirms that the datasets agree well with respect to tropospheric circulation variability.

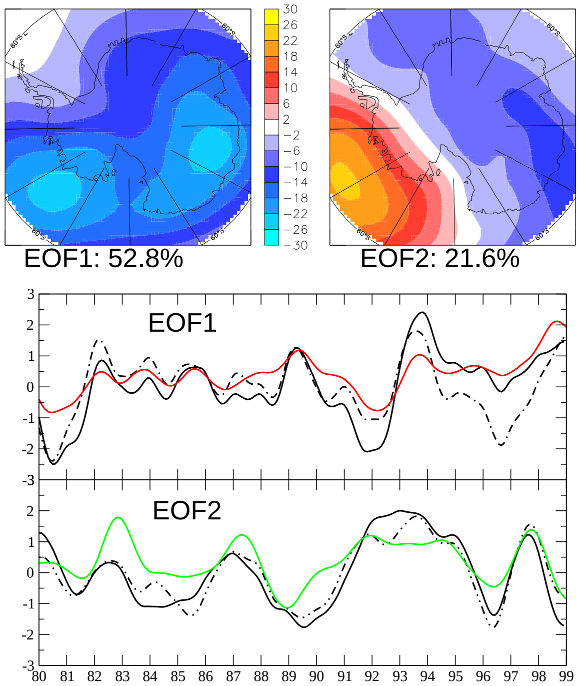

Figure 2: Combined EOFs of filtered g500 from NCEP/NCAR and nudged LMDZ, common patterns (upper plot) and respective time amplitude functions (full and dash-dot-dot, respectively, on the lower graphs), and the AOI and SOI as for figure 1.

5. COMMON NCEP REANALYSES AND LMDZ MODEL 1979-99 PRECIPITATION VARIABILITY

For consistency over the long and short periods through which the circulation variability is evaluated above (sections 3 and 4), we have so far used the NCEP/NCAR data throughout. Here we first turn to the NCEP2 dataset due to a small scale spatial noise problem in the NCEP/NCAR precipitation. Actually, this is a rather cosmetic step, as we find very similar results whether using the NCEP/NCAR or the NCEP2 precipitation data (Genthon et al. 2003). When performed independently on the NCEP2 and LMDZ data, EOF analysis results are in significantly less mutual agreement for precipitation than for g500: Common modes can be identified, in particular EOF1 of LMDZ and EOF2 of NCEP2 (figure 3. EOF2 of LMDZ is also common with EOF3 of NCEP2, not shown). Others are clearly distinct (EOF1 of NCEP2, figure 3). Also, weights are moderate compared to g500.

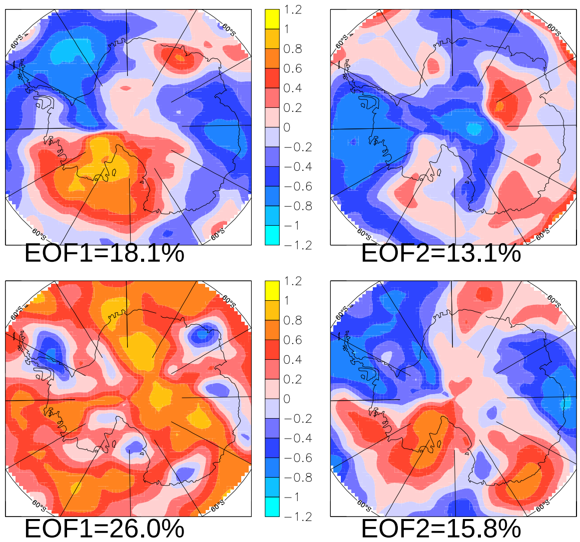

Figure 3: First 2 EOFs (spatial pattern) of LMDZ (upper plots) and NCEP2 (lower plots) (relative units for normalized precipitation).

A combined (NCEP2+LMDZ) EOF analysis of precipitation yields a 1st mode with a spatial pattern which is essentially that of the natural EOF1 of NCEP2 (figure 3), but which does not coincide with any of the natural EOFs of LMDZ. The associated time series (not shown) have only 33% of their variability in common (the combined EOF itself accounting for 16% of total variance), much of which as a long term trend indicating instationarity.

On the other hand, the 2nd mode of the combined analysis (CEOF2, figure 4) can be clearly tracked back in the natural EOF modes of both NCEP2 and LMDZ (EOF1 of LMDZ, EOF2 of NCEP2, figure 3). A main feature of this mode is an opposition between the 2 quadrants of west Antarctica, whereby higher precipitation than usual in sector 1 (Bellingshausen/Weddell) coincides with lower precipitation in sector 2 (Ross), and vice-versa (figure 4).

