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MODELLING THE VARIABILITY OF THE SOURCE REGIONS OF THE AGULHAS CURRENT AND INTER-OCEAN EXCHANGE

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1. INTRODUCTION

Exchanges of water south of Africa, between the South Indian and South Atlantic Oceans, are an important component of the global thermohaline circulation. [1]It has also been shown that the meso- through to interannual variability in these exchanges may influence weather and climate patterns in the southern African region (e.g. Walker and Mey, 1988; Crimp *et al.,* 1998; Reason and Mulenga, 1999).

The linkage between the South Indian and South Atlantic Oceans has been shown to be largely a function of mesoscale variability in the Agulhas Current proper, as well as in its source regions. There are thought to be three major sources in the South Indian Ocean for the Agulhas Current; namely, re-circulation in the South West Indian Ocean, flow through the Mozambique Channel, and the East Madagascar Current.

A recent experiment dedicated to the source regions of the Agulhas Current (ACSEX – Agulhas Current Sources Experiment) focused on the East Madagascar Current and flow through the Mozambique Channel (e.g. Ridderinkhof and de Ruijter, 2003; Schouten *et al.,* 2002). Data from current meters deployed during ACSEX indicate that the flow from the Mozambique Channel is mainly contributed to by anticyclonic eddies rather than an obvious southward current. However, these observations occur over a limited time and are unable to fully establish variability in the source regions, thus pointing to the need for model investigations.

Similarly the southern limb of the East Madagascar Current was previously thought to be a direct tributary to the Agulhas Current. However, satellite observations (e.g. Lutjeharms, 1988), have suggested that this current retroflects south of Madagascar and may only contribute to the Agulhas Current in the form of mesoscale eddies. During ACSEX, it was confirmed (de Ruijter *et al*., 2004) that this region is a source of both cyclonic and anti-cyclonic eddies. As in the case of the Mozambique Channel, there is no steady current here, but instead considerable variability due to eddies.

The most important source of the Agulhas Current is the re-circulation. Gordon *et al.* (1987) suggested that south of 32°S the Agulhas Current is in fact enhanced by a further 30 Sv from this re-circulation subgyre. However, although previous modelling and observational work has acknowledged the existence of Agulhas Current re-circulation, its influence on the current itself has not been considered.

2. THE MODEL

We have used the eddy-permitting, regional ocean AGAPE model (Biastoch and Krauß, 1999) to investigate the variability of the three source regions on monthly to interannual scales. AGAPE is based on the Modular Ocean Model (MOM version 2; Pacanowski, 1996). The model domain extends over the South Indian and South Atlantic Oceans from 65-6.5^{o}S and 60^{o}W to 115^{o}E. Within the South West Indian and South East Atlantic Oceans (20^{o}W - 70^{o}E), the horizontal resolution is 1/3^o × 1/3^o. Outside this region, it gradually coarsens in the zonal direction to reach 1.2^o at the meridional boundaries. There are 29 vertical levels from the surface to realistic bottom topography that resolve important features like the Walvis and Southwest Indian Ridge, the Agulhas Plateau and Bank, etc. Near the surface, the layers are 15 m thick in order to better resolve the mixed layer and thermocline, and this vertical grid coarsens to 250 m at deep levels. At the surface, the model is forced with monthly mean wind stresses and temperature fluxes from the 1986-1988 monthly climatology (Barnier *et al*., 1995) of the European Centre for Medium-Range Weather Forecast (ECMWF) model interpolated to three day values. The

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surface salinity is restored on a 50-day time scale to the Levitus *et al*. (1994) climatology. The model run was integrated for a further twelve years after the 30-year spin-up.

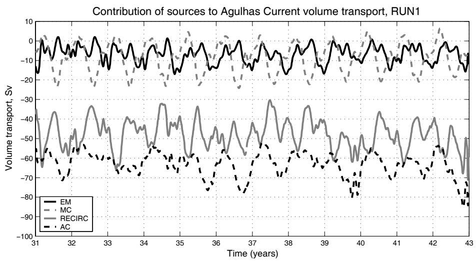
The model results support suggestions from previous observational (e.g. Quartly and Srokosz, 1993) and model (e.g. Matano *et al.,* 2002; Reason *et al.,* 2003) work that the Agulhas Current region and its sources are highly variable on eddy, seasonal and interannual time scales. Observations are sparse but those that do exist suggest that our model is able to realistically represent the circulation in the Agulhas Current region and its mesoscale variability; hence, there is a level of confidence in the model results.

3. RESULTS

In agreement with observations (e.g. Schouten *et al.,* 2003), flow through the model Mozambique Channel consists of a continuous train of southward moving eddies, focused in the western part of the channel. However, if the transport across the whole of the channel is considered, a strong annual cycle is seen, with maximum southward volume transport occurring in August and minimum in March.

The model East Madagascar Current was found to have an annual and semi-annual signal. This variability was partly related to that of the local wind stress curl and partly to that in the southern branch of the South Equatorial Current. Eddies were found to form south of about 20°S and the southern tip of Madagascar. On rounding the southern tip of Madagascar, the eddies drifted westwards. The model results suggest that this region is also influenced by the re-circulation of the Agulhas Current.

