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Atmospheric driving forces for the Agulhas Current in the subtropics

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[1] The Agulhas Current is the western boundary current of the South Indian Ocean and is thought to play an important role in the global overturning circulation. In this study, we investigate the contribution from the wind stress field over each ocean basin of the southern hemisphere to the variability of Agulhas Current transport. We ran a series of experiments using the Modular Ocean Model 2. The model grid extends from 20°S to 70°S and has a horizontal resolution of $\frac{1}{2}°$ with 25 levels in the vertical. The first experiment was forced with monthly means of the wind stress field from the project ERA 40 from ECMWF. In three other sensitivity experiments, the model was forced with the climatological mean over the whole domain plus the monthly wind stress anomalies (Jan/1979–Dec/2001) over one of the three ocean basins to whit: the South Atlantic, the South Indian and the South Pacific. The results show that inter-annual variations in the Agulhas Current transport are due largely to the wind field over the South Indian Ocean, whereas annual variations are driven by the wind field over both the South Atlantic and South Indian oceans. The annual signal from the South Atlantic is shown to move equatorward along the southeastern coast of Africa through coastally trapped waves. **Citation:** Fetter, A., J. R. E. Lutjeharms, and R. P. Matano (2007), Atmospheric driving forces for the Agulhas Current in the subtropics, *Geophys. Res. Lett.*, *34*, L15605, doi:10.1029/2007GL030200.

1. Introduction

[2] The exchange of water, salt and heat between the upper layers of the Indian and Atlantic oceans comes about largely through ring shedding at the Agulhas retroflection. Numerous estimates of these inter-ocean fluxes have been made [e.g., *De Ruijter et al.*, 1999], but these may depend to some degree on variations in the volume flux of the Agulhas Current itself. Estimates of this current flux lie between 85 Sv ($1\ Sv = 10^6\ m^3/s$) [*Toole and Warren*, 1993] and 137 Sv [*Jacobs and Georgi*, 1977]. The most accurate observations to date, using ADCP and current meter moorings [*Beal and Bryden*, 1999], give an average value of 69.7 Sv. It has furthermore been shown [*Donohue et al.*, 2000] that the depth of the Agulhas Current may decrease from 3000 to 2300 m over a period of less than 3 months, leading to short-term changes in volume flux of at least 2 Sv. Studies of the South Indian subtropical gyre [*Ffield et al.*, 1997], which may be the main source of variations in the volume flux of the Agulhas Current, have shown seasonality in its strength and in its geographic location. Although it seems reasonable to expect that these variations would be reflected in the transport of the Agulhas Current, and models do suggest this [e.g., *Reason et al.*, 2003; *Matano et al.*, 2002], no seasonal variability has been ascertained by direct observations [e.g., *Bryden et al.*, 2005].

[3] Changes in the transport of the Agulhas Current are likely to affect the Agulhas retroflection, and thus probably inter-ocean leakage [e.g., *Lutjeharms and van Ballegooyen*, 1984; *Ou and de Ruijter*, 1986]. This leakage has considerable consequences for interocean exchanges [e.g., *Garzoli et al.*, 1997; *Weijer et al.*, 1999], but in spite of their relevance to the meridional overturning circulation, the dynamical mechanisms that drive the variability of the Agulhas Current transport remain largely unknown. However, since the Agulhas Current is a typical, wind-driven, western boundary current it is expected that its variability would be strongly influenced by the wind field over the South Indian Ocean and neighboring basins. In this article, we present the results of a series of numerical experiments designed to investigate the relative contribution of the wind field over the three major ocean basins of the southern hemisphere (South Indian, South Pacific and South Atlantic oceans), to the transport variability of the Agulhas Current.

