Circumpolar response of Southern Ocean eddy activity to a change in the Southern Annular Mode

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Received 4 April 2006; revised 29 June 2006; accepted 7 July 2006; published 19 August 2006.

Analysis of satellite altimeter data reveals anomalously high Eddy Kinetic Energy (EKE) in the Antarctic Circumpolar Current (ACC) during the period 2000–2002. Around 2–3 years earlier (1998), the circumpolar eastward wind stress (as quantified by the Southern Annular Mode; SAM) showed a significant positive peak, and we have shown previously that the ACC peaked around 1998 in response. An eddy-resolving ocean model is used to investigate the delay between wind forcing and the eddy response, and demonstrates that the lag is due to the time taken to influence the deep circulation of the ACC. Winds over the Southern Ocean have shown a strong climatic increase over the past few decades. If this increase in winds is also reflected as an increase in eddy activity (as our analysis suggests it might), then the increased poleward heat flux may have played a significant role in the observed warming of the Southern Ocean. Citation: Meredith, M. P., and A. M. Hogg (2006), Circumpolar response of Southern Ocean eddy activity to a change in the Southern Annular Mode, Geophys. Res. Lett., 33, L16608, doi:10.1029/2006GL026499.

1. Introduction

The Southern Ocean is characterised by high levels of eddy energy associated with the frontal systems of the Antarctic Circumpolar Current (ACC) [Gille, 1994; Hughes, 1995; Morrow et al., 1994]. These eddies play a variety of roles in the dynamics of the Southern Ocean, and in influencing the formation rates and properties of high-latitude water masses that participate in the global overturning circulation [Hallberg and Gnanadesikan, 2006; Johnson and Bryden, 1989; Killworth and Nanneh, 1994; Marshall and Radko, 2003]. However, these modelling studies are poorly constrained due to the sparsity of field data and short satellite record of the Southern Ocean.

One of the key roles played by the mesoscale Southern Ocean eddy field concerns the balance of forces contributing to the ACC. For the latitudes of Drake Passage, where the eastward flow is unblocked above a depth of around 2000m, the northward Ekman transport must be balanced by a southward transport of dense waters below the depth of the shallow ridges. This balance maintains the density structure and hence the ACC, and can be facilitated by both standing and transient eddies, as well as diabatic circulations [Hallberg and Gnanadesikan, 2001]. The Southern Ocean mesoscale eddy field is also responsible for a poleward heat flux that balances the heat lost to the atmosphere at high latitudes and the heat carried equatorward in the Ekman layer [de Szoekc and Levine, 1981]. Furthermore, eddies play a role in controlling the zonal momentum balance of the ACC through mechanisms such as interfacial and bottom form stress [Wolff et al., 1991].

It is known that the ACC transport variability depends on variability in the eastward wind stress over the Southern Ocean, as quantified by the Southern Annular Mode (SAM) [Thompson and Wallace, 2000]. This response has been shown to hold on timescales from days and weeks [Aoki, 2002; Hughes et al., 2003] to years [Meredith et al., 2004]. In addition, the ACC can show intrinsic variability independently of changes in wind forcing, through positive feedback between the generation of mesoscale eddies through baroclinic instability and the dynamics of the mean circulation [Hogg and Blundell, 2006].

On longer (interannual) timescales, it is notable that the ACC transport varies by a comparatively small amount (around 7 Sv [Meredith et al., 2004], or roughly 5% of its mean), despite much larger comparative changes in the eastward wind stress. It has been argued that, for relatively weak wind forcing or strong diabatic constant (i.e., a buoyancy dominated regime) the ACC transport should be linearly related to the wind stress, but that for stronger winds an eddy-dominated regime exists where changes in the wind stress induce changes in intensity of the eddy field but relatively little change in ACC transport [Hallberg and Gnanadesikan, 2001]. This effect, noted by a number of authors, has been dubbed “eddy saturation”.

In this paper, we provide direct evidence that the eddy activity of the Southern Ocean shows a response to changes in the zonal wind stress, as quantified by the Southern Annular Mode, and that this response is lagged by a small number of years. We elucidate the mechanisms responsible for the magnitude and lag of the response, and comment on the implications of these findings for Southern Ocean dynamics and ocean climate.

2. Methods

Satellite altimeter sea level anomaly (SLA) data were obtained from AVISO on a 1/3° Mercator grid at 7 day intervals [Ducet et al., 2000]. Eddy Kinetic Energy (EKE) was calculated by deriving surface geostrophic current anomalies from the SLA gradients, and then calculating half the sum of the average eastward and northward velocity anomalies squared. An averaging period of 1 year was used to enable examination of the interannual changes in EKE without the effects of seasonal variability.

An initial analysis using merged multi-satellite mission data revealed anomalously low EKE in 1994. This
Corresponds to the ERS1 ice-monitoring and geodetic mission, during which there were no ERS data available suitable for eddy variability studies. For this period, TOPEX/Poseidon (T/P) data alone were used in the merged product, and the different spatial/temporal sampling resulted in derived EKE being affected by around 30% globally [Ducet et al., 2000]. Accordingly, we used solely T/P data from 13 October 1992 to 6 August 2002 inclusive, and Jason data (which has the same orbit characteristics as T/P) from 13 August 2002 to 4 January 2005.