Re-circulation of the Agulhas Current back into the South West Indian Ocean was shown to be the most significant source region for the volume transport of the Agulhas Current north of 35°S. Although the re-circulation is by far the major contributor to the volume transport in the Agulhas Current (Figure 1), the other source regions make a significant contribution to the temperature transport. There are occasions when the temperature transport into the Agulhas Current is contributed to mostly by flow from the East Madagascar Current due to the higher heat content of the tropical water in that current.



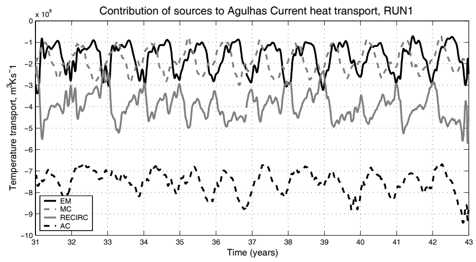


Figure 1 (upper) The contribution of the flow through the Mozambique Channel (grey, dashed), the East Madagascar Current (black) and re-circulation (grey) to the Agulhas Current volume transport (Sv) at 35°S (black, dashed); (lower) as for a but for the temperature transport (m^3Ks^{-1}).

A significant relationship was found between the volume flux of the model re-circulation and the Agulhas Current on interannual timescales. A semi-annual signal was also present in the re-circulation and was partly in phase with that of the wind stress curl over the subtropical South Indian Ocean. However, certain regions of the re-circulation may be affected by local winds leading to the annual cycle not being completely in phase with the basin scale winds. Previous work has not examined the variability of the re-circulation of the Agulhas system, yet because it is the major contributor to the Agulhas Current (e.g. Stramma and Lutjeharms, 1997) it is probable that it will have more influence on the variability on the Agulhas Current system than the other two sources.

A retroflection index (R) was created in an attempt to monitor the position and strength of the retroflection:

$$R = 1 - \left(\frac{|T_1| - T_2}{|T_1|} \right)$$

where T_1 is the maximum westward volume flux of the Agulhas

Current over the area 19-22°E, 35-40°S and T_2 is the maximum eastward volume flux of the Agulhas Return Current over the area 25-35°E, 35-45°S. Using the maximum transport over the defined boxes allows for any shifts in the position of the system, without affecting the index itself. When R=1, a complete retroflection occurs with no leakage, whereas if R=0 then the flow is completely into the South Atlantic Ocean, with no return flow back into the SW Indian Ocean. For intermediate values of R, partial retroflection occurs, and the degree determines the fraction that leaks into the South Atlantic.

The index showed that the retroflection varied on eddy to interannual timescales (Figure 2). Typically there was rarely a complete retroflection in the model and always some amount of leakage into the South Atlantic. More leakage occurred during austral winter.

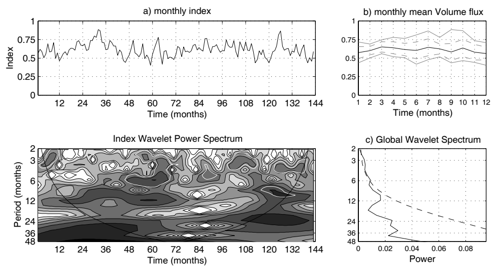


Figure 2 (left upper) Monthly time series of the index for the first run; (lower) wavelet analysis of this time series, 95% significance levels are shown by white contours and cone of influence by black line; (right, upper) the monthly mean value of R (black line) together with the maximum (upper line) and minimum (lower line) values and one standard deviation above and below the mean (grey, dashed lines); (lower) power of wavelet analysis significance shown by dashed line;

The sensitivity of the transport in the source regions and the retroflection index to a southward shift in the mean anticyclonic winds was investigated. It was found that the transport increased in the re-circulation subgyre and that there was increased mesoscale activity as well as reduced leakage into the South East Atlantic Ocean (Figure 3). The increase in eddy scale variability in the run with modified wind forcing was found to be consistent with altimeter observations from years with a similar wind pattern.

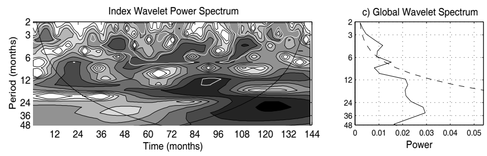


Figure 3 (left) Wavelet analysis of the index for the second run, 95% significance levels are shown by white contours and cone of influence by black line; (right) power of wavelet analysis, significance shown by dashed line.

4. CONCLUSIONS

Considerable variability exists in the model Agulhas region and its source regions on a range of timescales. The model variability on interannual timescales is generated internally by ocean processes since the monthly forcing is repeated each year. Internal ocean variability can be caused by instabilities of wind-driven currents. Jochum and Murtugudde (2005) found the largest internal variability occurred in their model in areas of high EKE (as found here) and related this to the fact that a large part of the Indian Ocean mesoscale variability explains a substantial part of the observed interannual variability. The peak in interannual variability in the recirculation and Agulhas Return Current region in our model is at least of the same order of magnitude as the annual cycle, suggesting its importance in this region.

This study has focussed on variability generated through ocean processes; how it might change under the full spectrum of atmospheric variability (which is not represented in the monthly climatology used to drive the model) is not yet known. Observations, although limited, indicate that the region is highly variable from one year to the next and therefore, were the model forced with the observed winds for particular years rather than a monthly climatology, one would naturally expect the simulated ocean variability to be even greater than analysed here. The second model run reinforces the suggestion that such an increase would be the case, given the changes evident in the variability of the southern Agulhas region in response to the southward shifted wind forcing.

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