2. Model and Experiment Description

[4] The experiments described in this study were carried out using the Modular Ocean Model 2 (MOM 2) [*Pacanowski*, 1995]. The model encompasses the entire Southern Hemisphere from 20°S to 70°S and has a horizontal resolution of $\frac{1}{2}°$ and 25 levels in the vertical. The model topography was generated from the ETOPO5 data set. Horizontal mixing was parameterized with a Laplacian operator using a mixing coefficient of $A_M = 500\ m^2.s^{-1}$. The surface momentum fluxes used to force the model were obtained from the project ERA 40 of ECMWF. Surface salinity and temperature were restored to *Levitus* [1982] annual mean climatological values. All experiments were started from rest and spun-up during a 40-year period using the climatological mean wind stress of the 1979–2001 period. To asses the contribution of each individual ocean basin to the variability of the Agulhas Current transport, we ran four experiments. In the control experiment the model was forced with time-varying wind stresses over the entire domain. In the other three sensitivity experiments the model was forced with the climatological mean stresses over the entire domain plus monthly wind stress anomalies over individual ocean basins. The statistical technique of Principal Estimator Patterns (PEP) was used to investigate the patterns of covariability between the ocean and the atmosphere [e.g., *Davis*, 1977]. PEP is a mathematical decomposition that looks for a linear combination of a

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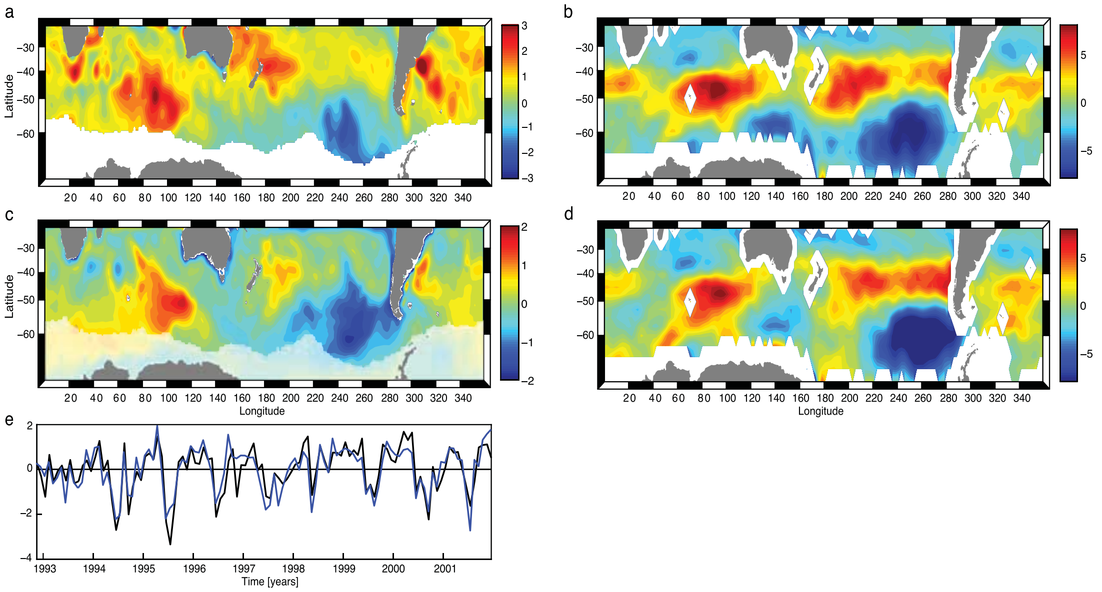

Figure 1. First PEP between SSHA from (a) altimetry data and (b) wind stress curl, and the first PEP between SSHA from the (c) control run of the model and (d) wind stress curl. (e) A time series of the first PEP between wind stress curl and SSHA from altimetry (black line) and from the model (blue line). SSH fields are in cm and wind stress curl fields are in N/m^3 times 10^7. SSHA data were smoothed using a low-pass, spatial filter to remove features smaller than 5 degrees. This extra filtering step was necessary to accommodate the different resolutions of the model and the satellite data. The white areas over the Southern Ocean, in Figures 1a and 1c, represent the maximum sea ice extension.

set of estimators (the wind stress curl) that explains most of the variance of the estimand (the SSH field and the zonal section of the Agulhas Current velocity).

