Modeling the Variability of the Greater Agulhas Current System

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ABSTRACT

An eddy-permitting, regional ocean model has been used to examine the variability in the source regions of the Agulhas Current on a range of time scales. These source regions are the East Madagascar Current, the flow through the Mozambique Channel, and the recirculation of the southwest Indian Ocean. The effect of variability in these source regions on the interocean leakage at the Agulhas retroflection south of Africa has been quantified using a retroflection index.

On the annual mean, the recirculation in the southwest Indian Ocean subgyre is by far the dominant contribution to the volume transport of the Agulhas Current in the model. On average the recirculation also contributes the largest amount of heat, although the difference between the three sources is not as great as that seen in the volume flux since the water in the Mozambique Channel may be warmer than in the recirculation. Local winds seem to be the dominant forcing mechanism of variability in this recirculation, although it is also partly in phase with the zonally averaged wind stress curl over the subtropical Indian Ocean. A strong relationship was found between the transport of the recirculation and that of the Agulhas Current, particularly on interannual time scales.

Consistent with observations, the model flow through the Mozambique Channel is dominated by eddies, with a strong annual cycle, lagging the South Equatorial Current by 1 month and a weaker semiannual cycle. The southern limb of the East Madagascar Current also shows an annual and semiannual variation in transport at 20°S, partly in phase with the local winds. South of about 24°S, the East Madagascar Current breaks up into eddies.

An investigation into the sensitivity of the flows in the source regions and in the retroflection index to a 2° southward shift in the mean winds was conducted. In the model run with the shifted winds, the transport strengthened in the recirculation subgyre together with increased mesoscale activity as well as reduced leakage into the southeast Atlantic Ocean when the winds were shifted south by 2°.

1. Introduction

The Agulhas Current is the strongest western boundary current in the Southern Hemisphere and transports warm tropical water southward along the east coast of South Africa. There are thought to be three major sources in the south Indian Ocean for the Agulhas Current: recirculation in the southwest Indian Ocean, flow through the Mozambique Channel, and the East Madagascar Current. Based on all available hydrographic data up until the mid-1990s, Stramma and Lutjeharms (1997) estimated that, in the upper 1000 m, around 35 Sv (1 Sv $= 10^6$ m^3 s^{-1}) of the 65-Sv Agulhas Current transport at 32°S was contributed to by recirculation in the southwest Indian Ocean subgyre, around 5 Sv came from the Mozambique Channel, and about 25 Sv originated from east of Madagascar.

A more recent experiment dedicated to the source regions of the Agulhas Current (the Agulhas Current Sources Experiment, ACSEX) focused on the East Madagascar Current and flow through the Mozambique Channel (de Ruijter et al. 2002; Ridderinkhof and de Ruijter 2003; Schouten et al. 2002b). 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 (Ridderinkhof and de Ruijter 2003). However, these observations occur over a limited time and are unable to fully determine the range of 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

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to the Agulhas Current. However, satellite observations (Lutjeharms 1988a), drifter tracks (Lutjeharms 1988b), as well as hydrographic data (Lutjeharms et al. 1981) have strongly suggested that this current retroflects south of Madagascar instead and may only contribute to the Agulhas Current in the form of mesoscale eddies. During ACSEX, it was found (de Ruijter et al. 2004) that this region is a source of both cyclonic and anticyclonic eddies. As in the case of the Mozambique Channel, there is no steady current here, but instead considerable variability due to the formation of eddies.

Previous modeling and observational work has acknowledged the existence of recirculation in the southwest Indian Ocean; however, the influence of this third source of the Agulhas Current on the current itself has not been considered. Gordon et al. (1987) suggested that south of 32°S the Agulhas Current is in fact enhanced by a further 30 Sv from this recirculation subgyre, implying that of the three sources it contributes the most volume flux to the Agulhas Current. It is also possible that the recirculation may be influenced by seasonal shifts of the south Indian Ocean anticyclone (Preston-Whyte and Tyson 1988). Since the recirculation seems to be the major contributor to the Agulhas Current it is conceivable that a seasonal variability to the inflow to the Agulhas Current may occur. The seasonal movements in the south Indian Ocean anticyclone also vary considerably from year to year, which in turn may cause interannual variations in the flux of the Agulhas Current.

All these variations have a considerable influence on the water exchange south of Africa. Van Leeuwen et al. (2000) demonstrated that Natal pulses, solitary meanders on the trajectory of the Agulhas Current (Lutjeharms and Roberts 1988), are responsible for the timing of ring shedding at the Agulhas retroflection. These Natal pulses in turn are triggered by offshore eddies (de Ruijter et al. 1999) and Schouten et al. (2002a) demonstrated at least one case in which an eddy from the Mozambique Channel triggered a Natal pulse that was subsequently responsible for the occlusion of an Agulhas ring at the Agulhas retroflection. Observational evidence for the impact of other examples of flow variability in the source regions of the Agulhas Current on interocean exchange south of Africa is still to be presented. Appropriate modeling may therefore be of substantial benefit in pointing to regions that need more observational attention.

Using the Parallel Ocean Climate Model (POCM), Matano et al. (2002) traced the annual cycle of the transport in the Agulhas Current to the Mozambique Channel and the northern branch of the East Madagascar Current. The variability appeared to be driven by the large-scale winds in the western part of the tropical south Indian Ocean, north of Madagascar, since topographic features in the central and eastern Indian Ocean tend to prevent propagation of the annual-period Rossby wave from the eastern south Indian Ocean (Matano et al. 1998, 1999). Biastoch et al. (1999) suggested that an increase in flow through the Mozambique Channel derived from the Agulhas as Primitive Equations (AGAPE) model during austral winter was due to increased Ekman transport when the south Indian Ocean anticyclone is situated farther to the north. By tracing the model tropical surface water, they found evidence that this flow through the channel contributes substantially to the seasonality of the Agulhas Current.

The eddy-permitting, regional ocean AGAPE model has been shown to realistically reproduce the general circulation of the Agulhas Current system (Biastoch 1998; Biastoch and Krauß 1999; Biastoch et al. 1999; Reason et al. 2003), and we have used this model to investigate the variability of the three source regions on monthly to interannual scales. Since the model is forced with the same monthly fluxes and winds each year, any interannual variability that occurs must be due to internal ocean processes. For example, Jochum and Murtugudde (2005) showed that the instability processes that generate internal ocean variability within the south Indian Ocean are nonlinear and thus the SST will be different from year to year, even under climatological forcing.

The model output allows us to explore the variability of the Agulhas retroflection and possible relationships with changes in the source regions. Where possible, we test the model results against known sources of variability. This work extends previous modeling studies (e.g., Matano et al. 2002) by exploring not only the annual cycle but also the semiannual and eddy time scales of the source regions of the Agulhas Current, with a particular focus on the recirculation in the southwest Indian Ocean.

The paper is structured as follows. The next section describes the model and the wavelet analysis tool used to assess the variability on various time scales. Section 3 discusses the annual cycle and monthly to interannual variability of the various source regions and, in section 4, a retroflection index for the Agulhas Current is used as a tool to monitor the variability in that region. Section 5 analyses the effect of a shift in the wind forcing, with the final section containing the conclusions.

