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Coherence of Antarctic sea levels, Southern Hemisphere Annular Mode, and flow through Drake Passage

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[1] It is known from small sets of tide gauges that sub-surface pressure (sea level corrected for the inverse barometer effect) around Antarctica varies coherently around about half of the continent, and that this coherent signal is related to atmospheric forcing in the form of the Antarctic Oscillation, or Southern Hemisphere Annular Mode. We here confirm that this coherence extends to a more extensive network of tide gauges, and to parts of the continental shelf far from the shore, as measured by bottom pressure gauges. We use time series from an eddy-permitting ocean model with realistic forcing to relate the coherent mode to fluctuations in transport through Drake Passage, and confirm, using a 1° resolution barotropic model, that the fluctuations are predominantly due to barotropic dynamics, although baroclinic dynamics are expected to play an increasing role at interannual timescales. *INDEX TERMS:* 4556 Oceanography: Physical: Sea level variations; 4504 Oceanography: Physical: Air/sea interactions (0312); 4207 Oceanography: General: Arctic and Antarctic oceanography; 1620 Global Change: Climate dynamics (3309); 4255 Oceanography: General: Numerical modeling. **Citation:** Hughes, C. W., P. L. Woodworth, M. P. Meredith, V. Stepanov, T. Whitworth, and A. R. Pyne, Coherence of Antarctic sea levels, Southern Hemisphere Annular Mode, and flow through Drake Passage, *Geophys. Res. Lett.*, *30*(9), 1464, doi:10.1029/2003GL017240, 2003.

1. Introduction

[2] In recent years, the predominant atmospheric mode of the southern hemisphere has been identified and suggested as the primary forcing for a number of climatic indicators. Variously known as the Antarctic Oscillation (AAO) or the Southern Hemisphere Annular Mode (SAM) [*Thompson and Wallace*, 2000], this consists of an oscillation of sea level atmospheric pressure between polar and subtropical latitudes, associated with oscillations in circumpolar winds in the troposphere and stratosphere, including at the sea surface. Relationships have been suggested with Antarctic ozone [*Thompson et al.*, 2000], trends in Antarctic temperatures [*Thompson and Solomon*, 2002], circumpolar sea ice extent and transport of the circumpolar current [*Hall and Visbeck*, 2002], among other things.

[3] In parallel with this identification of an atmospheric mode, a similar oceanic mode has been identified [*Woodworth et al.*, 1996; *Hughes et al.*, 1999] from ocean models. Its existance has been confirmed by in-situ sub-surface pressure (SSP) measurements from Antarctic tide gauges [*Woodworth et al.*, 1996, 1999, 2002; *Aoki*, 2002]. Unlike the atmospheric mode, which is almost zonally symmetrical, the ocean mode is strongly constrained by bottom topography, and is predominantly confined to the region south of the Antarctic Circumpolar Current (ACC).

[4] *Hall and Visbeck* [2002] used a very coarse resolution coupled climate model to suggest a relationship between the SAM and ACC transport on a variety of time scales, from daily to multidecadal. At the longer, interannual periods this relationship results from the perturbation of stratification which results from the meridional overturning cell driven by the wind stress. At shorter time scales, the suggestion of *Hughes et al.* [1999] was that the dynamics are essentially barotropic, with an Ekman flux away from Antarctica producing a sea level drop and related transport increase.

[5] *Aoki* [2002] demonstrated a correlation between measured Antarctic SSP and the SAM for periods shorter than annual. Here we present data from a more extensive set of tide gauges and bottom pressure recorders (BPRs) than hitherto used, and combine these datasets with satellite altimetry, and modelled transport through Drake Passage to further elucidate the relationships.

2. Data

[6] Figure 1 shows a map of tide gauges and BPRs used in this study. The network consists of coastal tide gauges of different types and off-shore BPRs in depths of approximately 1000 m and extends from Vernadsky (Faraday) on the west side of the Antarctic peninsula eastwards to Cape Roberts south of New Zealand. The establishment of such a network is an excellent international achievement within the Global Sea Level Observing System [*IOC*, 1997].

