Generation of cyclonic eddies by the Agulhas Current in the lee of the Agulhas Bank

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Abstract. Anti-cyclonic rings are shed from the Agulhas Current at its retroflection. They subsequently drift off into the South Atlantic. Smaller, cyclonic eddies have also been observed in this region. The origin of these latter eddies has remained unknown. We present model results that indicate that the configuration of the southern Agulhas Current and the poleward termination of the continental shelf of Africa allows shedding of cyclonic lee eddies by a flow detachment process. Hydrographic data, thermal infrared satellite images and altimetric observations are furnished that show that this model simulation is consistent with the characteristics and the behaviour of cyclonic eddies in the region.

Introduction

The inter-ocean exchanges brought about by the shedding of Agulhas rings south-west of Africa has been much studied because of their global climatic implications [*Lutjeharms*, 1996; *De Ruijter et al.*, 1999]. Recent models have shown that this movement of warm water from the Indian to the Atlantic may in fact control the rate of thermohaline overturning of the whole Atlantic [*Weijer et al.*, 1999]. There are also other, smaller sources of exchange including Agulhas filaments [*Lutjeharms and Cooper*, 1996] and intrusions of cold subantactic water [*Shannon et al.*, 1989]. In addition, a number of cold, cyclonic eddies have been incidentally observed in the South-east Atlantic [e.g. *Duncombe Rae et al.*, 1996; *Gründlingh*, 1995]. For a proper quantification of the inter-ocean exchanges the characteristics of all these components need to be known. The origin, behaviour and potential role in inter-ocean exchanges of the cyclonic eddies has not been established. We use a model with a high spatial resolution for the southern Agulhas Current in order to investigate the origin of such cyclonic eddies.

The Model

The ocean model is the Regional Ocean Modeling System (ROMS) that solves the free surface, hydrostatic, primitive equations over variable topography using stretched, terrain-following coordinates in the vertical and orthogonal curvilinear coordinates in the horizontal. It is an evolution of the SCRUM model [*Song and Haidvogel*, 1994], featuring high order schemes and innovative parameterizations. The curvilinear grid is pie-shaped to follow the South-Western corner of the African continent from 40°S to 28°S and from 10°E to 24°E (Figure 1a). The resolution ranges from 9 km at the coast up to 16 km off-shore. Twenty vertical levels preserve a high resolution near the surface. The model was forced with winds, heat and salinity fluxes from the COADS ocean surface monthly climatology [*Da Silva et al.*, 1994]. At the 3 lateral boundaries facing the open ocean, an implicit active radiative boundary scheme [*Marchesiello et al.*, in press], forced by seasonal time-averaged outputs of the AGAPE basin scale ocean model [*Biastoch and Krauß*, 1999], connects the model to the surroundings. In addition, a one-way radiative nesting scheme [*Flather*, 1976] is employed for the barotropic contribution. Starting from rest, using temperature and salinity fields derived from AGAPE, the model has been integrated for 10 years. Volume integrated quantities reveals that after a spin-up of 2 years, the model has reached a statistical equilibrium.

Results

The model gives a realistic portrayal of the known circulation in this ocean region (Figures 1a and 3b), including mesoscale details associated to the Agulhas Current such as Agulhas rings, shear edge features on the landward border of the current, and the wind-driven coastal upwelling along the west coast. The Agulhas Current overshoots the concave eastern part of the Agulhas Bank - the wide continental shelf south of Africa - and has its maximum surface velocities of about 1 $m.s^{-1}$ at the southernmost tip of the shelf. These simulations are all in very good agreement with observation [e.g. *Lutjeharms et al.*, 1989]. The features evident in the modelled sea surface height (SSH) are also well represented in the SSH observed by altimetry (Figures 1a and 1b). These consist of an anti-cyclonic Agulhas ring as well as some cyclonic eddies of unknown origin. One of these cyclonic eddies lies between the Agulhas Current and the western side of the Agulhas Bank in both portrayals. Cyclonic eddies are prevalent at this particular location in the model and this portrayal is therefore quite characteristic in this respect. An analysis of the generation, drift and persistence of cyclonic eddies at this location as observed in satellite altimetry is highly consistent with the model simulations (Figure 2). They are formed at roughly the same location, drift off in the same westerly direction, are produced with the same frequency, and can dissipate rapidly or grow in intensity. These results give us confidence that these features are not model artefacts. It would be important to establish the hydrographic characteristics of these particular cyclonic eddies.