3. Results and Discussion

[5] The overall goal of our experiments is not to make the most realistic representation of the Agulhas Current, but to investigate how wind-driven perturbations generated over the entire southern hemisphere contribute to its variability. To assess the realism of the control experiment, therefore, we compared the spatial and temporal patterns of the first PEP between wind stress curl and sea surface height anomalies (SSHA) derived from altimetry data (AVISO) [*Ducet et al.*, 2000] and from the model (Figure 1). PEPs are formed as a linear combination of a reduced, rotated subset of the original Empirical Orthogonal Functions of the fields and, therefore, are a robust and compact comparison tool. The result of a PEP computation is a set of modes explaining decreasing amounts of the variance of the estimator (SSH). Each mode is composed by a field of anomalies of the estimand (wind stress curl) that are covarying with the field of anomalies of the estimator. The time scales at which these two anomaly fields are covarying is represented by the amplitude time series of the mode. There is a reasonable good correspondence between the model and the observations, although the amplitudes of the later are larger on account of the limited model resolution (Figure 1). The main differences are close to the northern boundary, where the model's configuration does not allow the resolution of the tropical circulation. Also, since the model is not eddy-resolving, the mesoscale variability of the Agulhas Current retroflection is not fully captured by our experiments. Model and observations, however, show similar SSHA amplitude maxima east of the Kerguelen Islands, east of New Zealand, west of the Drake Passage and over the Brazil-Malvinas Confluence Zone (Figures 1a and 1c). Note also, that the wind stress curl fields associated with both SSH anomalies are similar (Figures 1b and 1d. There is a strong correlation between the time series of both PEPs (0.85, Figure 1e), which indicates that the model is able to capture most of the large-scale, wind-driven variance of southern hemisphere oceans.

[6] The general circulation in the control experiment is characterized by the eastward flow of the Antarctic Circumpolar Current (ACC) at high latitudes, and the subtropical gyres of the south Atlantic, Indian and Pacific oceans on the northern part of the domain. The ACC transport in our experiment is ~30% lower than the value estimated from observations, but that is expected in low-resolution models. The location of the Brazil-Malvinas Confluence in the model is ~40°S, compared to ~38°S in observations [*Matano et al.*, 1993]. The transport of the Agulhas Current from the model is ~42 Sv at 34°S. The Agulhas Current retroflection is located at ~19°E, which is also in good agreement with observations [*Lutjeharms and van Ballegooyen*, 1984].

[7] To assess the contribution of the wind stress forcing over the different ocean basins to the variability of the Agulhas Current, we calculated the Agulhas transport at 32°S (Figure 2). The control run shows annual and interannual changes with amplitudes of ~10 Sv, which fall well within the observed range of variability [e.g., *Bryden et al.*, 2005]. Approximately 34% of the variance of the Agulhas Current transport is accounted for by the annual harmonic and 47% by interannual oscillations. The sensitivity experiments indicate that most of this variability is driven by variations of the winds over the South Indian and South