[7] SSP time series were constructed for each site using either the measured BP, or by inverse barometer correction of the measured sea level. Daily means were calculated by filtering out the semi-diurnal and diurnal tides [*IOC*, 2002] and the average annual and semiannual cycles were

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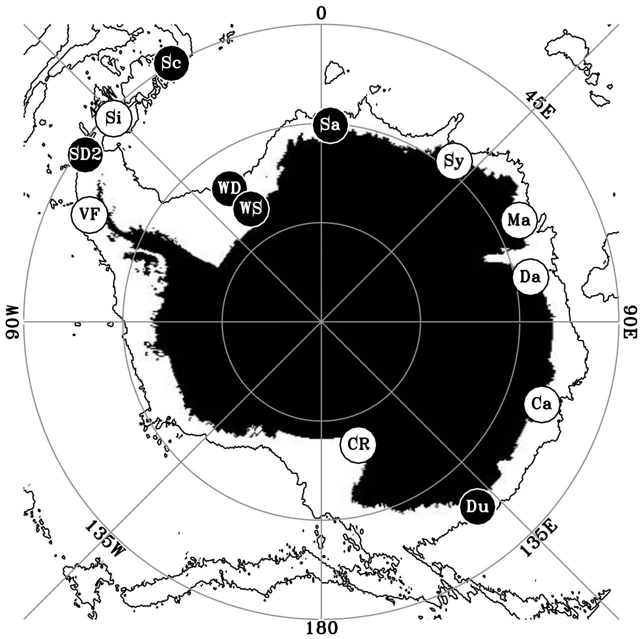

Figure 1. Map showing positions of BPRs (black) and tide gauges (white) used in this study, plus the 3000m depth contour. CR is Cape Roberts, Du is Dumont d'Urville BPR, Ca is Casey, Da is Davis, Ma is Mawson, Sy is Syowa, Si is Signy, Sa is Sanae BPR, SD2 is the South Drake BPR, VF is Vernadsky/Faraday, Sc is the Scotia BPR, WD is the Weddell Deep BPR, and WS is the Weddell Shallow BPR.

removed from each record. The annual and semiannual cycles were found to be significantly different at different locations, perhaps indicating the importance of local conditions for the freeze/melt cycle of nearby ice. Where the data have been further smoothed this is by convolution with a cosine bell with width given by the smoothing period stated, taking due account of gaps in the data.

[8] A time series of transport through Drake Passage (closely related to circumpolar transport at all longitudes) was taken from the OCCAM global ocean model. This run was at 0.25° resolution, forced by 6-hourly winds and atmospheric pressures from the ECMWF reanalysis [*Webb and de Cuevas*, 2002]. An alternative barotropic version of the model was also constructed at 1° resolution. The transport time series from the two models are highly correlated (correlation coefficient 0.7 for 8 years of daily values), despite the lower resolution and therefore different representation of topography in the barotropic model, confirming that the transport fluctuations are predominantly due to barotropic processes. Transport from the baroclinic model is used here.

[9] We used a version of the SAM index generated from NOAA Climate Data Assimilation System reanalysis data sets. It is constructed by projecting the daily 700 mb height anomalies poleward of 20S onto the "loading pattern of the Antarctic Oscillation" which is defined as the leading mode of an EOF analysis of monthly mean 700 mb heights during 1979–2000. See http://wesley.wwb.noaa.gov/cdas_data.html.

[10] Several attempts were made to construct a useful time series from satellite altimetry. The data used are the weekly joint ERS/Topex gridded products produced on a (1/3)° mercator grid by the ENACT programme, available from ftp://ftp.cls.fr/pub/oceano/enact/msla/ [*Ducet et al.*, 2000]. Simple point measures of height from altimetry were found to be too noisy in this region (compared to the typically 2–3 cm rms signal expected), so some kind of averaging was necessary. EOF analysis was contaminated by the high eddy energies close by, and by the seasonal ice cover cycle. The best altimetric time series was found by averaging altimetric heights over the region south of 56.7°S, where correlation of point altimetric values with model transport was greater than 0.25 (both positive and negative correlations were found, and the average weighted accordingly). The correlation coefficient is mapped in Figure 2 (this figure includes regions excluded from the averaging because there are fewer than 100 good measurements at those points). The pattern is remarkably similar to that seen in model data [*Woodworth et al.*, 1996; *Hughes et al.*, 1999]. This confirms that the model dynamics are similar to dynamics of the real ocean.