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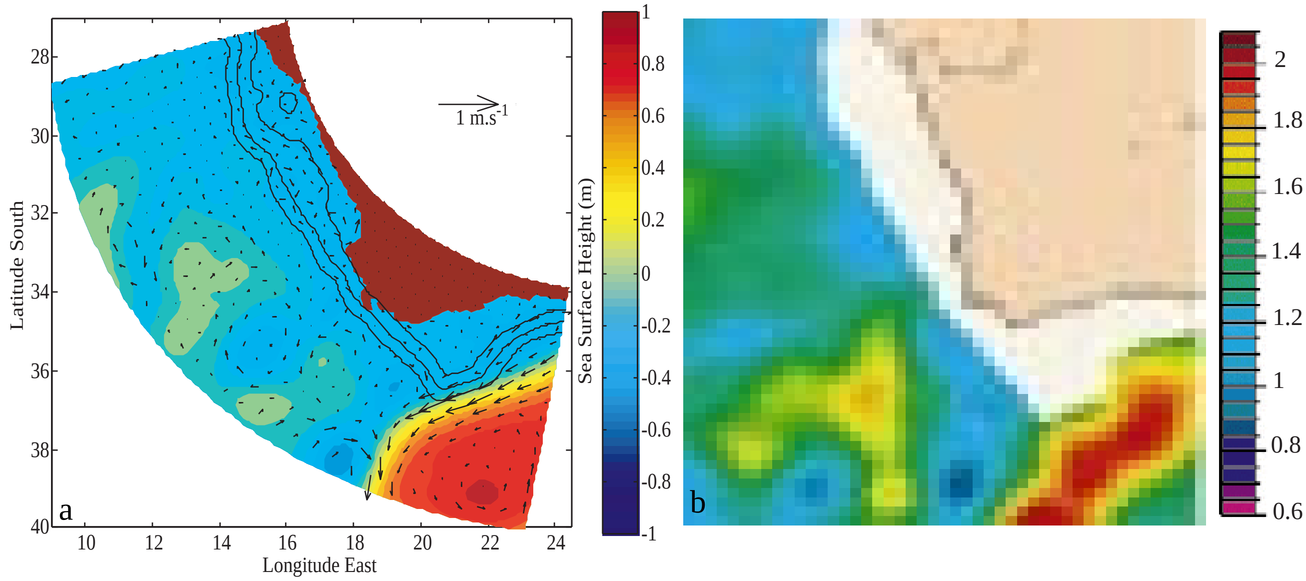

Figure 1. (a) Model simulation of the sea surface height and barotropic velocities (1 vector every 4 grid points) on 27 April of model year 2. (b) Naval Research Laboratory, MODAS 2.1, sea suface height derived from in-situ and satellite altimetry data on 16 January 1993. The dashed line shows the model offshore boundary.

The sea surface temperature and current portrayals in the upper panels of Figure 3 exhibits substantial agreement. The model shows a plume of warm surface water that encircles a cyclonic eddy in the lee of the continental shelf (Figure 3b). To the north there is faint indication of an anti-cyclonic eddy in the current vectors, encircled by the extension of the warm filament. The satellite thermal infrared image shows much the same (Figure 3a), except that the locations of the two features are slightly displaced. A vertical temperature section through the two eddies in the model shows the warm surface filaments as well as an anti-cyclonic eddy centred at 35.3°S and a cyclonic eddy at 36.7°S (Figure 3d). In the model, the eddy is still noticeable at 1500 m depth. An XBT section was undertaken across this region in a very similar location [*Bathmann et al.*, 1994] (Figure 3c). Regrettably, the sea surface temperature image was largely obscured by cloud on the day of the hydrographic section. Nonetheless, the position of the feature could be located and is shown relative to that of the 27 November 1992 by the dotted line in Figure 3a. The vertical temperature section for this line closely resembles that of the model. The similarity appears in the surface filaments and in the presence of both cyclonic and anticyclonic eddies (Figure 3c and 3d). The strong resemblance of hydrographic and model results shows that the cyclonic eddies generated off the Agulhas Bank in the model are not inconsistent with observations and extend to subtantial depths.