2. Data and methods

The results were obtained from a climatological run of the eddy-permitting AGAPE model (Biastoch and

Krauß 1999), 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° to 6.5°S and 60°W to 115°E. Within the southwest Indian and southeast Atlantic Oceans (20°W–70°E), the horizontal resolution is 1/3° × 1/3°. Outside this region, it gradually coarsens in the zonal direction to reach 1.2° at the meridional boundaries. There are 29 vertical levels from the surface to a realistic bottom topography (Fig. 1 in Biastoch and Krauß 1999) 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.

A regional model such as this includes several open boundaries (Drake Passage, the Indonesian Throughflow, the equatorial Indian and Atlantic Oceans, and the southeast Indian Ocean south of Australia) where it must be connected to the rest of the ocean. These connections have been achieved through the open boundary condition formulation of Stevens (1991) so that waves and other disturbances can propagate out of the domain and not be reflected at the open boundaries. In this formulation, the linearized horizontal momentum equations are used to calculate the baroclinic velocities at the open boundaries so that the vertical current shear may adjust to the local density gradients. Temperature and salt are transported out of the domain using a radiation condition plus advection if the normal component of the velocity at the boundary is directed outward. For those boundary points where the normal velocity is into the domain, the restoration of the temperature and salinity to the monthly climatology of Levitus et al. (1994) and Levitus and Boyer (1994) occurs. Information about the barotropic circulation in the rest of the World Ocean is supplied to the model by prescribing the barotropic streamfunction at the open boundaries from the POCM 4A run (Stammer et al. 1996) of the POCM of Semtner and Chervin (1992).

Potential temperatures and salinities from the *World Ocean Atlas 1994* (*WOA94*) dataset (Levitus et al. 1994; Levitus and Boyer 1994) are used to initialize the model, which is spun up from rest for 30 model years with a time step of 1/2 h. At this stage, the wind-driven circulation is stationary with a seasonal cycle. Since the thermohaline circulation takes hundreds of years to adjust, a slow drift remains in the temperature and salinity, particularly at depth. Achievement of equilibrium conditions at this resolution is impossible with the current computing facilities available to the authors. However, it has been shown that the general circulation and intermediate to upper-ocean water masses are well represented by the model (Biastoch and Krauß 1999).

At the surface, the model is forced with monthly mean wind stresses and temperature fluxes from the 1986–88 monthly climatology (Barnier et al. 1995) of the European Centre for Medium-Range Weather Forecasts (ECMWF) model interpolated to 3-day values. The 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 12 yr after the 30-yr spinup, and the model volume and temperature fluxes were calculated from the surface to the model ocean floor, as in Reason et al. (2003). It is important to note that since the model is forced with the same monthly forcing each year, the interannual variability evident in the model arises from internal ocean processes and not from any imposed atmospheric forcing.

When compared to the ECMWF winds calculated over 1949–2000, the average ECMWF wind pattern for 1986–88 displays reduced easterlies both southwest and east of Madagascar and increased westerlies south of Africa, implying that the South Indian anticyclone was shifted slightly southeastward during these 3 yr (not shown). Since these 3 yr contained the 1986/87 El Niño event and part of the 1988/89 La Niña, it is not surprising that there are some differences from the long-term mean. However, the differences in the southwest Indian Ocean are relatively small compared to those outside the model domain such as over the North Pacific or the North Atlantic, or south of 50°S, which is outside of our area of interest. Therefore, the impact of the 1986–88 forcing on our results is likely to be small, although caution is needed when comparing to observations. We further test the sensitivity of the circulation in the greater Agulhas system in section 5 when we consider the impact of forcing the model with the mean wind stress over the subtropical south Indian Ocean shifted south by 2°.

Wavelet transforms have been used here to investigate the temporal variability in the various transport time series derived from the model. Wavelet analysis is chosen, rather than more traditional methods such as Fourier analysis, since it allows decompositions into time–frequency space and, thus, can show the evolution in the relative strength of the dominant modes with time through the series. Wavelets have been successfully used in oceanic applications to investigate equatorially trapped waves (Meyers et al. 1993), to study intraseasonal variability in surface winds over the Benguela upwelling system (Risien et al. 2004), and in many other oceanographic or meteorological applications. In this study, the Morlet wavelet (Morlet 1983) is used

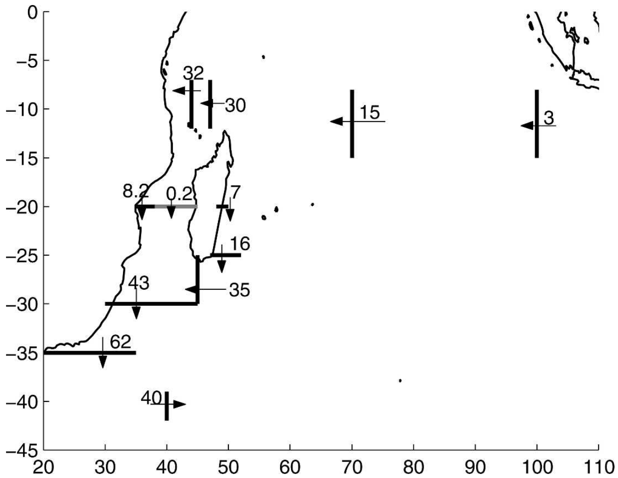

FIG. 1. Sections used over the source regions of the Agulhas Current and their corresponding volume transports in Sv.

since it allows both time-dependent amplitude and phase to be detected for different frequencies exhibited in the time series:

$$g(t) = \pi^{-1/4} e^{-t^2/2} e^{i\omega_0 t},$$

with $i = (-1)^{1/2}$ and the plane wave of the frequency, $\omega = \pi(2/\ln 2)^{1/2}$ (Daubechies 1992), large enough to ensure that $g(t)$ satisfies an admissibility condition.

Unless stated otherwise, wavelet analysis has been performed on the normalized three daily time series of the volume flux time series, and the 95% significance contour level is indicated in the wavelet plots. To indicate the region of the wavelet analysis that is not subjected to edge effects and the period over which the analysis can be considered robust, the cone of influence has also been indicated in each diagram (C. Torrence and G. Compo 2005, personal communication).

3. Variability of the source regions of the Agulhas Current

Figure 1 shows the annual mean volume transport for various sections in the model south Indian Ocean, including the South Equatorial Current (SEC), the Agulhas Current, and source regions for the latter such as the East Madagascar Current, Mozambique Channel, and the recirculation in the SW Indian Ocean. The model volume and temperature transports compare well with previous model work (e.g., Biastoch et al. 1999; Matano and Beier 2003). The model Agulhas and Return Currents transport vary on interannual through to annual time scales and the respective means of 62 Sv (at 35°S) and 40 Sv (at 40°E) compare well with observations (Bryden et al. 2005; Boebel et al. 2003).

a. *Mozambique Channel*

No clear and continuous throughflow is evident in the model Mozambique Channel; instead, the flow consists of a train of eddies consistent with recent observations from ACSEX (de Ruijter et al. 2002). The model eddies are formed by instabilities of the SEC at the northern tip of Madagascar (Biastoch and Krauß 1999). Some of these model eddies disperse, whereas others pass through the narrows of the Mozambique Channel, causing an increase in volume flux through the narrows and the formation of an eddy there (Fig. 2), similar to observations (Ridderinkhof and de Ruijter 2003). The model eddies typically drift southward on the western side of the channel (Fig. 2), which is also consistent with observations (Sætre and Jorge da Silva 1984; de Ruijter et al. 2002; Schouten et al. 2003).

