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Changes in the ocean transport through Drake Passage during the 1980s and 1990s, forced by changes in the Southern Annular Mode

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[1] We present the first direct evidence that interannual changes in ocean transport through Drake Passage are forced by variability in the Southern Annular Mode (SAM). This evidence is derived from two decades (1980s and 1990s) of subsurface pressure measurements from the tide gauge at Faraday station (western Antarctic Peninsula), combined with the output of an ocean general circulation model. In recent decades, the SAM has moved toward a higher-index state (stronger circumpolar winds); this trend is not simply monotonic, but is the product of a long-term change in the seasonality of the SAM. Whilst we cannot address directly the effect of the long-term trend on circumpolar transport, bottom pressure data from Drake Passage during the 1990s demonstrate that ocean transport showed the same changes in seasonality as did the SAM. This offers a mechanism for atmospheric climate change to influence directly the large-scale ocean circulation. *INDEX TERMS:* 4207 Oceanography: General: Arctic and Antarctic oceanography; 4215 Oceanography: General: Climate and interannual variability (3309); 4532 Oceanography: Physical: General circulation; 1635 Global Change: Oceans (4203); 4556 Oceanography: Physical: Sea level variations. **Citation:** Meredith, M. P., P. L. Woodworth, C. W. Hughes, and V. Stepanov (2004), Changes in the ocean transport through Drake Passage during the 1980s and 1990s, forced by changes in the Southern Annular Mode, *Geophys. Res. Lett.*, *31*, L21305, doi:10.1029/2004GL021169.

1. Introduction

[2] The Southern Ocean is unique in being zonally unbounded, with direct connections to all the other major oceans. Consequently, the region is key to the global climate system, with large quantities of heat, salt and freshwater being distributed by the Antarctic Circumpolar Current (ACC), the world's largest current in terms of volume and mass transport [*Macdonald and Wunsch*, 1996; *Ganachaud and Wunsch*, 2000]. Many studies have been devoted to trying to quantify the transport and/or variability of the ACC at different longitudes. Drake Passage has been the most well-studied location, since it is where the ACC is constricted to its narrowest extent (Figure 1); consequently logistics are easiest, and complications with possible additional flows from the subpolar or subtropical gyres are avoided [*Whitworth*, 1983; *Whitworth and Peterson*, 1985; *Meredith et al.*, 1996; *Cunningham et al.*, 2003]. Typical values for transport through Drake Passage from hydrographic sections are of order 130 Sv (1 Sv = 10^6 m^3/s), however there remain significant questions relating to the interannual and longer-period variability in transport, and its forcing.

[3] At subseasonal timescales, the circumpolar transport variability is predominantly barotropic (independent of depth), and hence is well-measured by bottom pressure or sea level (corrected for the inverse barometer effect) [*Meredith et al.*, 1996; *Hughes et al.*, 2003]. Strong circumpolar coherence in transport has been demonstrated using data from various Antarctic tide gauges and bottom pressure recorder (BPR) deployments [*Aoki*, 2002; *Hughes et al.*, 2003]. It has also been demonstrated that this subseasonal transport variability is forced (with undetectable lag) by the varying circumpolar eastward winds associated with the Southern Annular Mode (SAM; [*Thompson and Wallace*, 2000; *Thompson et al.*, 2000]). This is the dominant mode of climate variability in the Southern Hemisphere outside the tropics, and is characterised by an oscillation in barometric pressure between a node over Antarctica, and a ring over the lower-latitude Southern Ocean at approximately 40–50°S. The eastward winds over the Southern Ocean change zonally with the SAM, time series of which resemble a red-noise process with an e-folding timescale of ~10 days and increased power at longer periods. Given the range of timescales over which the SAM operates, it can have teleconnections with diverse other phenomena: links with ENSO and the semi-annual oscillation (SAO) have been proposed, for example.