In the model, the coastal part of the Agulhas Current tends to follow the topography at the southern tip of the Agulhas Bank, carrying warm surface filaments spreading northward towards Cape Peninsula. At times, the southern part of this flow detaches from the topography and a cyclonic meander developes. After approximately 1 month, it detaches from the Agulhas Bank, taking away the warm filament (see Figures 3-a and 3-b). Occasionally, a cyclonic perturbation may follow the shelf break from the eastern Agulhas Bank and trigger the cyclonic eddy generation process. The averaged values of the Rossby ($R_o = 0.04$) and Burger ($S = 3.8$) numbers have been computed as described in *Boyer and Tao* [1987], taking the width of the Agulhas Current as a characteristic length scale (100 km). They lie in the cyclonic eddy shedding regime found in rotating tank experiments, when a linearly stratified flow encounters an obstacle [*Boyer and Tao*, 1987]. Thus, the generation of cyclones past the Agulhas Bank can be explained by a flow detachment process. Their characteristic diameters range from 50 km to 200 km. Although they are generated irregularely, the number of eddy shed each year is relatively constant, respectively from year 1 to year 10: {3,3,4,4,4,5,4,5,4,5}. Because the model domain has a limited size, most of the

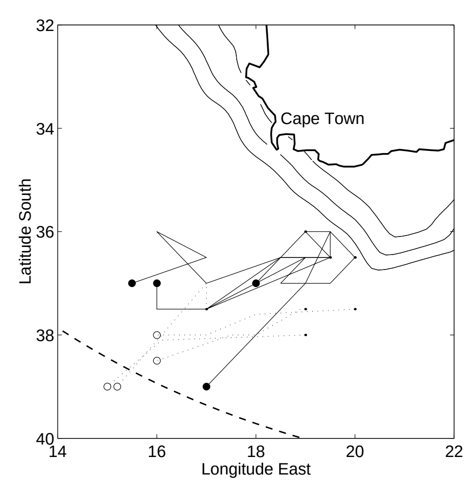

Figure 2. The drift patterns for a few characteristic cyclonic eddies west of the continental shelf. The bold tracks are for model eddies shed during model year 3; the dotted tracks for cyclones observed in Naval Research Laboratory, MODAS 2.1 sea surface height analysis for 1993.