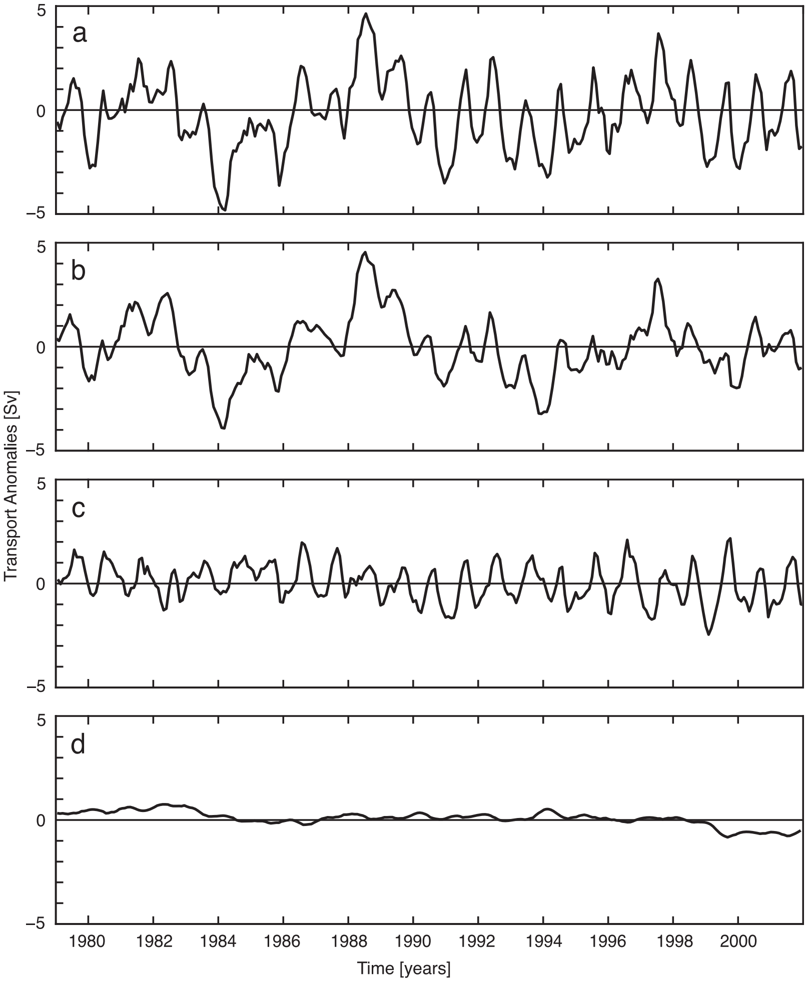

Figure 2. Transport anomalies of the Agulhas Current at 32°S in (a) the control experiment, (b) the Indian experiment, (c) the Atlantic experiment and (d) the Pacific experiment.

Atlantic oceans. Although the equatorial Pacific could influence the Agulhas Current flux through variations in the Indonesian throughflow, those influences are not captured by our model set up, which focuses on the influence of the winds over the southern basins. The sensitivity experiments also indicate that while the wind stress forcing over the South Indian Ocean controls the interannual variations of the Agulhas transport, the annual variability is equally partitioned by contributions of the winds over the South Indian and South Atlantic oceans.

[8] To quantify the relative contribution of each basin to the seasonal variations of the Agulhas transport, we computed the amplitudes and phases of variations in a latitudinal stripe between 27°S and 35°S, and following the southeastern coast of Africa (Figure 3). The amplitude of the annual harmonic at 32°S in the control experiment is 1.6 Sv. The sensitivity experiments indicate that the contributions from the Atlantic Ocean are larger south of 31°S whereas those from the Indian Ocean are higher north of that latitude. The linear slope of the phase plot suggests a northward propagation of coastally trapped waves along the southern tip of Africa (Figure 3). These waves move with a phase speed of approximately 0.4 $\mathrm{m.s^{-1}}$ (thin, continuous line in Figure 3b). The propagation of coastally trapped waves along the coast of South Africa was investigated by *Schumann and Brink* [1990]. Based on sea level measurements, they found waves propagating equatorward along the east coast of South Africa at $\sim$2.5 $\mathrm{m.s^{-1}}$. An auxiliary theoretical computation estimated phase speeds of the first barotropic mode ranging from 0.65 $\mathrm{m.s^{-1}}$ to 2.17 $\mathrm{m.s^{-1}}$. The dispersion relation of coastally trapped waves, however, is very sensitive to the stratification and the shelf slope. The narrow shelf of the east coast of South Africa is not well represented in our model, and that may partially explain the lower phase speed observed in our experiments. To determine the region of the South Atlantic that influences the variability of the Agulhas Current transport, we computed the PEP between the meridional velocities of the Agulhas Current at 32°S, and the wind stress curl over the South Atlantic for the Atlantic experiment (Figure 4). This calculation indicates that the bulk of the annual variations are restricted to the upper 1500 m of the water column (Figure 4a), and are largely driven by seasonal variations of the South Atlantic's wind stress curl in the latitudinal band between 35° to 45°S (Figure 4b). The most energetic signal of the first PEP is the annual cycle (Figure 4c). Note that the PEP calculation also shows a region of high wind stress curl anomalies, located between 55°S and 65°S, that covaries with the Agulhas Current transport (Figure 4b). The PEP decomposition, however, is purely statistical and does not take into