Cyclonic features may occur in the north of the model channel near 12°S (Fig. 2a) but are short lived and do not appear to move away from this region. Other cyclonic features in the southeastern Mozambique Channel have been noted in the model (Fig. 2a) and in satellite observations (G. D. Quartly et al. 2004, unpublished manuscript) as appearing to the southwest of Madagascar but are believed to have origins farther east or southeast (de Ruijter et al. 2004). In the southeastern part of the Mozambique Channel, the southward flow interacts with the westward flow from the East Madagascar Current and can cause weak cyclonic features (Fig. 2a), as suggested from observations (Gründlingh 1995).

This range of mesoscale variability displayed by the model and its general consistency with a variety of observations to date gives us confidence that the model results may be representative of actual current behavior in the real ocean. On this basis, we use the model to investigate the variability of the greater Agulhas Current system on seasonal to interannual time scales.

On average, four to six model eddies pass through a section at 20°S in the southern Mozambique Channel per year in agreement with what has been observed (Schouten et al. 2003; Ridderinkhof and de Ruijter 2003). Some of the eddies get trapped near 20°S and then dissipate, but the majority head southward and contribute to the Agulhas Current. At 20°S, the volume flux in the model Mozambique Channel has a strong annual cycle, with an amplitude of over 10 Sv and a standard deviation of less than 2 Sv (Figs. 3a–c). This annual cycle has been noted in satellite data (Heywood and Somayajulu 1997) but is not obviously present in in situ observations due to the short duration of such observations (Ridderinkhof and de Ruijter 2003). The annual mean transport through the channel of 8.4 Sv is

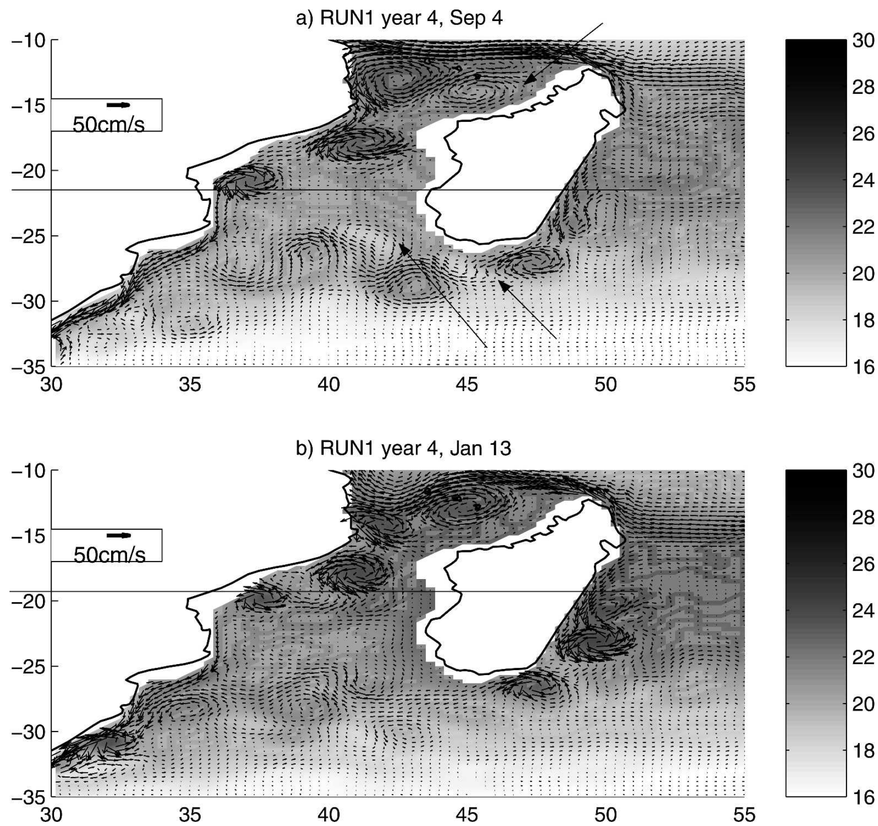

FIG. 2. (a) Snapshot of surface model currents (cm s^{-1}) and SST (°C) for 4 Sep, model year 4. A scale vector of 50 cm^{-1} is shown. The contour range is 16°–30°C. The large arrows mark the position of the cyclones. (b) As in (a) but for 13 Jan, model year 4.

considerably less than the 15 Sv estimated by de Ruijter et al. (2002) on the basis of four eddies per year, each in excess of 300 km in diameter. However, this observational estimate does not take into account the observed undercurrent in the Mozambique Channel that transports around 5 Sv northward (Ridderinkhof and de Ruijter 2003) and which is also present in the model. Adding this 5-Sv-deep flow results in an observed net annual southward transport of 10 Sv, which is more comparable to the model value of 8.4 Sv.

Matano et al. (2002) used "the island rule" (Godfrey 1989) to show that only around 2.2 Sv of the flow through the Mozambique Channel is due to the wind-driven circulation. In the AGAPE model, the maximum (August) and minimum (March) transports in the model Mozambique Channel are out of phase with the local wind stress curl (Fig. 3b), and occur a month after those seen in the South Equatorial Current at 47°E (Fig. 3d). This maximum in Mozambique Channel transport occurs during the time the South Equatorial Current is displaced to the north, allowing more transport past the northern tip of Madagascar. This timing implies that the seasonal signal originates in the South Equatorial Current, with the 1-month time lag resulting from southward advection of the signal, similar to that found by Matano et al. (2002).

A semiannual signal is also evident in the Mozambique Channel (Figs. 3a and 3c), with the secondary maximum occurring in November, coinciding with a maximum in salinity in the intermediate waters of the channel, suggesting the presence of Red Sea water (Hermes 2005). Figure 3a shows that the secondary minimum in October, when the south Indian Ocean anticyclone is shifted to the northeast, is much more prominent in some years (e.g., 35 and 36) than others (e.g., 32 and 37). A semiannual signal in Mozambique Channel transport is also seen in the POCM model (Matano et al. 2002).

After removing the annual and semiannual signals from the data, a strong 2–3-month signal remains (Fig. 3e), consistent with four to six model eddies passing through the channel per year. The eddy signal is stronger in January–March (JFM) and weaker during July–September (JAS) as is apparent in the eddy kinetic