3. Comparison of Datasets

[11] Figure 3 shows daily data for the tide gauges and BPRs for two periods during which particularly good cover-

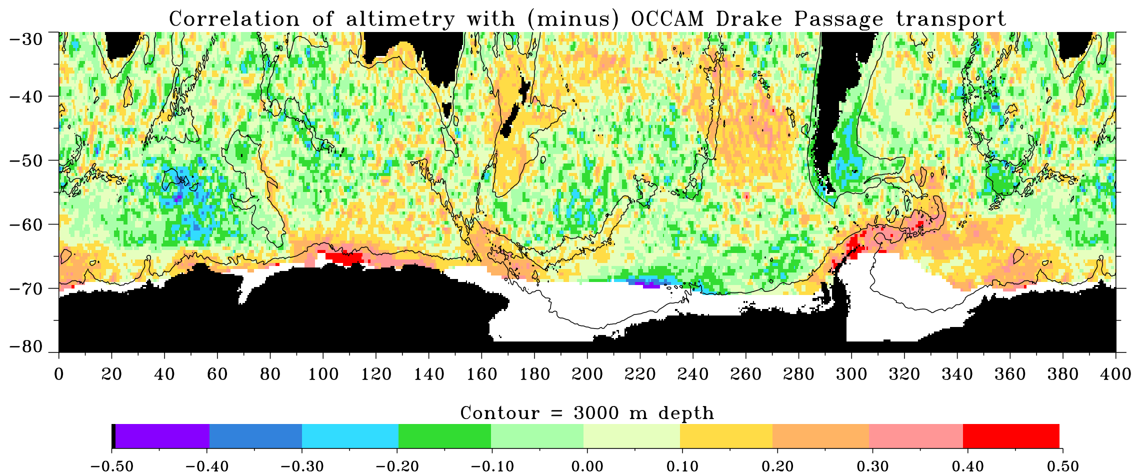

Figure 2. Correlation coefficient for SSP from altimetry with modelled transport through Drake Passage. The 3000 m depth contour is also shown.

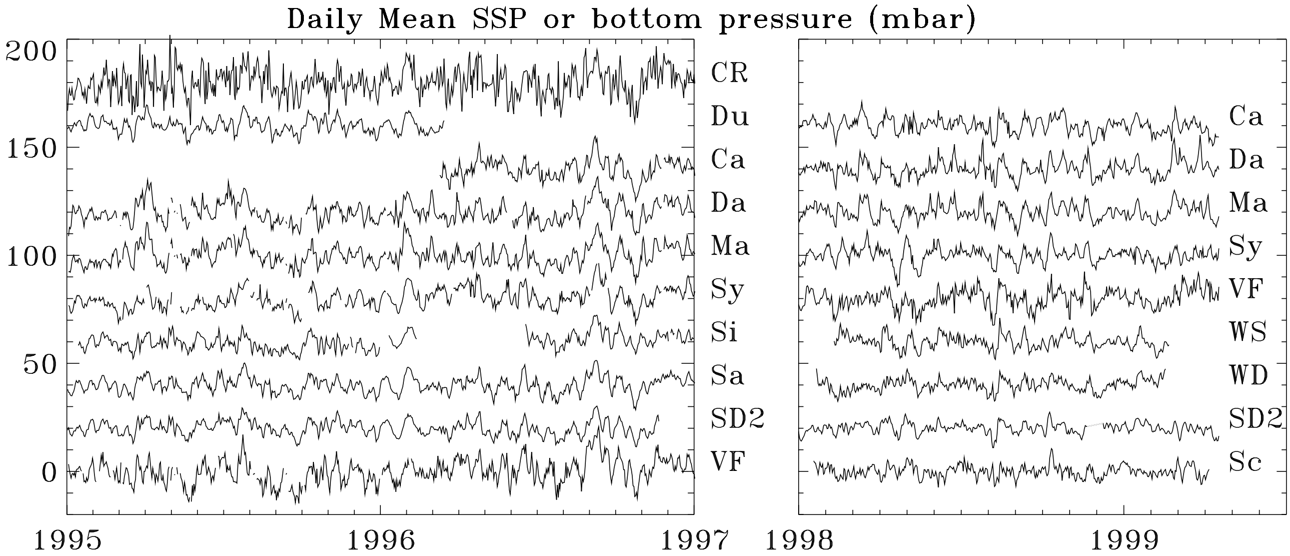

Figure 3. Daily values of bottom pressure or SSP (mbar) for two periods which afforded particularly good coverage.