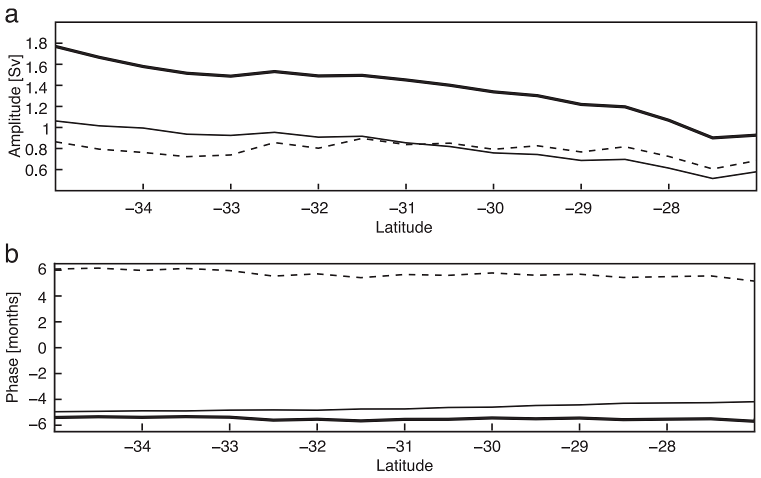

Figure 3. (a) The amplitude of the annual cycle of the Agulhas Current transport along the African coast, for: the control experiment (thick line), the Atlantic experiment (thin line) and the Indian experiment (dashed line), (b) same as in Figure 3a, but for the phase of the annual cycle.

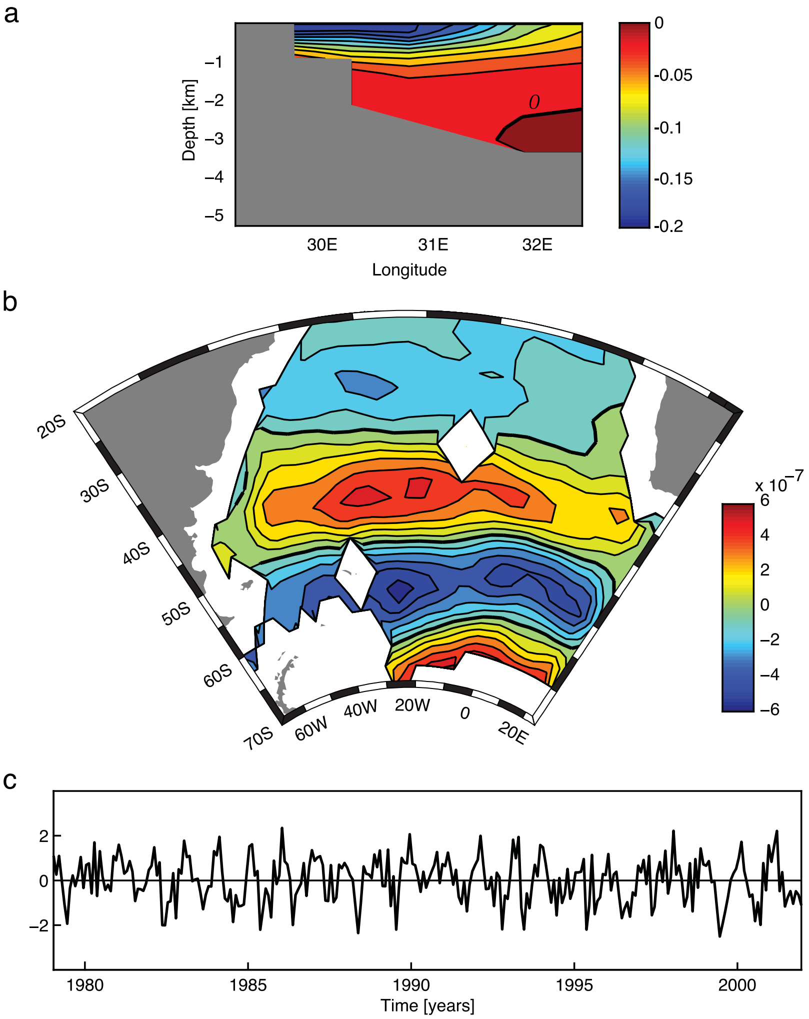

Figure 4. First PEP of (a) the meridional velocity of the Agulhas Current at 32°S for the Atlantic experiment (−0.02 cm/s contour interval), (b) the wind stress curl (1×10^{-7} N/m^3 contour interval, negative wind stress curl is shaded). (c) The amplitude time series of the first PEP.

