variability in the Southern Ocean results primarily from a passive response of the oceanic mixed layer to atmospheric forcing, with ocean-atmosphere coupling playing a second-order role.

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The Causes of Full Ocean Depth Interannual Variability in Drake Passage

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Introduction

In recent years a number of large scale modes of Southern Hemisphere climate variability have been observed, most notably the Southern Annular Mode (SAM, e.g. Thompson and Solomon, 2002), the Pacific South American modes (PSA, e.g. Mo and Peagle, 2001), the Antarctic Dipole (e.g. Martinson and Ianuzzi, 2003), the Antarctic Circumpolar Wave (e.g. White and Peterson, 1996), and of course the El Niño Southern Oscillation (ENSO). All have pronounced effects over or in the Southern Ocean, and may be expected to account for a significant part of the interannual variability observed there. Most studies analyse these phenomena from a large-scale point of view, often by extracting modes from Southern Hemisphere atmospheric and oceanic fields using various mathematical techniques. In this study we have taken an alternative approach, and tried to understand the causes of the full ocean depth variability in Drake Passage observed in the WOCE SR1b repeat hydrographic sections (Cunningham et al. 2003).

Variability in Drake Passage

Cunningham et al. (2003) find a mode of year-to-year variability in Drake Passage which is dominated by the north-south movements of the full-depth Polar Front. This is accompanied by vertically and laterally coherent shifts in isopycnal depth throughout most of the section. Figure 1 compares a set of isopycnal surfaces from the SR1b occupations in 1996 and 1997, Polar Front south and north years respectively. As the Polar Front moves north, isopycnals in the southern part of the section are on average elevated, and those in the north are depressed.

These vertically coherent shifts are well captured by satellite altimetry, since they have a clear effect on surface dynamic height relative to some deep level. We have found that altimetric sea level anomaly (SLA) extracted along the SR1b track is well correlated with surface dynamic height anomaly (r = 0.83, explaining 69% of the variance). As a consequence, Drake Passage SLA is a good proxy for the dominant mode of variability in SR1b, and can be used to examine full depth Drake Passage variability. The key advantage is greatly improved temporal resolution over the quasi-annual SR1b sections: we have used the ten-daily merged Topex / Poseidon and ERS-1/2 SLA data set. Figure 2 shows SLA averaged in the latitude band 56-58°S along the SR1b track, which is dominated by the north-south movements of the Polar Front and thus captures much of the dominant mode of variability in SR1b. While the time series contains some small amplitude and relatively rapid features, it is dominated by large amplitude variability

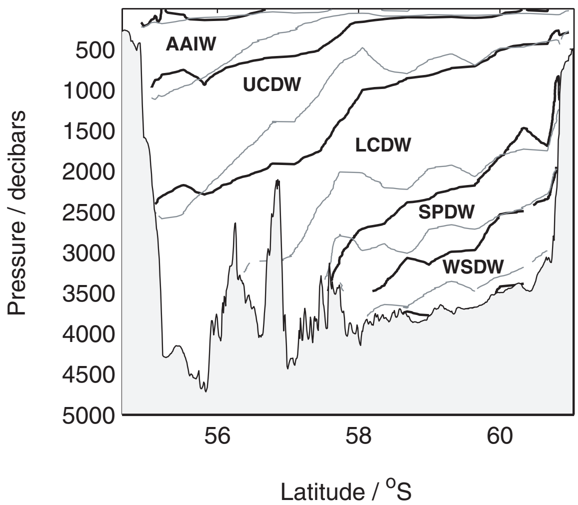

Figure 1: Isopycnal surfaces from SR1b 1996/7 (Polar Front south year, bold lines) and 1997/8 (Polar Front north year, faint lines). The contours are the boundaries in neutral density between the main water masses in the ACC, from top to bottom these are: Antarctic Intermediate Water, Upper and Lower Circumpolar Deep Water, Southeast Pacific Deep Water and Weddell Sea Deep Water

