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The importance of flow in the Mozambique Channel to seasonality in the greater Agulhas Current system

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Abstract. The temporal variability of the greater Agulhas Current system has important climatological consequences. Some recent results have suggested that this variability contains a large seasonal component, due to changes in the circulation at latitudes poleward of Madagascar only. A model simulation shows that the contribution of Tropical Surface Water to Agulhas Current waters, via the Mozambique Channel, also has a distinct seasonal characteristic that is brought about by the seasonal wind stress over the tropical Indian Ocean. This simulated flow through the Channel contributes substantially to the seasonality of the Agulhas Current. This model result is shown to be not inconsistent with available hydrographic observations.

Introduction

The Agulhas Current plays an important role in global ocean climate through its influence on interbasin exchange between the South Indian and South Atlantic Oceans [*Gordon*, 1986]. Temporal variations in the behavior of the Agulhas Current may have a significant effect on this role by influencing the frequency of ring shedding at the Agulhas retroflection [*Lutjeharms and van Ballegooyen*, 1988], the main mechanism by which this interbasin leakage comes about. *Pearce and Gründlingh* [1982] have suggested that there is no clear seasonality in this current, although a weak seasonality was suggested by measurements of the transport [*Gründlingh*, 1980]. Subsequent studies have indicated seasonal changes in the Agulhas retroflection region [*Quartly and Srokosz*, 1993] and in the South West Indian Ocean as a whole [*Ffield et al.*, 1997], but the statistical significance of these results is still weak, due to a lack of sufficiently long time series.

Matano et al. [1999] applied a GCM to the South Indian Ocean and showed two geographically distinct modes of variability separated by the submarine ridges south of Madagascar. West of these ridges where the greater part of the South West Indian Ocean subgyre is situated [*Stramma and Lutjeharms*, 1997], the seasonal variability in the Agulhas Current was dominated by local wind forcing. However, the *Matano et al.* model has a northern boundary at 20°S that intersects the Mozambique Channel, thus preventing a contribution of water to the Agulhas Current from here. It has been demonstrated [*Stramma and Lutjeharms*, 1997] that at least 8% of the baroclinic volume flux of the Agulhas Current does in fact derive from the Mozambique Channel. Furthermore, it is feasible that the dramatic changes in monsoonal winds north of about 15°S might provide strong seasonal forcing for currents near and in the Mozambique Current [*Maltrud et al.*, 1998]. This study uses a model that extends to 6.5°S which allows it to take the influence of the Mozambique Channel on the Agulhas Current system into account.

The Model

The model used here is based on the GFDL Modular Ocean Model [MOM2; *Pacanowski*, 1996] and covers the whole South Atlantic and the South Indian Ocean from 6.5°S to 65°S. The Agulhas region (20°W - 70°E) is modeled at eddy-permitting resolution (1/3° × 1/3°), and this is reduced to 1.2° at the boundaries. In the vertical, 29 levels are used.

The model was forced with winds and heat fluxes obtained from the consistent ECMWF climatology of *Barnier et al.* [1995]. At the lateral boundaries, an open boundary formulism connects the model to the rest of the world ocean. The necessary barotropic veloc-

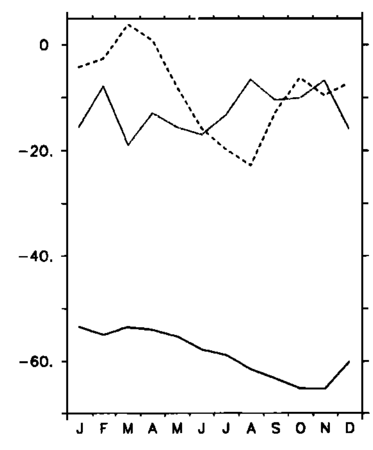

Figure 1. 5-year climatology of the model transport of the Agulhas Current at 32°S (solid), through the Mozambique Channel at 23°S (dashed) and of the East Madagascar Current at 23°S (dotted); in Sv (10^6 m^3s^{-1}). Note that flow south is negative.