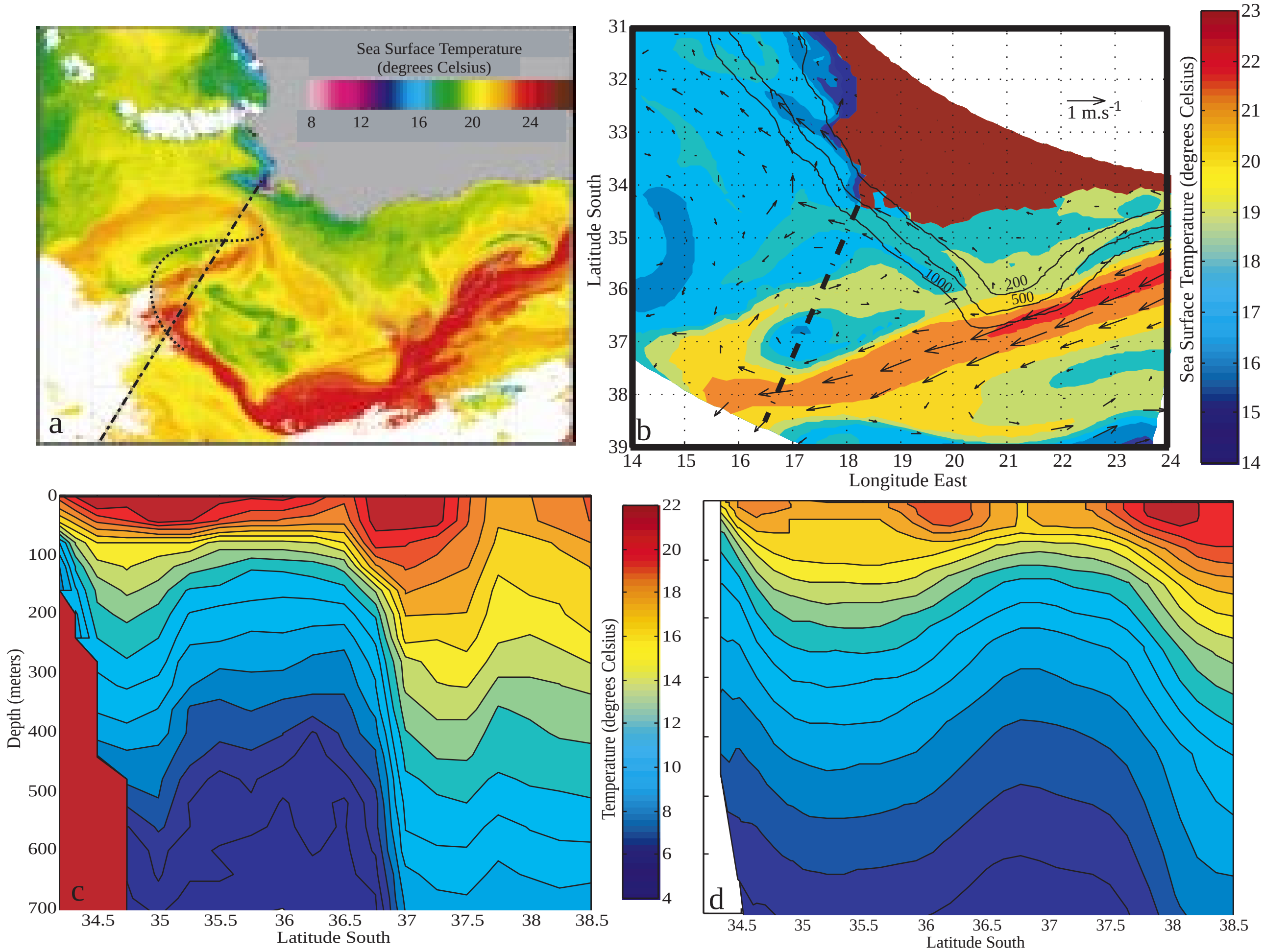

Figure 3. A comparison between a characteristic cyclonic eddy generated off the Agulhas Bank in the model (b and d) and one observed at sea (a and c). The panel b shows the simulated surface currents (1 vector every 5 grid points) and sea surface temperature on 21 November of model year 4. It also shows the line along which a vertical temperature section (d) has been extracted from the model at the same date. The sea surface temperature generated from NOAA 11 AVHRR data (a) is for 27 November 1992. The straight broken line shows the cruise track of the research vessel "Polarstern" that left Cape Town on 3 December 1992. The dotted line shows the location of the warm filament on 4 December 1992 when the vessel would have been in the center of this feature. The vertical temperature section (c) was measured by XBT (expendable bathythermograph) from the ship. The locations of the 200 m, 500 m and the 1000 m isobaths are shown in panels a and b.

cyclonic eddies are radiated through the offshore boundary before decaying (Figure 2).

Conclusion

The first simulations of the southern Agulhas Current by a model with high spatial resolution suggests that the disposition of the current relative to the southernmost part of the African continental shelf is such that cyclonic lee eddies may be generated. This may be an intermittent process since the Agulhas Current does not follow the most southerly part of the shelf consistently [*Lutjeharms et al.*, 1989]. The model indicates that these eddies may be shed at irregular intervals. They may subsequently move off in a number of directions in the South-West Indian Ocean [*Gründlingh*, 1995]. Their further dispositions, their contribution to the melange of water masses in this ocean region as well as their potential role in stabilising Agulhas rings (Kizner, personal communication) all need to be determined. If all cyclonic rings in the south-western Atlantic have this suggested origin, they will not contribute to inter-ocean exchanges since they are generated *in situ*.

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