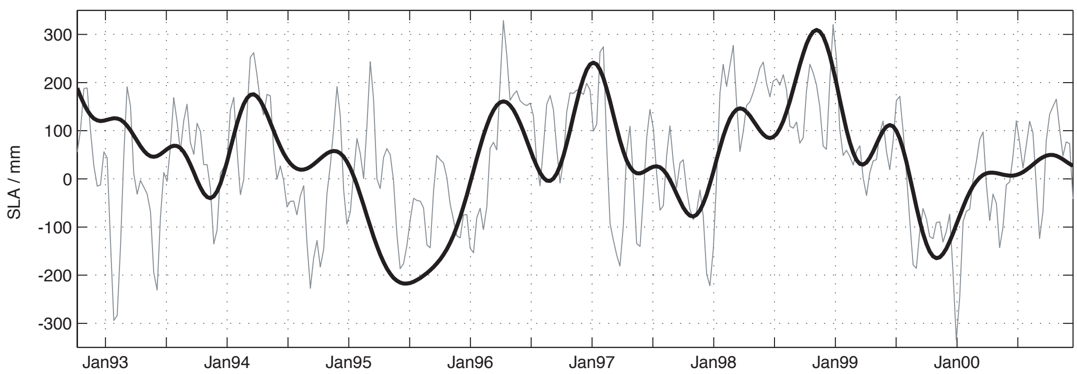

Figure 2: Sea level anomaly averaged 56-58°S along the SR1b track (faint line) and averaged over a larger region of Drake Passage (56-60°S, 56-68°W, bold line). The Drake Passage average series has been scaled up by a factor of three to make the comparison clear.

at interannual time scales. Figure 2 also shows a filtered Drake Passage average series of SLA, which captures essentially the same mode of interannual variability, so the vertically coherent mode in SR1b is not strictly local to the section, but is important in the whole region.

This Drake Passage averaged SLA series has been cross-correlated with Southern Hemisphere grid point SLA from the same data set to search for possible teleconnections forcing the vertically coherent mode in Drake Passage. A number of patterns emerge, the most significant of which is shown in Figure 3, which shows the correlation map at -10 months lag. There is a large region of positive correlation in the eastern tropical Pacific that extends southward along the west coast of South America. The whole lag-sequence of correlation maps shows the path of a Kelvin wave developing in the western equatorial Pacific, propagating along the equator, southward along the west coast of South America and into Drake Passage. The first part of this is clearly the path of a developing ENSO event, and the continued propagation of Kelvin waves along the coast of South America has been observed by others (e.g. Johnson, 1990). However the correlation coefficients seldom exceed the $r = 0.56$ level needed for 95% statistical significance (assessed using a Monte Carlo simulation), and similarly the number of locally significant correlations in this sequence never reaches the global significance level.

We have similarly searched for Drake Passage teleconnections in a wide range of oceanic and atmospheric data, including sea surface temperature, NCEP / NCAR reanalysis winds, sea level pressure, and EOFs of sea level pressure that are dominated by the SAM, PSA and ENSO modes. In every case there are hints at links between Drake Passage SLA and the large scale modes of Southern Hemisphere variability, but no globally significant teleconnection was found that could account for more than 20-30% of the variability in Drake Passage.

Locally generated variability?

While alternative or more sophisticated analysis techniques may be able to improve statistical confidence that teleconnections force SLA in Drake Passage, they are unlikely to increase significantly the percentage of variance explained. It seems likely that a significant part of the interannual SLA variability in Drake Passage is locally generated, probably by the interaction between the Antarctic Circumpolar Current and the topography in Drake Passage.

A simple zonally periodic channel model has been constructed using the Hybrid Co-ordinate Ocean Model (HYCOM). The model is 20° in latitude (centred on 60°S) by 120° in longitude, with 6 layers in the vertical and a lateral resolution of 0.25° latitude by 0.5° longitude. Layer interfaces slope upward from north to south to represent the density gradient across Drake Passage, and this interface slope is maintained by a relaxation at the side walls. The base configuration has a flat bottom at 4000 m depth with vertical side walls. In the run discussed here a Gaussian sea mount of height 500 m and diameter 440 km is added in the latitudinal centre of the channel at 20° longitude. The model ocean is driven by a steady eastward wind stress, which increases sinusoidally from zero at the side walls to a peak of 0.1 N/m^2 in the centre of the channel.