[4] Of more climatic importance than the subseasonal variability are the lower frequency (interannual period and longer) changes in circumpolar transport. The SAM has been moving toward to a higher-index state over the past three decades [*Thompson and Solomon*, 2002], with associated stronger circumpolar winds; there is also significant interannual variability in the SAM (Figure 2). Although modelling studies have hypothesised a link between the SAM and circumpolar ocean transport on these longer timescales [*Hall and Visbeck*, 2002], observational evidence of this has been crucially lacking. For example, previous investigations of Southern Ocean transport variability have not demonstrated a link between interannual changes in the SAM and circumpolar transport changes in the ocean [*Rintoul and Sokolov*, 2001; *Cunningham et al.*, 2003; *Sprintall*, 2003; *Sokolov et al.*, 2004]. As noted by *Visbeck and Hall* [2004], there remains a need to understand the changes in high-latitude ocean circulation and properties that occur as consequences of variability in the SAM.

[5] The trend of the SAM over the past three decades is not simply monotonic, but has been strongly modulated by season, being significant only for certain times of year (summer and autumn). It has been argued that this change in seasonality, and the trend to a higher-index state, are

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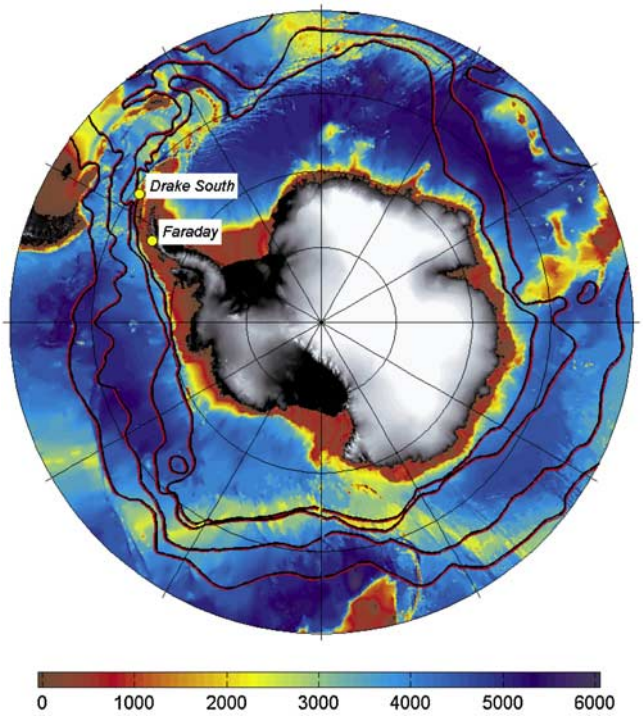

Figure 1. Location of the Faraday tide gauge and Drake South bottom pressure recorder. Schematic locations of the main fronts of the Antarctic Circumpolar Current are marked [*Orsi et al.*, 1995]. The background colouring is bottom depth, in metres.

consequences of anthropogenic influences, such as greenhouse warming or ozone depletion in the stratosphere [*Kushner et al.*, 2001; *Thompson and Solomon*, 2002; *Gillett and Thompson*, 2003]. It is of great interest to understand what effect this has had on ocean circulation.

2. Methods

[6] We have investigated variability in transport through Drake Passage using sea level data from Faraday Station on the west side of the Antarctic Peninsula (Figure 1); this is by far the longest series of sea level data from Antarctica. The installation at Faraday (now operated by the Ukraine, and renamed Vernadsky) consists of a conventional float gauge housed within a heated stilling well. It has provided data since 1958, as part of the UK's contribution to IGY activities, and is now maintained in association with Ukrainian colleagues. Sea level and air pressure data from Faraday were combined to provide a time series of Subsurface Pressure (SSP; sea level corrected for the inverse barometer effect) spanning 1981–2000. Data from before that period were not included because of concerns over data quality. For example, sea level at Faraday is known both from data analysis and modelling studies to respond to air pressure changes much as the local inverse barometer model would suggest. However, prior to the 1980s the data do not demonstrate such behaviour, a fact which we have so far assigned to unaccounted errors in either or both data sets. A nodal (18.6 year) long period astronomical tide term with an amplitude and phase based on the Equilibrium Tide (0.9 mbar peaking in late 1987) was subtracted from the SSP record.