[9] Values of the SAM index were obtained from the Joint Institute for the Study of the Atmosphere and Ocean. Full details of derivation of these values are available at http://www.jisao.washington.edu/aoa/slp/.

[10] The response of the ACC mesoscale eddy field is simulated using an eddy-resolving ocean model (Q-GCM, version 1.3.1) [Hogg et al., 2003]. The model uses three quasigeostrophic (QG) layers with fine horizontal resolution (10 km), biharmonic viscosity with a small coefficient (A4 = 10^10 m^2/s) and weak bottom drag (with a spindown timescale of 250 days) so that the strong eddy field in the Southern Ocean is well represented. Other model parameters are chosen so that the Rossby radius is small (r_d = 33km). The domain is a long (23040 × 3000 km) periodic channel, with topography derived from Smith and Sandwell [1997] truncated at 900m above or below the mean height (for consistency with the QG assumptions). The wind stress field which drives flow in the model is purely zonal with a simple maximum of 0.17 N/m in the Southern Ocean is well represented. Other model parameters are chosen so that the Rossby radius is small (r_d = 33km). The domain is a long (23040 × 3000 km) periodic channel, with topography derived from Smith and Sandwell [1997] truncated at 900m above or below the mean height (for consistency with the QG assumptions). The wind stress field which drives flow in the model is purely zonal with a simple maximum of 0.17 N/m at the centre of the domain (which is the same as the long term mean at 55oS in the National Centers for Environmental Prediction (NCEP) reanalyses).

3. Results

[11] The sequence of EKE shows a pronounced peak during 2000–2002 (Figure 1). This is most pronounced in the Pacific and Indian sectors of the Southern Ocean, but is present in the Atlantic sector also. The high EKE during 2000–2002 is concentrated in a circumpolar band that flanks the northern edge of the ACC (Figure 2); this is the band that has long been known to mark the highest mean EKE in the Southern Ocean. Within this band, the EKE values are elevated by around 50–100 cm^2/s^2 during 2000–2002, roughly equivalent to 5–10% of its long-term mean. Values outside this band show little change in EKE.

[12] Circumpolar wind stress, as quantified by the SAM index, shows a significant peak during 1998–99, around 2–3 years prior to the peak in EKE (Figure 1). It is known that, on interannual timescales, the ACC responds to changes in forcing by the SAM with a timescale of less than 1 year, and that ACC transport (as measured in situ by Antarctic sea levels) peaked during 1998 [Meredith et al., 2004]. To investigate the lag between the peaking of the SAM (and the ACC transport) and the peaking of circumpolar EKE, we conduct a series of numerical simulations in which wind stress perturbations can be imposed.

[13] The model is initially run for 30 years with steady wind stress. After this, the flow is in a quasi-steady state, but variations in the eddy field arise due to internal instability mechanisms [Hogg and Blundell, 2006]. We then conduct tests over four 15-year simulations. Each 15-year segment is conducted three times: once with steady wind stress, once with a peak in wind stress of 0.21 N/m^2 at year 1 (which is the observed value of wind stress in 1998 from the NCEP reanalyses), and once with a peak in wind stress of 0.25 N/m^2 (to test the sensitivity of the system to larger perturbations). The forcing scenarios are shown in Figure 3a, with the response of the system in Figures 3b–3f.

[14] The response of potential energy (PE) averaged over the whole domain is relatively fast – a peak in PE occurs in both of the perturbed cases in Figure 3b soon after the peak in wind stress. It is notable that the steady case (black line) shows internal variability – this variability is much smaller than the forced response in PE, but the natural variability in the kinetic energy (KE) field is more significant. For this reason, we plot three different realisations of the KE response in Figures 3c–3e, where KE is averaged over the entire domain. (Hogg and Blundell [2006] show that variations in KE are due to the transient eddy field, and thus that KE variability is analogous to EKE variability). The natural variability makes it more difficult to isolate the KE response. However, the evolution of the system depends strongly on the initial state, so that the salient comparison here is the difference between the perturbed cases and the steady case. In each case there is a discernible difference (10–25%) between the standard perturbation and the steady case. With the standard perturbation, the peak in KE lags the wind stress by 1.2–2.0 years; when the perturbation is larger, the response of the system is faster (1.0–1.5 years) and larger in amplitude. Figure 3f shows the ensemble mean

Figure 1. Annual means of EKE in the three different sectors of the Southern Ocean, for the period 1993–2004. Note the strong peak in EKE during 2000–2002 in all three sectors. Also plotted (light blue line) is the SAM index for the same period, which shows a strong peak around 3 years prior to the peaks in EKE. (The averaging areas used for the separate basins are shown as boxes in Figure 2a. These are constructed to enclose the high EKE areas of the northern ACC, but exclude regions where the ACC interacts with non-circumpolar current systems such as the Brazil and Agulhas currents).
zonal transport for each case, demonstrating that the transport is weakly dependent on wind strength.