age was obtained. Cross-spectra (not shown) show significant covariance at periods of about a week (or around 3 days in the case of some station pairs) through to at least intraseasonal (month to month) timescales, with no discernible lag. Larger signals are observed at Vernadsky than at the other sites.

[12] Several of the tide gauges permit long time series to be constructed, as well as one of the BPRs (Drake South). Figure 4 shows these longer time series, after 30-day smoothing, together with time series derived from satellite altimetry, the Ocean Circulation and Climate Advanced Modelling project (OCCAM) ocean model, and the SAM index. Cross correlations between these time series are shown in Figure 5, for periods of 30 days to 1 year (above the diagonal), and longer than 1 year (below).

[13] Most short period correlations can be seen to be in the range 0.5–0.7, and all are significant at the 99% level (following a Monte Carlo simulation of errors with realistic spectra, gaps, and smoothing). Even at longer periods, with 1-year smoothing, significant correlations occur. In particular, all but one of the ten correlation coefficients among the group (Altimetry, Vernadsky, Syowa, Mawson, -Transport) lie in the range 0.59–0.77, the exception being Mawson/Vernadsky (0.46), and correlations with altimetry in that group are all in the range 0.68 to 0.77, the lowest, surprisingly, being the correlation with (-Transport) which was used in constructing the altimetry time series as described above. Interannual correlations with (minus) the SAM index are weaker, peaking at 0.61 (Davis), 0.58