[7] We have also used BPR data from around 1000-m depth at the south side of Drake Passage (Figure 1). BPRs were deployed typically for 1–2 years duration prior to turnaround. Because of the loss of datum during the turnaround process, BPR data are not suitable for studying signals longer than the length of the individual deployments, hence we restrict their use to studies of seasonal variability, and use the Faraday SSP data for addressing longer (interannual) periods. For studying month-by-month trends in BPR data, the individual series were concatenated using endpoint matching, detided, and variability at timescales longer than annual was removed. Monthly means were derived, and trends based on month were calculated.

[8] SSP and BPR data can be good indicators of transport variability via the geostrophic relationship; it has been shown previously that such data perform well in this role at Drake Passage for subseasonal timescales, and that it is the data from adjacent to Antarctica that contain the true signals of circumpolar transport variability [*Hughes et al.*,

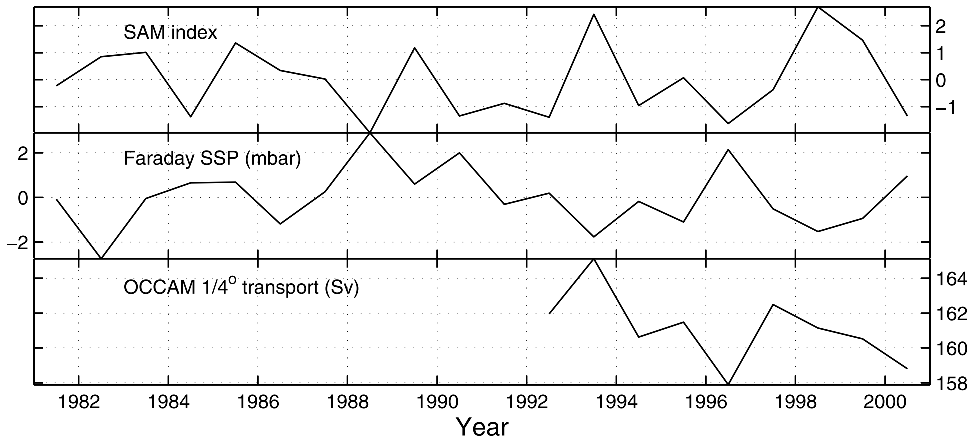

Figure 2. Upper panel is annual means of the SAM index during the 1980s and 1990s. Middle panel is annual means of Subsurface Pressure (SSP) from the Faraday tide gauge. Lower panel is annual means of transport through Drake Passage from the OCCAM general circulation model. Note the inverse correlation between the SAM index and Faraday SSP, and the direct correlation between the SAM index and the OCCAM transport.