Even in this basic configuration the model generates large amplitude interannual variability in the region downstream of the sea mount. Figure 4 shows a time-longitude diagram of SLA from years 1 to 30 along a line running just north of the

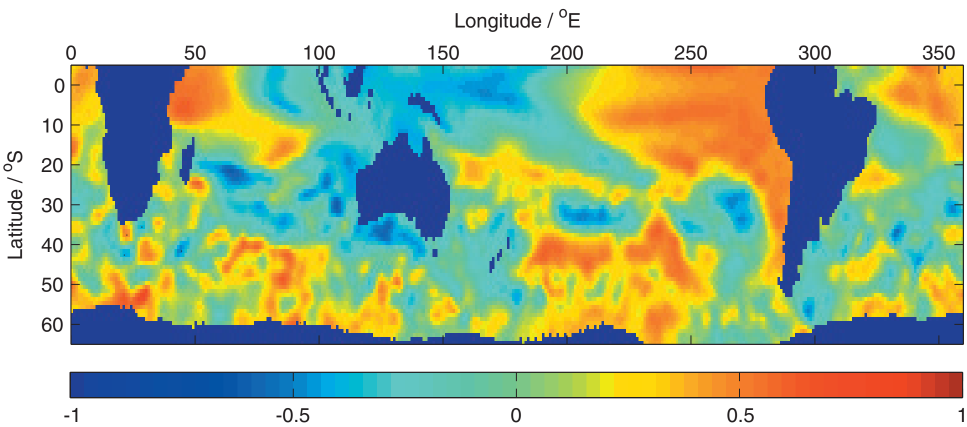

Figure 3: Correlation between Drake Passage SLA and Southern Hemisphere grid point SLA at –10 months lag.

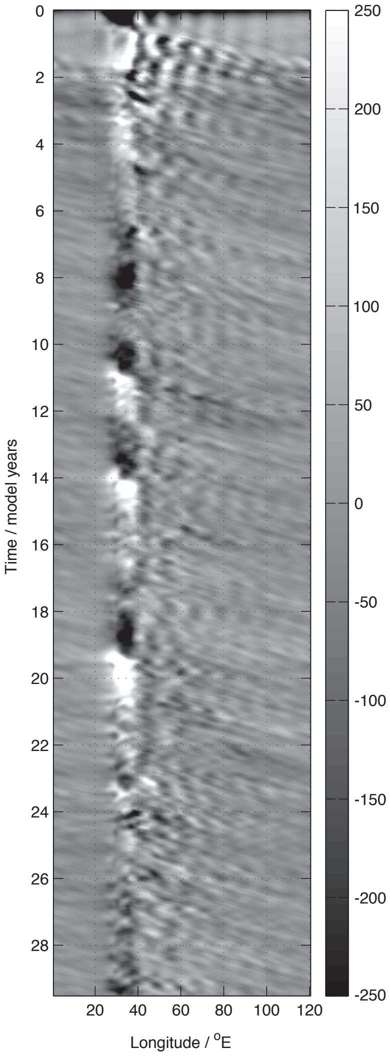

Figure 4: Time-longitude diagram of SLA (mm) in the HYCOM based zonal channel model along a latitude just north of the sea mount.

sea mount (where the variability is greatest). Downstream of the sea mount (which is at 20°E) SLA varies between low and high states with a period of 500-1000 days. The dominant flow feature in this region is a stationary Rossby wave, and the variability is caused by long period variations in its amplitude. In cross section the variability bears a strong resemblance to the variability seen in the SR1b hydrographic sections: high SLA in Figure 4 is accompanied by a southward redistribution of the flow and vertically and laterally coherent shifts in isopycnal depths. Runs with altered topography have confirmed that the amplitude of the variability depends on the meridional amplitude of the stationary Rossby wave, which in turn depends on the topography. In general topography with greater meridional extent generates larger amplitude variability. The mechanisms setting the time scale of the variability have not been clearly determined, but the advective time scale - the time taken to advect an anomaly right around the periodic channel - appears to play a role.

Aside from the simplicity of the model, there are key differences between the flow of the ACC through Drake Passage and the model described here. The similarities between the two should not be over emphasised, but the model does illustrate that flow-topography interactions can generate interannual variability without external forcing. It seems quite likely that variability will be generated dynamically by the flow of the ACC through Drake Passage, and at the least this locally generated variability complicates the question of how this region of the Southern Ocean will respond to the large scale modes of Southern Hemisphere variability like the SAM, ENSO, PSA modes and the ACW. Two papers are currently in preparation that will discuss the work described here in detail.

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