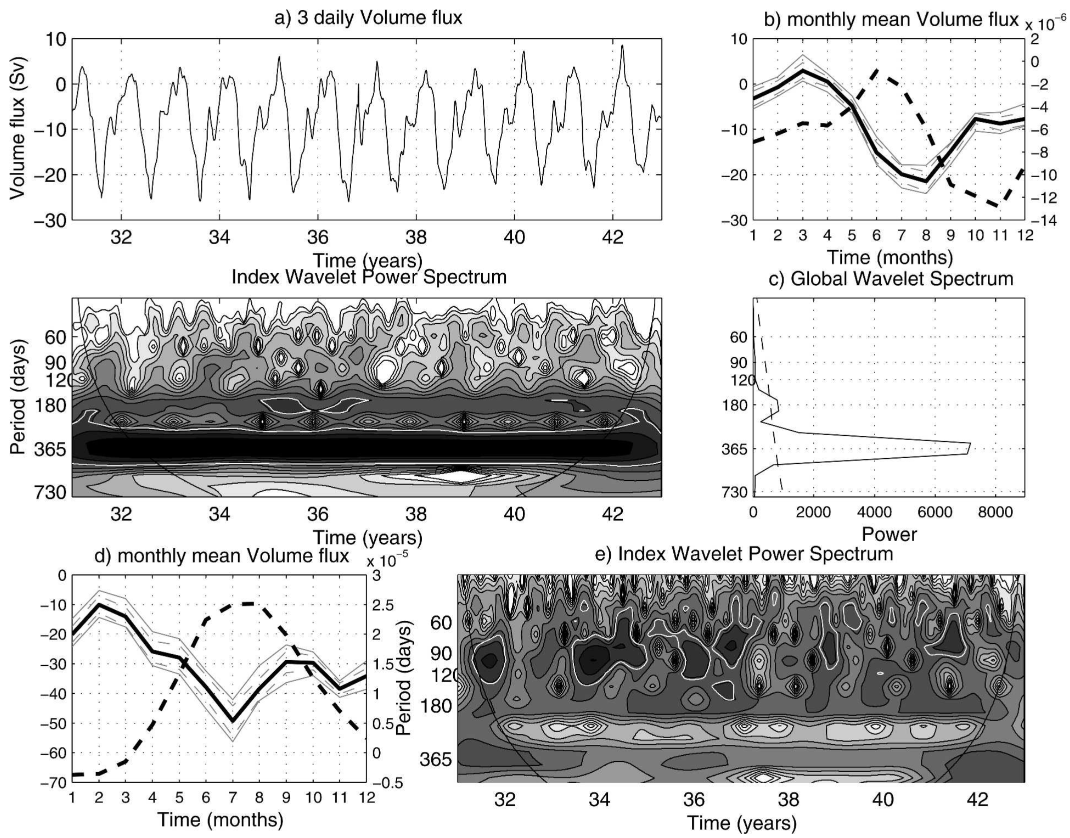

FIG. 3. (a) Time series of the volume flux through the Mozambique Channel (Sv) at 20°S, 35°–45°E, and wavelet analysis of this time series. Wavelet only extends to 2 yr for clarity; 95% significance levels are shown by white contours and cone of influence by black line. (b) The monthly mean volume transport (Sv; black line) together with the maximum (top line) and minimum (bottom line) values and one std dev above and below the mean (gray dashed lines). The wind stress curl (kg s^{-2} m^{-2}) over this region is plotted (black dashed), with a separate scale on the right of the axis. (c) Power of the wavelet analysis, with significance shown by dashed line. (d) As in (b) but at 7°–12°S, 47°E. (e) Wavelet analysis of the volume flux at 20°S, 35°–45°E, with annual and semiannual signals removed.

energy (Figs. 4a and 4b) and also in the vorticity (not shown). These results suggest that the 2–3-month eddy signal in the channel is masked by the annual and semiannual variability since it is not very evident in the unfiltered wavelet analysis (Figs. 3a,c). Note that the eddy signal in the Mozambique Channel is not necessarily visible in the net volume transport across the channel since only a small fraction of the model annual mean volume transport occurs via eddies. This small eddy contribution arises because the volume is carried in one direction on one side of the eddy and returned in the other direction on the other side (Ridderinkhof and de Ruijter 2003).

b. *East Madagascar Current*

Few actual observations of volume fluxes in the East Madagascar Current are available against which the model results can be compared. Donohue and Toole (2003) have calculated a geostrophic flux of 16 Sv, but on a zonal section that extends eastward beyond the borders of the southern branch of the East Madagascar Current. This value is comparable to observations made during the ACSEX II experiment (J. Nauw 2005, personal communication).

In defining the contribution of the East Madagascar Current (EMC) or water from east of Madagascar to the Agulhas system, previous modeling work has used different sections and found different contributions. For example, Biastoch et al. (1999) used a section east of Madagascar at 23°S to find a southward transport of between 9 and 20 Sv, whereas Matano et al. (2002) found a contribution of 30 Sv to the Agulhas Current by taking a section from the south coast of Madagascar to 32°S. Both sets of authors found a similar total volume

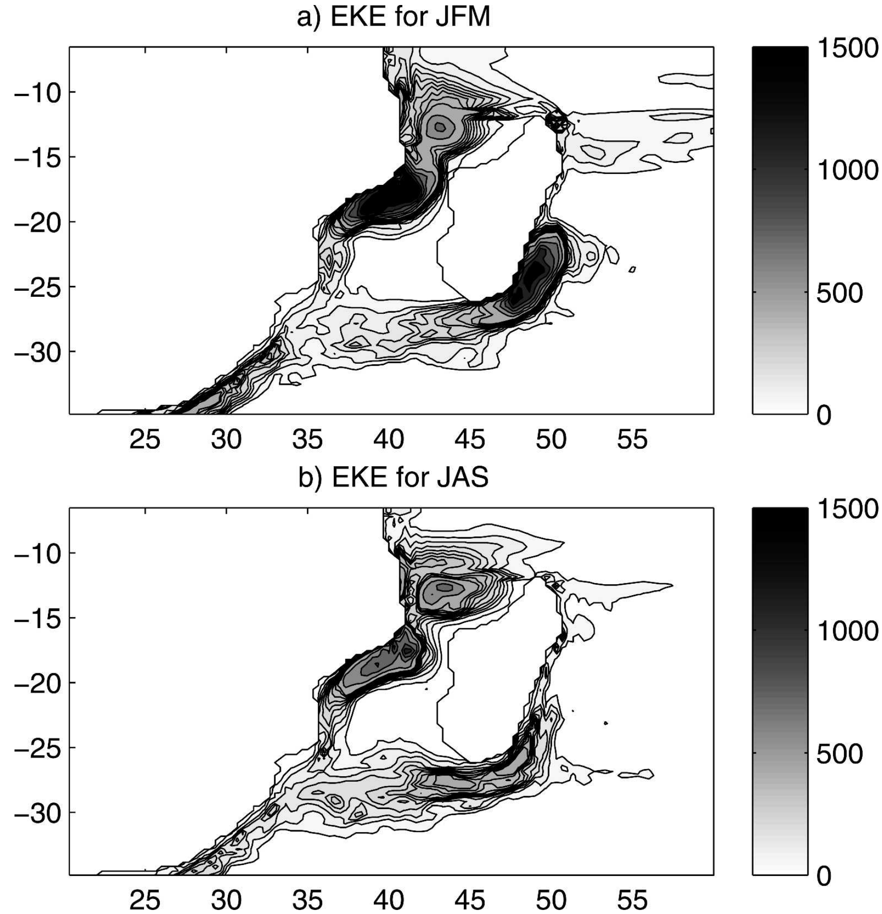

FIG. 4. (a) Eddy kinetic energy ($cm^2 s^{-2}$) for JFM. Contour range is from 0 to 1500 $cm^2 s^{-2}$; contour interval for 0–500 is 50 $cm^2 s^{-2}$, and from 500 to 1500 the interval is 200 $cm^2 s^{-2}$. (b) As in (a) but for JAS.

flux of the Agulhas Current off the east coast of South Africa of between 43 and 47 Sv.

In the model used here, the EMC volume transport increases from 16 Sv flowing southward for a section east of Madagascar (similar to the observations of Donohue and Toole 2003) to 35 Sv flowing westward for a section between the south coast of Madagascar and 30°S (Fig. 1). The differences between the model southward and westward volume fluxes appear to be due to the amount of recirculation that is included in the calculations. It is difficult to distinguish between the recirculation and the EMC as some of the recirculation enters the region from east of Madagascar and thus could conceivably contribute to the EMC. However, the model transports are consistent with previous model results and with the limited observations that do exist.