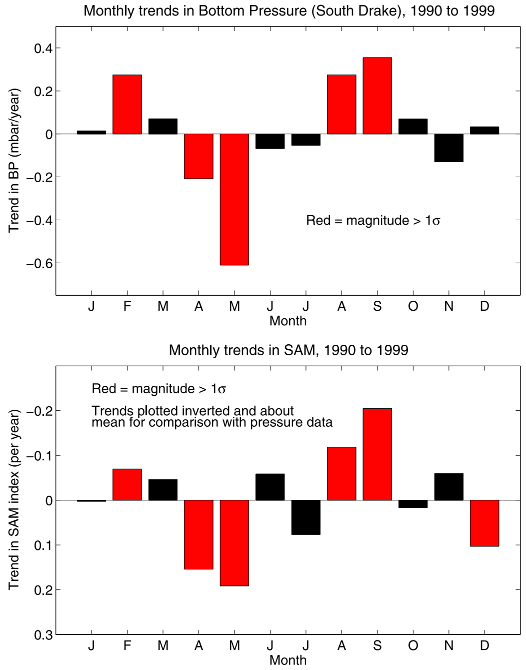

Figure 3. Upper panel is month-by-month trends in bottom pressure from the South Drake BPR (marked in Figure 1) for 1990–1999. Trends are shown as anomalies about the mean. Months marked in red are those with significant trends. Lower panel is the corresponding month-by-month trends for the SAM index, again shown as anomalies relative to the mean trend, but plotted inverted for comparison.

1999; *Hughes et al.*, 2003]. It will be seen below that this extends to seasonal and interannual timescales also.

[9] Various versions of the SAM index are available, differing primarily in their secular trends. We have previously made use of an index derived from NCEP-NCAR reanalysis fields [*Hughes et al.*, 2003]. An alternative (used here) is a station data-based index constructed from air pressure records from 12 stations (6 each at 40S and 65S) for the period to 2000 [*Marshall*, 2003]. To derive a SAM index from this, we differenced the northern and southern pressures, and normalized the series by scaling the variance of the pressure difference to match that of the Faraday SSP. Annual means of the NCEP-NCAR based index and that used here give a correlation coefficient of 0.86 for 1981–2000 (a similar coefficient with or without the secular trends in both time series removed).

3. Results

[10] Figure 2 shows annual means of the Faraday SSP record for the 1980s and 1990s, along with annual means of the SAM index covering the same period; the correlation coefficient is 0.68, significant at the 99% level. Both records have been detrended, thereby removing any contribution due to vertical land movements or long term sea level change in the SSP record, and systematic long-term errors in the SAM. Slightly larger or smaller coefficients are obtained with different versions of the SAM index (e.g., 0.76 with the *Thompson and Solomon* [2002] radiosonde-based index, which ends in 1998). That the SSP data is genuinely reflecting transport variability is demonstrated further in Figure 2, the lower panel of which shows annual means of the transport through Drake Passage from the $^1/_4$° OCCAM general circulation model (forced with 6-hourly winds and atmospheric pressures from the ECMWF reanalysis [*Webb and de Cuevas*, 2002]). The correlation between Faraday SSP and OCCAM transport is −0.79, significant at the 95% level; regression of Faraday SSP with OCCAM transport gives a scaling of −2.1 Sv/mbar.

[11] With available data, it is not possible to investigate directly the overall effect of the long-period trend in the SAM on the ocean transport through Drake Passage; for example, the Faraday SSP data will also contain trends due to processes such as land movements and global sea level rise. We are able, however, to investigate the effects of the long-term changes in the seasonality of the SAM, which combine to produce the observed trend [*Gillett and Thompson*, 2003; *Thompson and Solomon*, 2002]. For this, we have used the 10-year sequence of BPR data collected from 1000-m depth at the south side of Drake Passage (Figure 1). These data are preferable to the Faraday SSP data for investigating changes in seasonality, since they are recorded much deeper; the Faraday data will contain its own separate seasonality due to processes such as ice formation/melting and seasonal upper-ocean temperature changes, whilst the BPR data will not be affected in these ways.

[12] The upper panel of Figure 3 shows the changes to the seasonality of the bottom pressure from the south Drake Passage BPR during the 1990s; the lower panel shows the corresponding changes in the SAM index. For this, the monthly trends in the SAM have been plotted inverted for comparison with the bottom pressure data, and the mean monthly trend has been subtracted from both (this is a requirement for the bottom pressure data, due to the inevitable loss of datum during the recovery and redeployment process). Other versions of the SAM index show slightly different month-by-month relative trends, but the four most predominant months (April/May and August/September) are significant in all; these months are reflected (with the same signs) in the bottom pressure trends. It is thus clear that the significant seasonal changes in the SAM are reflected in the bottom pressure data, providing good evidence that the changing seasonality of the SAM during the 1990s has been inducing similar changes in the seasonality of the oceanic circumpolar transport. Whilst the similarity in seasonality of the SAM and the bottom pressure data is suggestive, further work (including possibly a modified fieldwork approach) is required to fully address the impact of the long-term trend in the SAM on ocean transport.