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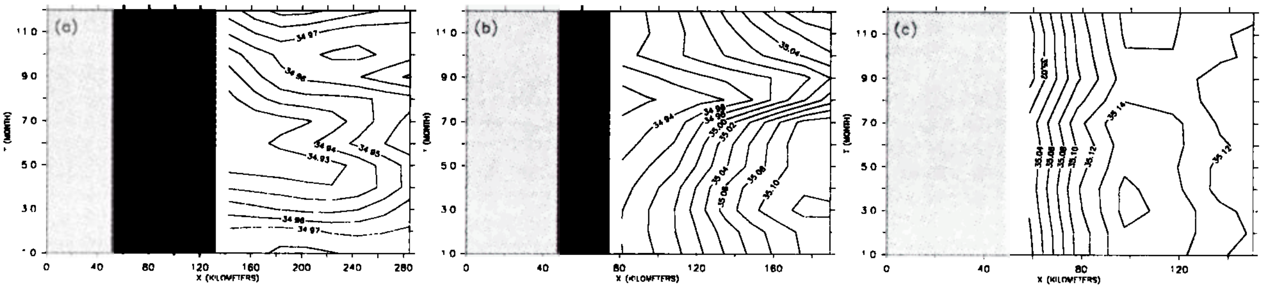

Figure 2. 5-year climatology of the model salinity at 200 m depth at 20°S (a), 24°S (b) and 31°S (c). All sections are perpendicular to the main flow direction. Light gray indicates the coastline and dark gray the ocean bottom topography at this location.

ities at these points are taken from the Semtner Model [*Stammer et al.*, 1996; run POCM_4A, which has similar forcing to the current model]. Surface salinity is restored with a timescale of 50 days to the monthly climatology of *Levitus et al.* [1994], these data also initialize the model. After spinning up from rest for 30 years, model fields are averaged over a further 5 year integration to a monthly climatology and this is analyzed below.

Further details of the model are given in *Biastoch* [1998]. The ability of this model to simulate both the large-scale circulation in the greater Agulhas system as well as its mesoscale variability has been demonstrated by *Biastoch and Krauß* [1999].

Results

Figure 1 shows that the model exhibits seasonality in Agulhas Current transport with the contribution from the Mozambique Channel varying from near zero in February/March to over 20 Sv in August. By contrast, there is little evidence of any seasonality in the East Madagascar Current. At 32°S, the southward transport of the Agulhas Current is weakest in January and March and the October/November maximum is displaced from the Mozambique Channel maximum of August. This lag suggests an advective link between the seasonal signal in the Channel and that off the South African coast. *Heywood and Somayajulu* [1997], who examined altimeter data in the South Indian Ocean and who showed strongest eddy kinetic energy in the Mozambique Channel, also suggested a seasonality in the Channel and in the Agulhas Current that is consistent with our model results.

It has previously been shown that the contribution to the flux of the Agulhas Current that comes through the Mozambique Channel consists largely of Tropical Surface Water [TSW; *Harris*, 1972]. This water, with characteristically low salinity values is found inshore of the core of the Agulhas Current [*Beal and Bryden*, 1998]. To test if the observed variability in the contribution from the Mozambique Channel shown in Figure 1 is evident in the TSW inshore of the Agulhas Current, the time variation of salinity at various sections across the model current was considered (Figure 2). The sections were constructed at 200 m depth so as to capture the simulated TSW at the depth at which it has been observed off South Africa.

At 20°S, the salinity minimum (which corresponds to model TSW) is evident from May to August. Note that the model TSW is found at the surface at 15°S in the Mozambique Channel and slowly sinks down as it is advected south on the inshore edge of the current