With a common pole of variability in the Amundsen sector, the 2 first combined EOFs of g500 (figure 2) can both contribute to explaining CEOF2: g500 higher than usual is associated with more warm and moist air advected from the lower latitudes toward sector 2 (more precipitation in sector 2), and with more cold and dry air emerging from the continental interior toward the sector 1 (less precipitation in sector 1), and vice-versa. Because the 1st combined g500 EOF is related to the AAO and the 2nd to the ENSO, the signature of both indices may be expected in the variability of precipitation.

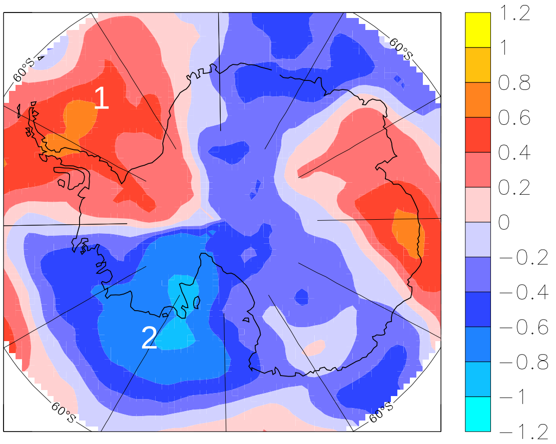

Figure 4: Second combined EOF (CEOF2) of filtered precipitation from NCEP2 and nudged LMDZ (relative unit). Fraction of variance explained: 14.3%.

Figure 5 shows time series of spatial regressions (Genthon et al. 2003) of precipitation from various origins (NCEP/NCAR, NCEP2, LMDZ, GPCP) on CEOF2. In the case of LMDZ and NCEP2, the regression series simply are the time amplitude functions associated with the common EOF. The fact that, over the common 1979-99 period, the regression series of NCEP/NCAR and NCEP2 are almost identical (linear correlation = 0.99) shows that 1) CEOF2 is a natural mode of variability for NCEP/NCAR, and 2) the problems affecting the NCEP/NCAR precipitation (e.g. small scale spatial noise) are not detrimental to the type of analysis we perform. Thus, the NCEP/NCAR data may be used to tentatively extend the analysis back in time.

Visual examination of figure 5 indicates high similarity between the various datasets and the SOI through the ~1990-2000 decade. There is little evidence of an SOI signature in the previous decade (1980-90), but conversely more similarity with the AOI. In the earlier times, the NCEP/NCAR data suggest a moderate signature of both the SOI and AOI (see also Genthon et al. 2003). All this is quantitatively confirmed by linear correlation calculations (tables 2 and 3).

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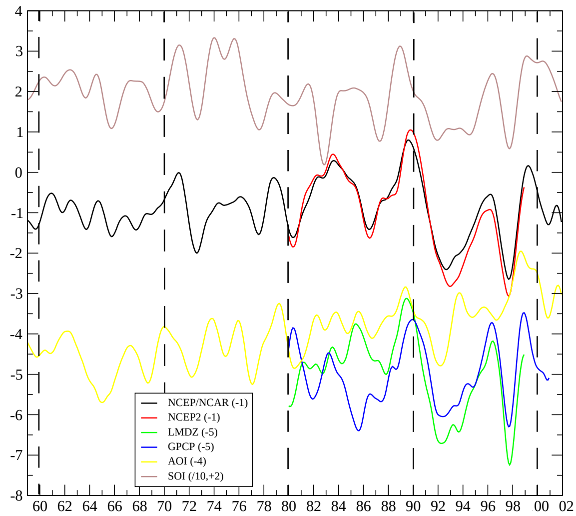

Figure 5: Time series of spatial regressions on CEOF2 of precipitation from NCEP/NCAR (black), NCEP2 (red), LMDZ (green) and GPCP (blue). The filtered AOI (yellow) and SOI (brown) are also shown. Curves are shifted by the number shown in legend to improve readability.