East of Madagascar at 20°S, the model EMC has a strong annual and semiannual signal, and a weaker spectral peak at 2–3 months (Figs. 5a–c). In contrast to this result, Matano et al. (1999) found no seasonality in their EMC section south of Madagascar and suggested that bottom topography prevented the propagation of the seasonal signal from the eastern south Indian Ocean where it exists in their model. In our model, the flow is mostly southward, with minima in April and August and maxima in November and, to a lesser extent, June (Fig. 5b). To investigate the cause of this variability further, the local wind stress curl averaged over the EMC at 20°S was calculated and is shown as the black dashed line in Fig. 5b.

The minimum in the wind stress curl in February and maximum in August are related to the seasonal shifting of the south Indian Ocean anticyclone. The maximum in May and the minimum in November occur at the same time as the transitional period between the NE and SW monsoons. The larger minimum in the volume transport of the EMC in August and the larger maximum in November as well as the secondary maximum in June follow the variations in the wind stress curl.

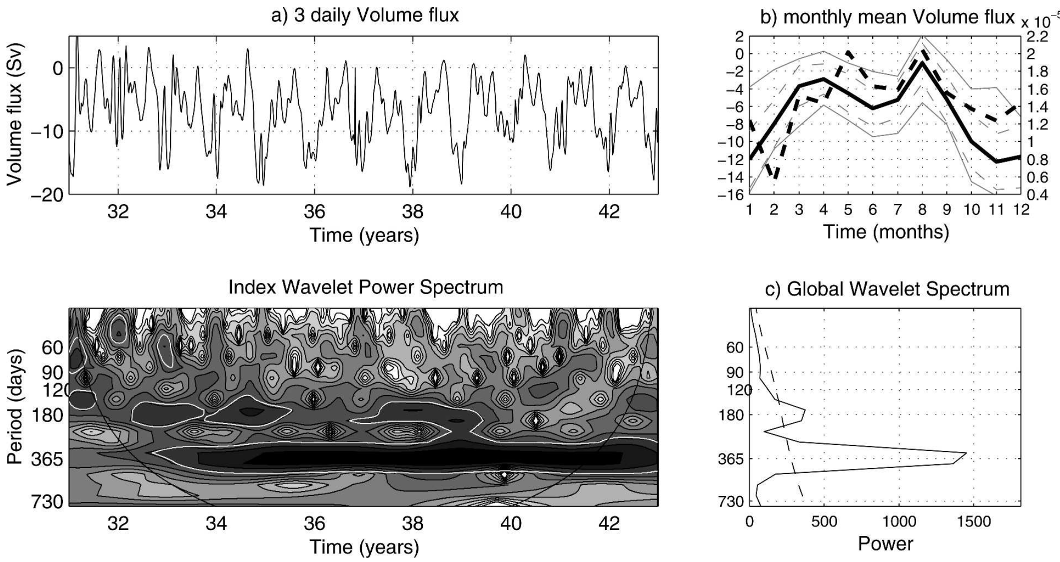

FIG. 5. (a) Time series of the volume flux east of Madagascar (Sv) at 20°S, 48°–50°E and a wavelet analysis of this time series. Wavelet only extends to 2 yr for clarity; the 95% significance levels are shown by white contours and cone of influence by black line. (b) The monthly mean volume transport (Sv) (black line) together with the maximum (top line) and minimum (bottom line) values and one std dev above and below the mean (gray dashed lines). The wind stress curl (kg s^{-2} m^{-2}) over this region is plotted (black dashed), with a separate scale on the right of the axis. (c) Power of the wavelet analysis, with significance shown by dashed line.

However, the relative minimum in April in the EMC transport is out of phase with the wind stress curl during this time of year.

To further investigate the seasonality of the EMC, individual snapshots of the current field around Madagascar were examined (e.g., Fig. 2). From this it is evident that the model EMC does not continue as a clearly defined current much beyond 22°S. South of this latitude, the EMC forms a series of eddies, which travel south, around the tip of Madagascar, and move westward with the background flow, rather than rounding the tip of Madagascar as a coherent current and retroflecting. This was evident in a section east of Madagascar at 23°S, which displayed a strong 4-monthly signal in transport (not shown). This instability in the southern branch of the EMC is a common feature of a number of models (e.g., Biastoch and Krauß 1999). However, the region of eddy formation shifts northward and strengthens in austral summer compared to winter (cf. Figs. 2a and 2b and Figs. 4a and 4b), leading to the eddy variability observed in the wavelet analysis in Fig. 5. This northward shift in the eddy formation region occurs at the same time as the out of phase relationship between the wind stress curl and the transport that is evident during the first half of the year (Fig. 5c). Figure 4 further emphasizes this result as the eddy kinetic energy is much stronger in JFM than JAS and is located farther north. We believe that it is this northward shift in the eddy breakdown of the EMC that causes the out of phase relationship between the wind stress curl and the model EMC between January and May. Whether or not this happens in the real ocean is not known; the few observations that exist suggest that the current retroflects over the shallow ridge south of Madagascar, rather like the situation seen in the Agulhas Current (DiMarco et al. 2000; Lutjeharms et al. 2000). However, G. D. Quartly et al. (2004, unpublished manuscript) analyzed satellite data to find evidence that anticyclonic eddies coming from the east cause the apparent retroflection of the EMC.

Anticyclonic motion and its associated eddies have been observed (DiMarco et al. 2000; Lutjeharms and Machu 2000) south of Madagascar at higher latitudes than the eddies seen in the model. Observational work (de Ruijter et al. 2004) has tracked eddy dipole pairs from the termination of the EMC and it appears that such dipole pairs are also evident in the model (Fig. 2). These eddy pairs are formed by interactions between the EMC anticyclonic eddies and the cyclonic eddies in the east of the Mozambique Channel. However, the cyclones often remained trapped in the termination region of the EMC. Thus, the model East Madagascar Current seems to be consistent with the most recent observations.

South of Madagascar, the transport seen flowing west through 45°E is due to the train of eddies (Figs. 1 and 2)

