Eddy-mean flow interaction in the Southern Ocean

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Introduction

In many eastward flows it is known that the eddies interact with the mean flow to produce a series of narrow jets. This occurs in the atmospheric jet stream (Starr, 1968), and in many numerical simulations of ocean flows including both quasigeostrophic models (McWilliams et al., 1978; Treguier and McWilliams, 1990; Wolff et al, 1991) and primitive equation models (Ivchenko et al., 1997; Best et al., 1999). The eddies produce jets by acting as a "negative viscosity", extracting eastward momentum from the wings of jets and accelerating the jet centres. A study of the effect of eddies in the Southern Ocean using Geosat altimetry indicated that this process may also be occurring in the Antarctic Circumpolar Current (Morrow et al. 1992).

There is a difficulty, however, in calculating eddy-mean flow interactions when the mean flow is poorly known. Hydrographic data are too poorly distributed in space and time to resolve processes on the length scale appropriate to eddies. Here we use gradients in the mean sea surface temperature field, which is well determined by satellite measurements, to indicate the position of jets in the mean flow. The combination of Along-Track Scanning Radiometer temperature data with gridded sea surface height measurements incorporating TOPEX/POSEIDON and ERS altimeter data is used here to deduce that eddies in the Southern Ocean do not act as a negative viscosity in the strongest jets. In some places the eddies act to decelerate the jets, while in others they act as a source of vorticity.

Figure 1a

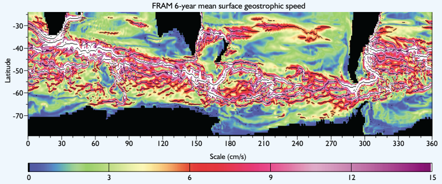
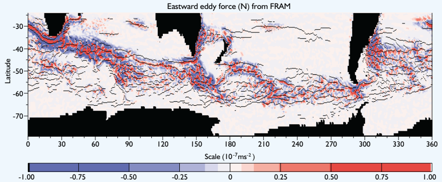


Figure 1b



Model Results

The results presented here are from the Fine Resolution Antarctic Model (FRAM), but are typical of a range of primitive equation model results with resolution of around 20 km (Ivchenko et al., 1997; Maltrud et al., 1998; Best et al., 1999). A six-year mean of the surface geostrophic speed is shown in **Fig. 1a**, with black lines superimposed to mark jet centres. The strong contrast in speeds demonstrates the spatial stability of these features, which interweave in a complex manner.

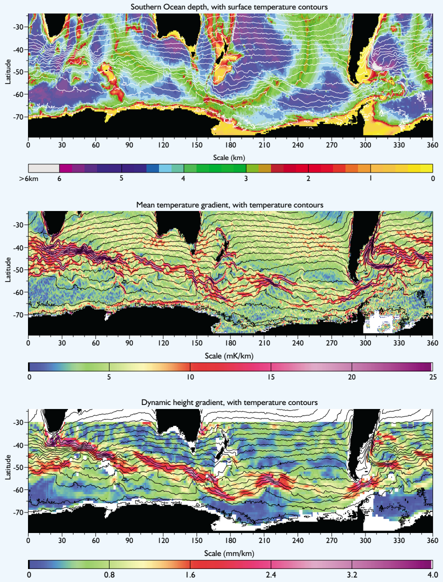
Figure 1b shows the eastward force exerted by eddies on the mean flow, for the same six-year average. Defining $p=\langle u'u' \rangle$, $q=\langle v'v' \rangle$, $r=\langle u'v' \rangle$, and $s=(p-q)/2$, the force represented here is given by $-(s_x+r_y)$. That force differs from the eastward component of the conventional reynolds stress divergence, since the gradient of eddy kinetic energy $(p+q)/2$ has been subtracted off. That gradient exerts a force with zero curl, which can be balanced by a small change to the mean sea surface height field and no associated mean velocity change. It was found to dominate the picture at the edge of regions of high eddy variability, while being dynamically unimportant.

It is clear that, in FRAM, the strongest jets are accelerated eastwards by eddies, although some jets lie along the boundary between eastward and westward forcing and are therefore subjected to a source of vorticity from the eddy field. It is also clear that the eddy-mean flow forcing changes over short length scales, of order 100-300 km. If this is to be interpreted correctly in the mean ocean, it is important to have a measure of the mean flow which includes these short scales. Hydrographic measurements do not have that spatial resolution throughout much of the Southern Ocean.

The Temperature Field

Monthly median values of temperature from ATSR, on a 0.5 degree grid, were used to calculate a mean temperature field and a mean temperature gradient, from 44 months of data. The mean field was calculated by averaging the monthly values, where more than 40 of the 44 months gave cloud-free data, and using the mean temperature gradient to interpolate elsewhere. The resulting mean and gradient is shown in **figure 2**. Although there are many small, filamentary structures in the mean gradient, most of these are stable over time: 22 month averages using the first and last half of the dataset give very similar pictures. It is also clear from the steering effect of topographic features more than 2 km deep that sea surface temperature gradients are reflecting the mean currents in some way. This impression is strengthened by comparison with the 0-1000 dbar dynamic height derived from the Hydrographic Atlas of the Southern Ocean (Olbers et al., 1992), which shows very similar features but with coarser resolution. It is not clear quite how the temperature gradient is related to the mean flow, and there could be systematic errors in the interpretation of large temperature gradients as jets, but this is the only data source with sufficient spatial resolution to compare with the eddy forces which can be derived from altimetry.

Figure 2



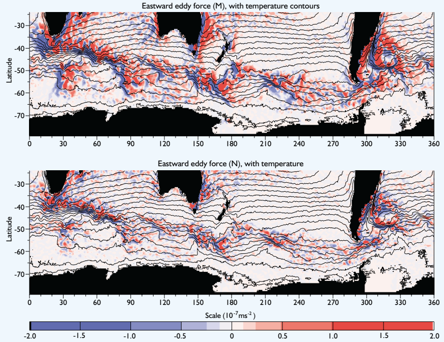
Eddy Forces

Eddy forces were calculated from five years of gridded sea level anomalies (Le Traon et al., 1998) incorporating TOPEX/POSEIDON and ERS altimetry. It was found that the gridded dataset produced results which were significantly less noisy than results of analyses at altimeter crossover points which did not make use of any optimal interpolation. The eddy quantities p,q,r,s were calculated at each (0.25 degree) grid point, and averaged over 5 grid points zonally and 3 grid points meridionally. The plots shown in **figure 3** are from slopes which were high pass filtered in time, passing all periods shorter than 1 year. Periods of 50 days and shorter give a very similar picture, whereas periods longer than 1 year produce a noisier-looking picture, possibly from the small number of cycles sampled by the 5-year record.

The eastward force is shown, with the effect of eddy kinetic energy gradient included (top) and removed (bottom). The lower picture shows the clearer relationship between jets and eddy forces, and clearly does not show eddies acting to accelerate jets. In some places the eddies are acting as a source of vorticity for jets, while in others they are decelerating the jets. Detailed comparison with the temperature gradient plot shows very few places where acceleration is clearly occurring.

There are two possible explanations for this: either the real ocean is behaving in a manner significantly different from the behaviour of models, or the sea surface temperature gradient is misaligned with the centres of jets. The tight relationship between sea surface temperature and narrow topographic features, and the agreement with the HASO atlas data, makes the second possibility implausible as a general explanation, although it is possibly true in certain regions. An unambiguous identification of the mean jets must await the high resolution geoid measurements which will hopefully be available soon.

Figure 3



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