Table 2: Linear correlations between the NCEP/NCAR regressions and the climate indices

Decade	**60-70**	**70-80**	**80-90**	**90-00**
AOI	0.36	0.54	**0.79**	0.47
SOI	0.51	0.30	0.21	**0.84**

Table 3: Linear correlations between the LMDZ and GPCP regressions and the climate indices

Decade	**LMDZ**		**GPCP**	
	80-90	**90-99**	**80-90**	**90-00**
AOI	**0.78**	0.21	0	0.45
SOI	0.54	**0.87**	0.1	**0.88**

The GPCP data agree with the other datasets to confirm high correlation with the SOI in the 1990-2000 decade (table 3). On the other hand, the GPCP precipitation is not correlated with the AOI (or even the SOI) in the 1980-90 decade. In fact, the GPCP precipitation differs markedly from the other datasets until ~1988, then shows very good agreement (figure 5). This is likely to be associated with a change in the method to obtain precipitation rates from satellite data in the course of 1987 (Huffman and Bovin 2001). The GPCP data in the Antarctic region are very suspect before that year.

6. ENHANCED ENSO IN THE 1990s

CEOF2 (figure 4) contributes to less than 15% of the overall variability of precipitation in the Antarctic region south of 60^{o}S. However, the relative contribution is locally much higher where CEOF2 shows major poles of variability (sectors 1 and 2, figure 4). This is thus where the signature of the AAO and the ENSO is most likely to emerge from the background. However, even there, the signature of one or the other large scale modes of variability cannot be expected to be stable in time, as argued in the previous section. In particular, the signature of the ENSO should be strongest in the 1990s, and particularly weak in the 1980s (tables 2 and 3). This is clearly confirmed when mapping the spatial distribution of the linear correlations of precipitation with the SOI (figure 6).

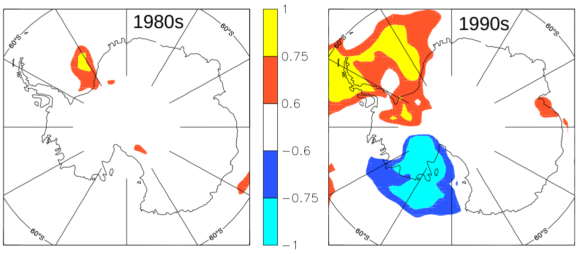

Figure 6: Linear correlation between a NCEP2+LMDZ precipitation composite and the SOI in the 1980s (left) and the 1990s (right).

The correlation is searched in a composite precipitation built by averaging the NCEP2 and the LMDZ precipitation datasets. There is hardly any significant relation between Antarctic precipitation and the SOI in the 1980s. On the other hand, in the 1990s, very high correlations show right where anticipated, that is in sectors 1 and 2 of figure 4. The correlations are actually as high as the strongest correlations found between precipitation and the SOI in the tropics (Trenberth and Carron 2000). For the 1990s, similarly high correlations are obtained with the GPCP data in the same Antarctic sectors (not shown). This is therefore a robust result. In sector 2, insignificant correlation with the SOI in the 1980s had previously been suggested using the ECMWF ERA15 data (Genthon and Krinner 1998). Using other ECMWF data, Bromwich et al. (2000) have suggested that correlations with SOI in sector 2 have changed signs from the 1980s to the 1990s. Here, we confirm high correlations in the 1990s, but find no significant correlation in the 1980s, in agreement with Genthon and Krinner (1998).

7. CONCLUSION

Two major aspects of the variability of precipitation in the Antarctic region emerge from our results: 1) Both the AAO (or HLM) and the ENSO modes of large scale variability significantly affect the Antarctic precipitation, but with a relative magnitude which varies through time (figure 5, tables 2 and 3); and 2) Two sectors of Antarctica are most affected, the Bellingshausen/Weddell and the Ross/Amundsen regions, and they are affected in phase opposition (figure 4). In addition, the signature of the ENSO is insignificant in the 1980s but highly significant in the 1990s (figure 6). Although merely a hint at this time, the early 21st century results suggest a decreased influence of the ENSO / increased influence of the AAO (figure 5).

The results presented here are based on meteorological analyses and forecasts, climate model results, and satellite data. Each of these sources of information, if taken independently, would not be considered sufficient and reliable enough for a firm assessment on the variability of the Antarctic precipitation. However, the results appear robust with respect to the various sources, which mostly confirm each other. In addition, the mode of Antarctic precipitation variability which we have focused on (CEOF2, figure 4) is physically consistent with the main modes of tropospheric circulation variability (figure 2). These modes confirm that the climate of the Antarctic region is linked to the lower latitudes as far as the tropics.

Genthon et al. (2003) provide a more comprehensive evaluation of the interannual Antarctic tropospheric circulation and precipitation variability. Copyright permitting, some of the paper and additional material may become accessible at http://lgge.obs.ujf-grenoble.fr/~christo/antvar/index.htm.

8. ACKNOWLEDGEMENTS

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