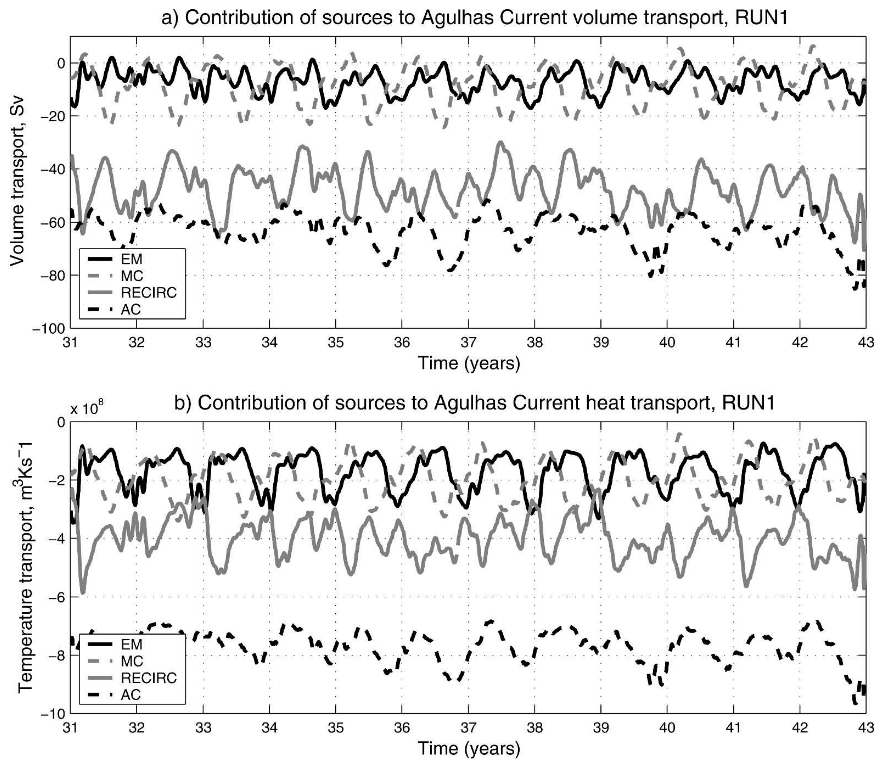

FIG. 6. (a) The contribution of the flow through the Mozambique Channel (gray dashed), the East Madagascar Current (black), and the recirculation (gray) to the Agulhas Current volume transport (Sv) at 35°S (black dashed). (b) As in (a) but for the temperature transport (m^3 K s^{-1}).

and thus the variability is no longer in phase with that at 20°S (not shown), nor with the local wind stress curl. This is in contrast to Matano et al. (1999), who hypothesized that since the variability here was blocked from the east by topography, it must arise from local wind forcing. We suggest however that it is the recirculation and eddy variability rather than the local winds that are important here.

c. Recirculation, the major source of the Agulhas Current

Due to difficulties in defining the Agulhas recirculation, there is little previous research on its variability. Most work determines the contribution of recirculation to the Agulhas Current by calculating the increase of the Agulhas Current from 30°S off the east coast of South Africa to its maximum flow south of Africa, assuming negligible input from transport induced by local winds (Stramma and Lutjeharms 1997; Lutjeharms and Ansorge 2001). Here, we define the recirculation in a similar manner as the increase in volume flux between the sum of the two other source regions and the Agulhas Current at its maximum flow at 35°S. The two source regions are taken as the flow through the Mozambique Channel at 20°S, and the narrow East Madagascar Current through 20°S from the east coast of Madagascar to 50°E. This method was chosen in order to include in the recirculation the flow that enters the system from the east, immediately south of Madagascar. The sensitivity of the calculation to different definitions (e.g., the northward volume flux along 39°S between 20°E and Australia) was investigated and gave similar results in terms of the actual amount transported, although there were differences in the eddy peaks between the different sections chosen. Regardless of the method used, the majority of the recirculation occurs north of 35°S.

Figure 6 shows the volume and temperature transport of the three sources along with the Agulhas Current at 35°S after smoothing with a 1-month running mean. The recirculation is clearly the major contributor to the volume flux of the Agulhas Current at 35°S. During late austral summer, the volume transport of the model Agulhas Current derives almost solely from the recirculation, when the net inputs from the EMC and the Mozambique Channel are virtually zero (respectively, 3 Sv northward and 4 Sv southward on average; see Figs. 3 and 5).

Although the modeled recirculation also contributes

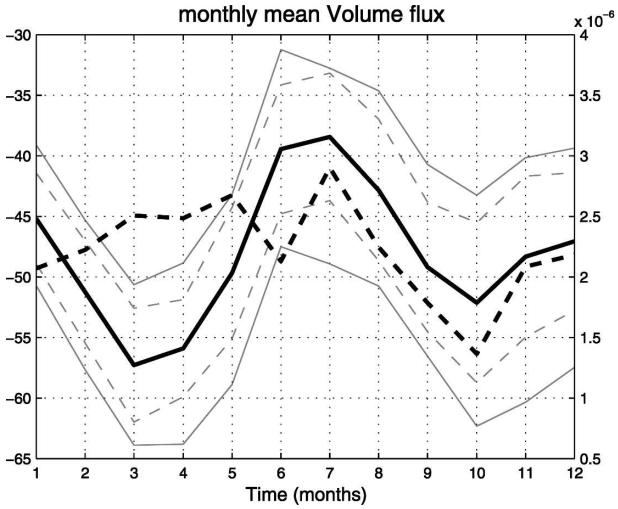

FIG. 7. The monthly mean volume transport of the recirculation (Sv) (black line) together with the maximum (top line) and minimum (bottom line) values and one std dev above and below the mean (gray dashed lines). The zonally averaged wind stress curl (kg s^{-2} m^{-2}) over the south Indian Ocean is plotted (black dashed), with a separate scale on the right of the axis.

the largest amount of heat of the three sources to the Agulhas Current at 35°S, the difference between the three sources is not as great as that seen in the volume flux (cf. Figs. 6a and 6b). Occasionally, the EMC contributes more heat to the Agulhas Current than the recirculation (such as the end of years 37 and 38). Contributions from the recirculation tend to be at a minimum during the spring when the temperatures of the upper layers and its flow are closest to their annual minimums (Fig. 6b). The transport entering the system from the EMC has a greater heat content than that from the recirculation since it emanates from the Tropics and therefore contains warmer water.

The zonally averaged wind stress curl over the south Indian Ocean from 20° to 45°S is plotted in Fig. 7, along with the monthly mean volume flux of the recirculation. The wind stress curl has a maximum in July when the winds over the south Indian Ocean are strongest and the South Indian anticyclone has shifted to the north. The wind stress curl reaches its minimum in October, as the south Indian Ocean anticyclone weakens and shifts farther east, and it appears to be closely related to the recirculation transport during the second half of the year.

A relatively strong annual and relatively weaker semiannual signal are evident in the recirculation transport (not shown). The July maximum in the wind stress curl corresponds to a reduced contribution of the recirculation to the Agulhas Current transport. This situation may arise because when the wind stress curl is strongest, the recirculation occurs farther to the east, entering the system by contributing to the EMC (corresponding to the secondary maximum in volume transport there) and is thus not accounted for in these calculations, making the overall recirculation weaker. A reduction in recirculation volume transport also occurs in December when the wind stress curl is increasing in strength (Fig. 7). The maximum volume transport of the recirculation occurs during March, coinciding with the minimum (in fact northward transport) in flow through the Mozambique Channel (cf. Figs. 7 and 3b) and a minimum in the East Madagascar Current (Fig. 5b). In contrast to June–December, the change in transport of the recirculation from January to June does not appear to be related to the wind stress curl.

Thus, the recirculation is not always directly related to the basin-scale winds. Matano et al. (1999) suggested that the retroflection region south of 30°S and west of Madagascar is dependent on the local wind stress forcing. We suggest that this is also the case for the recirculation in general, although it is difficult to show due to the large area from which the recirculation is formed. To further investigate this, the northward volume transport at 39°S, 25–110°E was calculated (not shown). The annual cycle compared favorably with the zonally averaged wind stress curl between 20° and 45°S over the Indian Ocean (as plotted in Fig. 7). However, when the northward volume transport at 39°S, 20°–25°E was plotted, the correlation with the wind was not evident.