4. Discussion and Conclusions

[13] The close relationships of the series shown in Figure 2 provide the first clear evidence that the interannual variability in transport through Drake Passage is dependent on the SAM. These relationships also demonstrate that the Faraday location, and specifically SSP recorded there, is useful for monitoring this transport variability. This is fortuitous: under circumstances of baroclinic variability (such as exist at interannual periods) there is no *a priori*

requirement that sea level (or SSP) should reliably reflect transport. The importance of baroclinic variability at interannual timescales was seen further by running a purely barotropic version of the OCCAM model code [*Hughes and Stepanov*, 2004]. The transports in this barotropic model (not shown) were very different to those in the full OCCAM run, and were not significantly correlated with interannual variability in the SAM. That Faraday SSP reflects transport variability on interannual timescales is an indication that such transport changes occur with a regular depth variation, even though they may not be purely barotropic.

[14] We have seen that the interannual variability in the transport through Drake Passage depends strongly on changes in the SAM on the same timescales. This raises the question why previous studies that have measured transport changes over several years using different techniques have not noted such dependence. Not all researchers will have examined their transport estimates for links with the SAM, however it is worth noting that studies based on annual repeat hydrographic sections across Drake Passage show a range in transport of around 20 Sv [*Cunningham et al.*, 2003], much greater than the total range in annual mean transport from OCCAM (around 7 Sv; Figure 2). The reason is obvious; the latter are based on annual means, whereas as the former are once-per-year samples, hence any local, smaller-scale (e.g., eddy) variability will be aliased by the former but averaged out in the latter. This is indicated further by considering "snapshots" of model transport corresponding to the times of the hydrographic sections presented by *Cunningham et al.* [2003]. These again had a range of around 20 Sv, comparable to the range in transports observed in the hydrographic sections, but much larger than the range of genuine annual means in transport.

[15] Studies that include data from sources additional to hydrographic sections (such as expendable bathythermographs [*Sokolov et al.*, 2004; *Sprintall*, 2003]) have more samples per year, and hence may suffer less from aliasing; maintaining such time series for an extended number of years is clearly desirable. Given that the genuine interannual variability in transport is rather small compared with the mean flow of the ACC (and hence large changes in the SAM are required to induce significant interannual changes in transport), techniques to monitor the interannual variability in flow must be very accurate as well as having a sufficiently rapid sampling interval.

[16] The transport through Drake Passage is an important factor in the global climate system. The intermediate and upper-layer waters constitute the "cold water" return path of the global thermohaline circulation [*Rintoul*, 1991], thus any changes in their transport have the potential to influence circulation and climate over a much broader area. Note that the instrumentation used here was deployed in the surface layer and around 1000 m depth, thus we can be certain that seasonal and interannual transport variability associated with the SAM affects these upper layers. Further work is required to fully address the impacts of changes in ocean transport through Drake Passage on the global climate system.

[17] We have seen that the ocean transport through Drake Passage is susceptible on interannual timescales to large-scale climate variability, and that the long-term changes in the seasonality of the transport through Drake Passage are correlated with corresponding changes in the SAM. These latter changes combine to produce the observed trend in the SAM, and are believed to be forced by anthropogenic processes over the past 30 years. Whilst our series are shorter than this, this is nonetheless suggestive of a mechanism whereby climate change could directly influence large-scale ocean circulation. It is thus vital that these series are maintained so that the effects on circumpolar ocean transport of longer-period changes in climate can be ascertained.

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