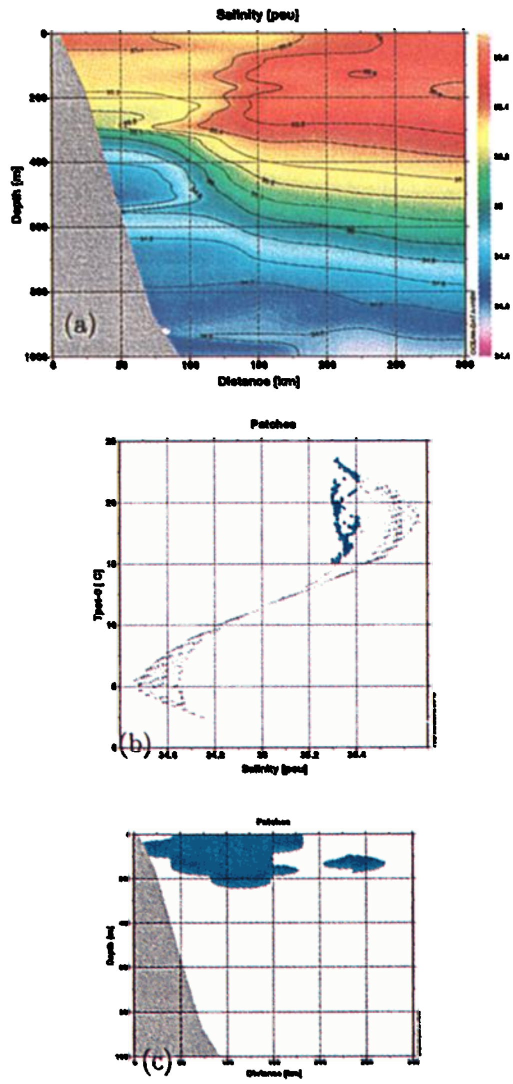

Figure 3. Zonal hydrographic section at 30°S in September 1987. Shown are salinity (a) and the Θ-S diagram for these stations (b). Tropical Surface Water (T $\geq$ 15° C, S $\leq$ 35.4) is marked by blue dots and its occurrence along the section is shown in (c).

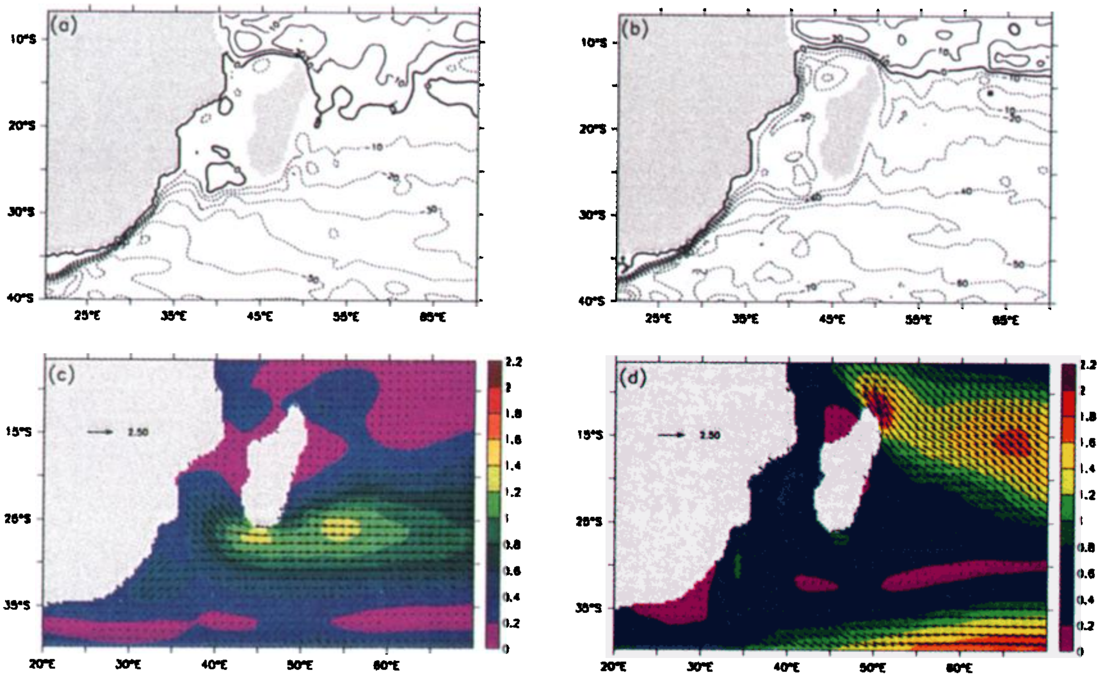

Figure 4. Streamfunction of the model transport in February (a) and August (b), in Sv. Absolute value and vectors of the wind stress in February (c) and August (d) (Note that only every third vector is drawn). Units are dynes cm^{-2}.

(not shown), so that at 20°S it is located at 200 m depth. Further south (24°S), this minimum can be seen in July and August while at 31°S in the Agulhas Current proper, there is a weak signature from September to December. Taking a typical current speed on the inshore edge of the Agulhas Current (where the TSW is located in the model) of 0.22 ms^{-1} (20-24°S) and 0.33 ms^{-1} (24-31°S) gives respective estimates of the time for this water to be advected between these transects of 23 days and 32 days. These estimates appear consistent with the advective time lags suggested by Figure 2.