In the AGAPE model, a tight recirculation cell is prominent near 20°E. The model produces more Agulhas rings than are seen in observations but these rings interact with each other so that around four to six rings per year eventually leave the basin (Biastoch 1998). Some of the rings remain trapped at 20°E, making the retroflection seem elongated and farther to the west than is observed (Lutjeharms 1996; de Ruijter et al. 1999). However, due to the lack of intensive observations in the region, it is difficult to state definitely whether this trapped feature is an artifact of the model, or whether a permanent recirculation cell in the retroflection region is in fact a feature of the Agulhas system. This recirculation cell has also has been seen in high-resolution Regional Oceanic Modeling System (ROMS) simulations (P. Penven 2005, personal communication) as well as being implied by observations (Stramma and Lutjeharms 1997). It is therefore conceivable that it is this particular area of the Agulhas Current recirculation that is dependent on more local wind stress forcing, while the large-scale recirculation is driven by the large-scale winds over the south Indian Ocean.

Some correlations were performed on the raw data after removing the annual and semiannual cycles to yield a value of r of 0.7 between the Agulhas Current and the recirculation at zero lag (significant at the 95% confidence level). Since the correlation coefficients between the other two source regions and the Agulhas Current are much weaker, this result suggests that the recirculation plays a strong role in the variability of the Agulhas Current. This correlation is further strengthened to 0.8 if the data are filtered to remove all signals at higher frequencies than a year and hence suggests that there is a strong link between the recirculation and Agulhas Current transports on interannual time scales.

Since the model is driven with the same monthly forcing each year, this link must occur via internal ocean processes. Internal ocean processes have been suggested as being responsible for a significant fraction of the interannual SST variability in the western Indian Ocean (Jochum and Murtugudde 2005). These authors used an eddy-resolving model forced with climatological seasonal winds to show that internal variability contributes significantly to the interannual variability in the tropical Indian Ocean and that this variability is driven by the influence of eddies on the mixed layer heat budget and hence the SST. In agreement with this result, plots of the model spectral density at eddy time scales (2–3 months) and interannual time scales (3 yr) over this region (not shown) displayed high eddy activity in the same areas as high interannual activity is found over the region of the recirculation and Agulhas Return Current. For the interannual variability to be influenced by the internal variability, the eddies should persist for long enough to change the oceanic conditions for the next season and the eddy scales should be smaller than the atmospheric Rossby radius (Jochum and Murtugudde 2005), as was indeed found to be the case in the recirculation region in our model.

4. A retroflection index for the Agulhas Current

Variability in the source regions of the Agulhas Current, and in particular the recirculation, may significantly influence not only the current itself but also its retroflection. Shifts in the retroflection position are an important part of the mechanism responsible for interocean exchange south of Africa, as well as an influencing factor on local weather and climate patterns (Walker and Mey 1988; Crimp et al. 1998; Reason 1998; Reason and Mulenga 1999).

Since there is a considerable need to better understand the link between the shifts of the retroflection and the actual interocean exchange south of Africa, an appropriately defined index to monitor the shifts in the position of the Agulhas retroflection is needed. For this index to be of use, it should indicate when an early or late retroflection occurs (i.e., farther to the east or west of the normal position) and whether more or less water has been fed into the South Atlantic Ocean.

A retroflection index based on that proposed by Dijkstra and de Ruijter (2001) has been used here to measure the amount of retroflection that occurs in the model. The index R used here was defined as the ratio of the maximum westward volume transport of the Agulhas Current, south of Africa, and the maximum eastward volume transport of the Agulhas Return Current over an area southeast of South Africa:

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

where T_1 is the maximum westward volume flux of the Agulhas Current over the area 35°–40°S, 19°–22°E and T_2 is the maximum eastward volume flux of the Agulhas Return Current over the area 35°–45°S, 25°–35°E. The index was calculated using a large region due to the variability in the position of the Agulhas and Return Current and allows for any meridional 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 southwest Indian Ocean. For intermediate values of R, partial retroflection occurs, and the degree determines the fraction that leaks into the South Atlantic.

The mean value for R is 0.6, suggesting that typically 40% of the model Agulhas Current flows into the South Atlantic Ocean and 60% retroflects, which is slightly greater than observations (e.g., Boebel et al. 2003). Using monthly data, a wavelet analysis of this index (Fig. 8) shows that there is variability on interannual, quasi-biennial, and annual time scales, but most significantly on semiannual and eddy scales, with R tending to its minimum (i.e., less retroflection) during September and December and its maximum (i.e., greater retroflection) during March, July, and October (Fig. 8b). Examination of model snapshots showed that the retroflection position does in fact vary substantially on interannual time scales. Similar variability in the retroflection is also suggested in hydrographic data (e.g., Lutjeharms and van Ballegooyen 1988). Furthermore, Molinari et al. (2002) used altimeter data to show that significant interannual variability exists in ring shedding at the Agulhas retroflection. These authors found a correlation between ring-shedding events and peaks in the transport into the South Atlantic, with between four and seven rings being shed per year. Similarly, the

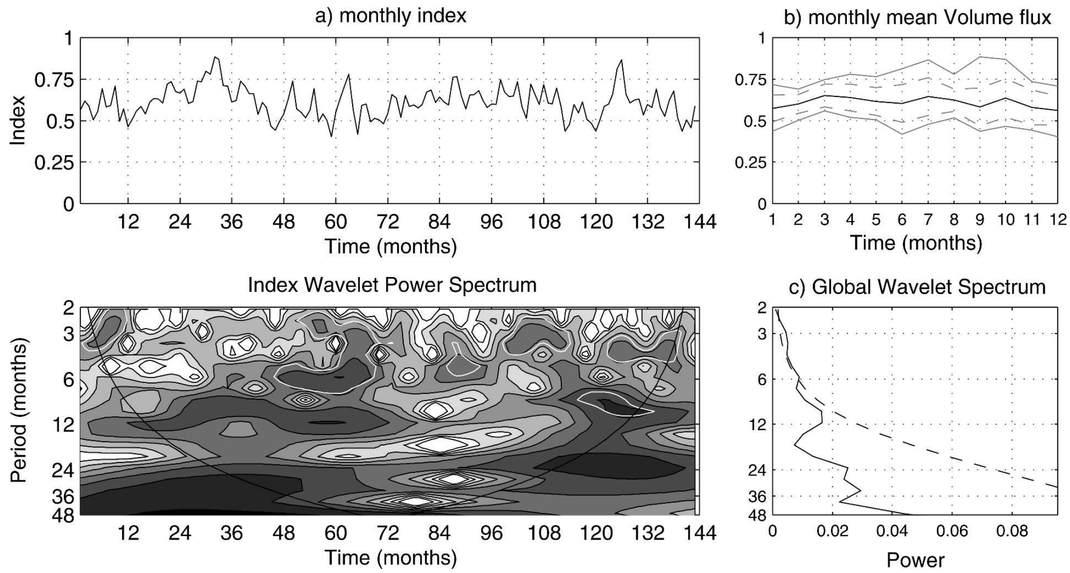

FIG. 8. (a) Monthly time series of the index for the first run and wavelet analysis of this time series; the 95% significance levels are shown by white contours and cone of influence by black line. (b) The monthly mean value of R (black line) together with the maximum (top line) and minimum (bottom line) values and one std dev above and below the mean (gray dashed lines). (c) Power of the wavelet analysis significance is shown by the dashed line.

minima in the R index in Fig. 8 occur around four to six times a year and an examination of model snapshots showed that rings were visible at the same time as many of these minima. This result implies that there is interannual variability in the ring-shedding events in the model Agulhas Current that may be related to the amount of Agulhas Current leakage into the South Atlantic.