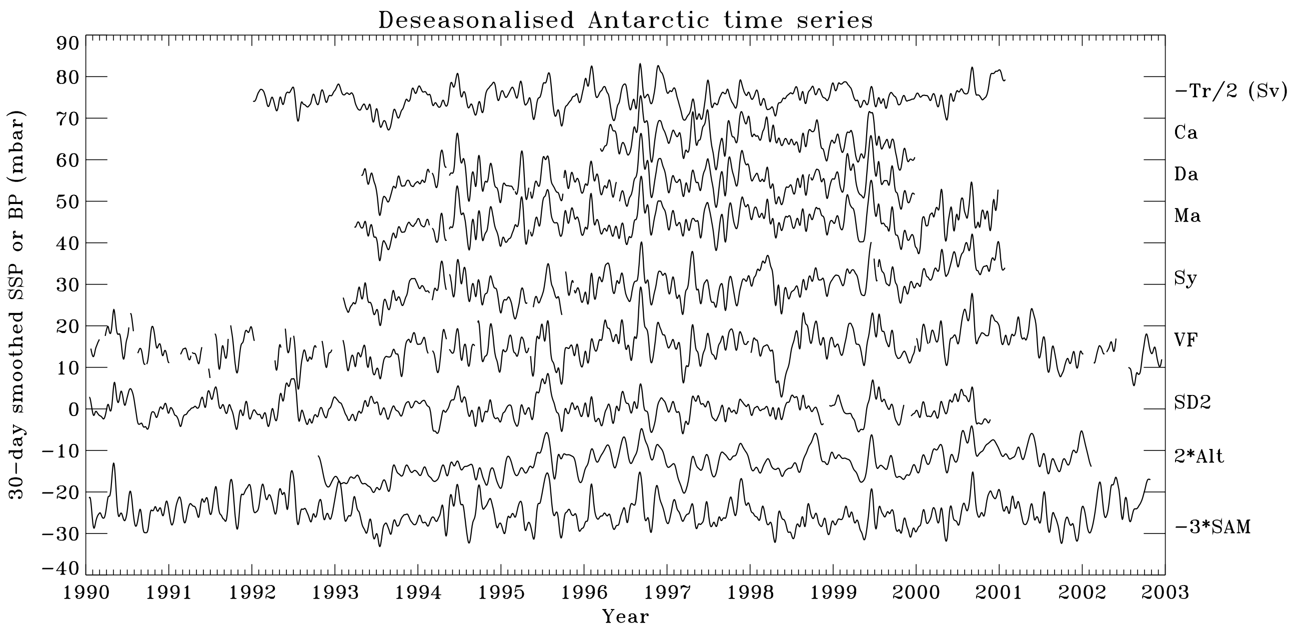

Figure 4. Time series of SSP and bottom pressure (mbar), SAM index, and modelled Drake Passage transport, from the records which provide long time series, after 30 day smoothing. Alt is satellite altimetry, Tr is modelled transport through Drake Passage (Sv = 10^6 m^3 s^{-1}), other abbreviations as in Figure 1.

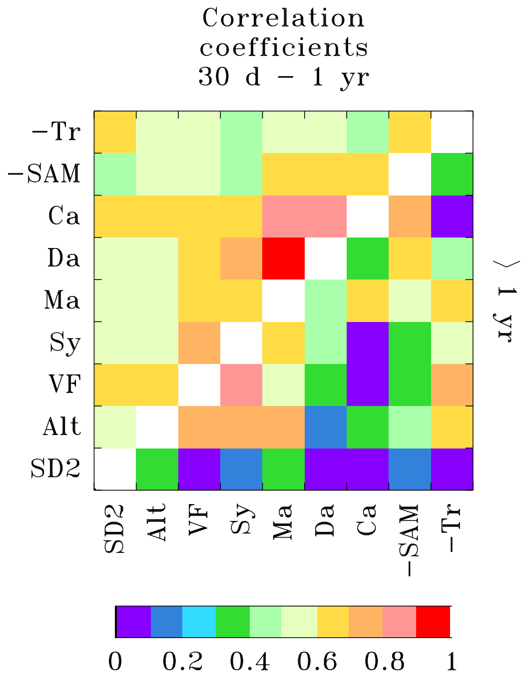

Figure 5. Correlation coefficients between all pairs of time series in Figure 3. Abbreviations as in Figures 1 and 4. Periods 30 days to 1 year are shown above the diagonal, periods longer than 1 year below the diagonal.

(Mawson), 0.44 (Altimetry), and 0.39 (-Transport). For comparison, the 95% confidence limit for 7 degrees of freedom is approximately 0.67.

[14] For periods less than 1 year, a linear regression of transport on the SAM index gives a ratio of 2.8 Sv(unit SAM)$^{-1}$. Since this sample of the SAM index has a standard deviation of 1.25, a change in SAM index of 1 standard deviation produces a transport change of 3.5 Sv, significantly more than the 0.67 Sv produced in the model of *Hall and Visbeck* [2002]. The difference may be due to the high viscosity necessary in such a coarse resolution model, and to the longer timescales investigated with the model. Similar regression of transport on the SD2 bottom pressure data gives -1.2 Sv mbar^{-1}, and on the altimetry gives -2.1 Sv mbar^{-1}.

4. Conclusions

[15] There is strong coherence between SSP and bottom pressure fluctuations at many locations around Antarctica, and on the continental shelf a considerable distance offshore, although there are also significant differences between these time series, most notably at annual and semiannual periods. The longest records suggest that this coherence may extend to interannual timescales, but longer records are needed to confirm this.

[16] Model comparisons demonstrate that the coherent mode relates to fluctuations in transport through Drake Passage, and that these fluctuations are predominantly barotropic in nature for periods shorter than 1 year. Comparison with satellite altimetry demonstrates the difficulty of measuring this mode from space, as a result of the small amplitude of the signal and the seasonal ice coverage in most of the relevant region. This stresses the importance of maintaining an Antarctic tide gauge network. However, with careful processing, the altimetry can be used to demonstrate the accuracy of model simulations of the region occupied by this circumpolar ocean mode.

[17] Both the measured coherent mode in SSP and the modelled transport fluctuations are closely related to the atmospheric forcing as represented by the SAM index. The influence of the SAM thus extends from the stratosphere to the seabed around Antarctica. Longer time series are needed, however, before this can be demonstrated for the interannual periods at which baroclinic dynamics are expected to become important.

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