One feature of the observations is that the increase in EKE is seen simultaneously in each sector of the Southern Ocean. Figure 4 shows the same information as Figure 1, but for the ensemble average of model data over four different simulations for the steady case and the perturbed case. While there are regional differences, each sector shows a response to the wind perturbation which is greater than any peak (for that sector) from the steady case, and that there is a lag between the wind stress forcing and response of approximately 2 years. The model response is a factor of two larger than observed in the Indian and Pacific sectors, and a factor four larger in the Atlantic; this is considered to be a relatively close match, given the weak constraints on model parameters, differences in resolution between satellite and model data, and differences in the averaging areas.

4. Discussion and Conclusions

The response of eddy energy in the Southern Ocean to wind stress variations observed from satellite altimetry is consistent with the model response shown above. In both cases there is a delay of a small number of years between the peak amplitude of the forcing and the response in the eddy field, and the eddy activity is distributed circumpolarly around the Southern Ocean. We propose that the dynamics that lead to this delayed response are related to the internal variability of wind-driven channel flows, as outlined by Hogg and Blundell [2006]. The excess wind energy is initially stored as potential energy. The amplification of EKE is slower, but as eddies increase they act to transfer momentum from the upper layer to the lower layers (via interfacial form stress), where bottom topography steers the flow. This steered flow is more baroclinically unstable and produces a slow positive feedback, so that EKE increases over several years, until excess PE is drained. After ap-

Figure 2. Spatial distributions of EKE anomalies during (top) 1993–1999, (middle) 2000–2002, and (bottom) 2003–2004. Black lines mark schematically the main fronts of the ACC. The temporal division into three plots is arbitrary, and based on the EKE peak in 2000–2002 shown in Figure 1. Note that the raised EKE during 2000–2002 is circumpolarly coherent, and follows the band of high EKE along the northern ACC.

Figure 3. Time series showing (a) wind stress forcing, (b) potential energy evolution, (c–e) three realisations of kinetic energy from the model, and (f) the ensemble mean zonal transport. In each plot the black line shows the control case with steady forcing, the red line a perturbation experiment with forcings designed to match observations and the light blue line a perturbation experiment with double the observed amplitude.

Figure 4. Modelled kinetic energy anomalies for (a) the steady case and (b) the standard perturbation case in the three sectors defined for Figure 1, from an ensemble average of four different simulations. Also plotted (light blue line) is the wind stress anomaly used to force each experiment.
proximately four years the system returns to its original state and the natural levels of variability of the flow ensue.

[17] The model has also been used to survey parameter space for sensitivity to parameters. For example, Figure 3 shows how the response to a larger perturbation occurs faster. Other tests (not shown) have indicated that the response is delayed by increasing stratification. Both of these trends are consistent with the proposed hypothesis.

[18] The eddy saturation regime of the ACC describes a state in which zonal wind stress changes do not alter the zonal ACC transport; instead this transport is dominated by eddy effects. The modelling results here use a parameter set which is close to the eddy saturation regime, in that the steady state transport does not depend upon wind stress (see Hogg and Blundell [2006]) and the sensitivity of the transport to wind perturbations is weak (Figure 3f). The agreement between the modelled response of the Southern Ocean eddy field to a perturbation in wind stress and that observed is evidence in support of the real ACC being close to the eddy saturation regime.

[19] One of the most significant recent climatic changes in the Southern Hemisphere has been the shifting of the SAM toward a higher index state over the past three decades [Thompson and Solomon, 2002], with associated strengthening of the circumpolar wind stress over the Southern Ocean. It has been discussed by several authors what impact this may have on the ACC transport [Hall and Visbeck, 2002; Meredith et al., 2004], and a recent study argued that the ACC should show a significant increase in transport and a change in position [Fyfe and Sælenko, 2006]. It was noted by these authors, however, that their study (which used relatively coarse resolution climate models) could not include the possible effects of a response in the Southern Ocean eddy field. We have shown that this response is key in determining the impact of wind stress changes on ACC transport, and its inclusion results in very different findings. In particular, the long term increase in ACC transport is questioned.

[20] Another very significant change in Southern Hemisphere climate reported recently has been the pronounced warming of the circumpolar Southern Ocean [Gille, 2002]. We speculate here that these changes are not independent. As shown above, changes in the wind stress can induce changes in the intensity of the Southern Ocean eddy field, and it is known that these eddies contribute to the poleward heat flux across the ACC. A strengthening of the eastward winds could thus reasonably be assumed to have an associated increase in the poleward heat flux, thus potentially contributing to the warming of the Southern Ocean. Furthermore, most of the warming shown by Gille [2002] occurred south of the band of high EKE in the Southern Ocean, and north of this band a cooling was evident. We conclude that enhancements to the eddy field of the type shown here offer a plausible explanation for the warming of the Southern Ocean.

[21] Acknowledgments. We thank Paolo Cipollini, Chris Hughes and two anonymous reviewers for useful input and suggestions. This study was funded by the U.K. Natural Environment Research Council (NERC) and an Australian Research Council Postdoctoral Fellowship (DP0449851). Numerical computations were supported by an award under the Merit Allocation Scheme on the National Facility of the Australian Partnership for Advanced Computing.

References

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