5. Further experiments

The results presented above suggest that the recirculation in the southwest Indian Ocean responds to wind forcing over the basin and, hence, influences the interocean exchange. To investigate the affect of the local wind forcing on the region, the model was rerun for 12 years with the mean wind pattern in the south Indian Ocean shifted southward by 2°. This investigation was done in order to assess the sensitivity of the regional circulation to a southward shift in the south Indian Ocean anticyclone and is motivated by various observational anomalies. For example, a wind circulation anomaly of this type was observed during JFM 1997 (Reason and Lutjeharms 1998) and in the annual mean surface winds in 2000 and 2003 (not shown). A southward shift of the south Indian Ocean anticyclone is also present during subtropical dipolelike SST events in the basin (Hermes and Reason 2005) that influence the rainfall variability over southern Africa.

Although 12 years is an insufficient time period for the model to completely adjust to this new forcing, limited local computational resources precluded a longer integration. However, analysis of the model fields shows that most of the adjustment of the upper ocean occurs during the first 5 years and therefore we consider the final 7 years in the discussion below.

The model Agulhas Current became wider and shallower during the run with southward-shifted winds. However, there was no appreciable difference in the volume transport at 32°S, although there was a reduction in the temperature of the upper layers of the model Agulhas Current and a corresponding reduction in heat flux to the atmosphere. This reduction was due to a change in the contributing sources of the current, which include more recirculation water and less water from east of Madagascar.

The strength of the recirculation in the south Indian Ocean increased in response to the shifted anticyclone, contributing more to the Agulhas Current south of 30°S. After removing the annual and semiannual cycles from the data, the correlation coefficient between the Agulhas Current and its recirculation increases from 0.7 in the climatological run to 0.8 in the shifted wind run. The recirculation strengthened to the west of 50°E, but weakened east of this, with more eddy activity than in the climatological run. As a result, it is clear that the model recirculation is sensitive to a shift in the wind patterns over the south Indian Ocean.

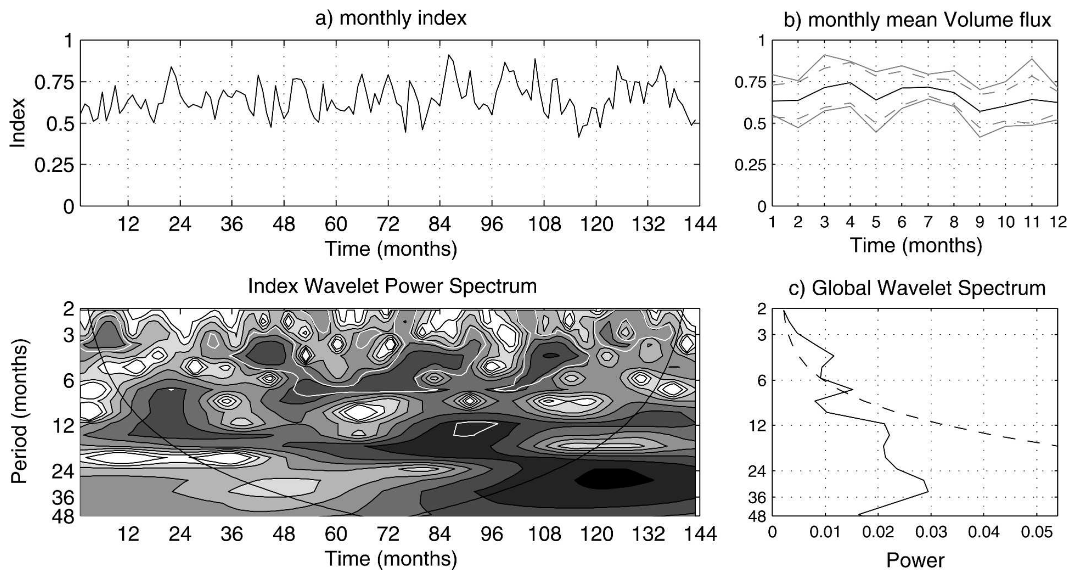

Fig. 9. (a) Monthly time series of the index for the second run and wavelet analysis of this time series; the 95% significance levels are shown by white contours and cone of influence by black line. (b) The monthly mean value of R (black line) together with the maximum (top line) and minimum (bottom line) values and one std dev above and below the mean (gray dashed lines). (c) Power of the wavelet analysis significance is shown by the dashed line. The first 60 months are considered the adjustment period of the second run.

To assess the effect of the shifted winds on the position of the retroflection, the retroflection index was calculated for the run with southward-shifted winds (Fig. 9). On the annual mean, the index increased to 0.66, implying that less leakage occurs into the South Atlantic when the mean winds are shifted south, consistent with the associated shift in the position of zero wind stress curl from 34.5° to 36.5°S at 30°E. Furthermore, in contrast to the climatological run (Fig. 8c), the eddy signal is a much stronger component in the variability (Fig. 9c), suggesting that more rings are shed in the run with southward-shifted winds. However, some of these rings do not travel into the southeast Atlantic Ocean and remain trapped near the retroflection, leading to an increase in the tight recirculation cell at around 20°E.

To investigate whether increased eddy activity might also occur in the real ocean in this region, Ocean Topography Experiment (TOPEX)/Poseidon sea surface height (SSH) anomalies were examined for the 1997, 2000, and 2003 periods when the south Indian Ocean anticyclone was effectively shifted south of its mean position. A strong increase in sea surface height anomalies was seen during these periods in the region 35°–40°S, 10°–20°E. These observational results therefore suggest that the increase in eddy activity in the model retroflection region may in fact also occur in the real ocean.

6. Conclusions

Considerable variability has been shown to exist in the model Agulhas region and its source regions. 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 (de Ruijter et al. 1999) 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.

In agreement with observations (Ridderinkhof and de Ruijter 2003; 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 annual and semiannual signals at 20°S. This variability was partly related to the local wind stress curl and partly to the variability 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, evident as a 4-monthly signal in volume transport at 23°S. On rounding the southern tip of Madagascar, the eddies drifted westward. The model results suggest that this region is also influenced by the recirculation of the Agulhas Current.

Recirculation of the Agulhas Current back into the southwest 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 recirculation is by far the major contributor to the volume transport in the Agulhas Current, the other source regions make a significant contribution to the temperature transport. For example, there are several 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. A significant relationship was found between the volume flux of the model recirculation and the Agulhas Current on interannual time scales.

During the second half of the year, the recirculation appeared to be in phase with the annual cycle in the wind stress curl over the subtropical south Indian Ocean but this was not the case for the months of January–May. However, certain regions of the recirculation may be affected by local winds leading to the annual cycle not being completely in phase with the basin-scale winds (both the recirculation and the wind stress also display a marked semiannual signal). Previous work has not examined the variability of the recirculation 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.

This variability apparent in the model source regions of the Agulhas Current may have an influence on the retroflection region and thus interocean exchange. In an attempt to monitor the position and strength of the retroflection, a retroflection index was created. The index showed that the retroflection varied on eddy to interannual time scales. Typically, there was rarely a complete retroflection in the model and always some amount of leakage into the South Atlantic, with more leakage occurring during austral winter.

The model variability analyzed here supports the suggestions from previous observational and model work that the southern Agulhas Current region is highly variable on eddy, seasonal, and interannual time scales. This study has focused 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 analyzed here. The second model run with southward-shifted wind forcing reinforces the suggestion that such an increase would be the case. An increase in the eddy scale variability in this second run was found to be consistent with altimeter observations from years with a similar southward-shifted wind pattern.

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