While the seasonal signal of the TSW shows up clearly in the model, the sparsity of available hydrographic observations at appropriate spacing makes it difficult to resolve in the real world. Seasonality averaged over a number of years may be hard to detect by synoptic hydrographic sections if the flow of TSW were spasmodic or consisted of special events, which might well be the case. Nevertheless, we have examined all appropriate hydrographic data in the region. Figure 3 represents one such section and shows evidence of the distinct presence of TSW along a transect across the Agulhas Current. This water mass can be seen extending from the current core to the coast and from the surface to about 250 m depth. It is a bit fresher than the model TSW; however, this is not unexpected given that the model freshwater flux simply involves a relaxation to *Levitus et al.* [1994] data at the surface on a 50 day timescale. Hence the currently available observations are inadequate to unequivocally confirm the hypothesis that seasonal variations in the transport of TSW through the Mozambique Channel contribute to the seasonality of the Agulhas Current. However, they are certainly not inconsistent with this concept and their sparsity re-inforces the need for an extended field study in this important region.

Why would there be a marked seasonality in the flow through the Mozambique Channel? A plausible mech-

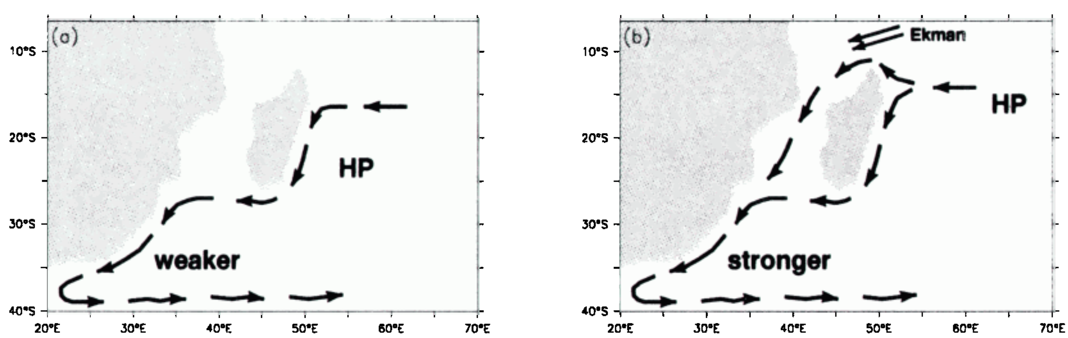

Figure 5. Hypothesis of the main circulation in the greater Agulhas Current System in austral summer (a) and winter (b). "HP" indicates the center of the high pressure cell, blue arrows the additional Ekman transport.

anism is suggested in Figure 4. In austral summer, the core of the South Indian Anticyclone lies to the south (Figure 4c). However, in winter, it is far enough north (Figure 4d) that the associated barotropic transport can flow north of Madagascar and can be driven into the Mozambique Channel (Figures 4b,5b). The Ekman transport associated with the southeasterly winds northeast of Madagascar has been calculated as contributing about 25% of the total flow into the Channel. This flow then transports TSW from the Indian Ocean into the Channel during winter with advection of this signal into the Agulhas Current by spring (Figure 2).

During summer however, the Anticyclone lies too far to the south (Figure 4c) for the transport to extend into the Mozambique Channel (Figures 4a,5a) and the net southward transport in the Channel is near zero (Figure 1). Hence, there is no signature of TSW in the model (Figure 2); instead the Agulhas Current receives a greater preportion of its water from the South West Indian Ocean gyre [*Stramma and Lutjeharms*, 1997] 2-3 months later.

Conclusion

Simulations with a model that includes the Mozambique Channel show evidence that the flow through this Channel may contribute significantly to the seasonal signal in the Agulhas Current. This extends the previous work of *Matano et al.* [1999] who did not include the Mozambique Channel in their model domain and who focussed on the role of the Madagascar Ridge in preventing midlatitude barotropic Rossby waves from communicating the seasonal signal in the South Indian Ocean to the northern Agulhas Current. At lower latitudes, these waves are less sensitive on seasonal scales to the bottom topography and our results show the potentially important role that the Mozambique Channel can play in influencing the seasonality of the Agulhas Current system.

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