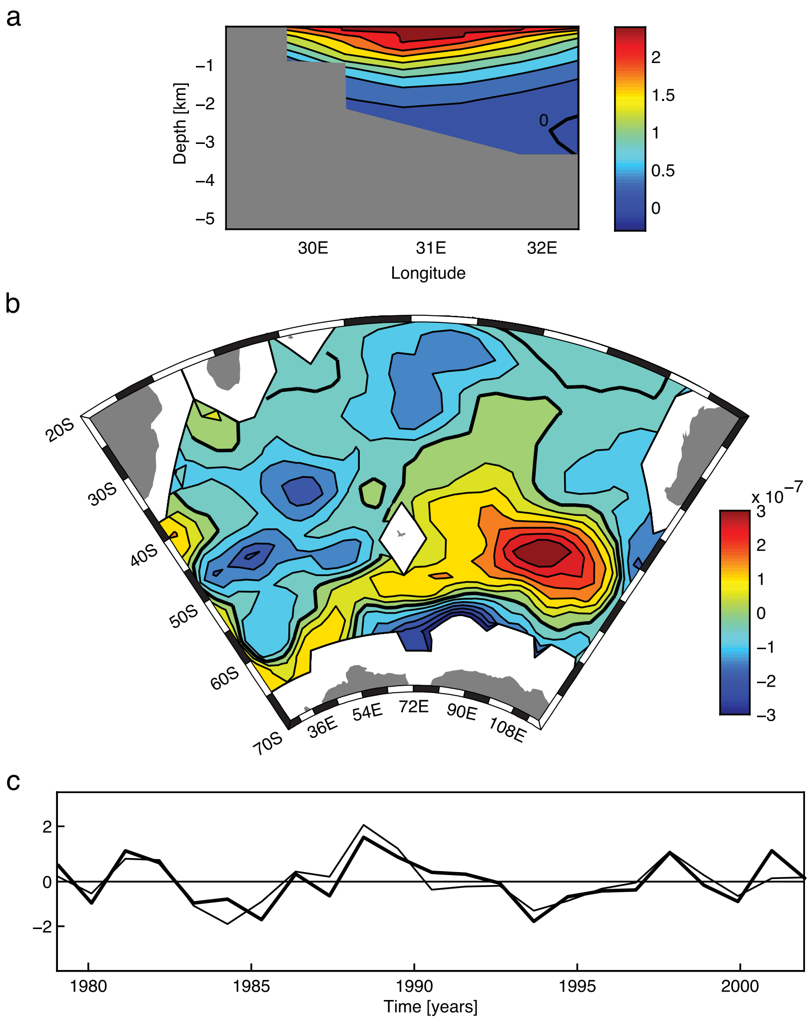

Figure 5. First PEP of (a) the inter-annual variability of the Agulhas Current at 32°S for the Indian experiment (0.3 cm/s contour interval), (b) the wind stress curl (0.5×10^{-7} N/m^3 contour interval, negative wind stress curl is shaded). (c) The amplitude time series of the first PEP of the meridional velocity of the Agulhas Current (thick line) and inter-annual anomalies of the volume transport of the Agulhas Current (thin line).

consideration the ocean dynamics. For this reason we concluded that the variability of the Agulhas Current transport is largely driven by wind stress curl anomalies in the subtropical region and is not likely to be influenced by wind variations in the polar region.

[9] The relatively small amplitude of the annual cycle in the Agulhas transport is consistent with previous modeling studies that indicate that although the wind stress curl over the Indian Ocean has significant annual variations, the westward propagation of these variations is arrested by the effect of the bottom topography [*Matano et al.*, 1999]. Although other modeling studies have suggested that the Agulhas transport could be affected by seasonal variations in the tropical region [*Biastoch et al.*, 1999; *Matano et al.*, 2002], our model configuration does not allow us to resolve the details of the tropical dynamics.

[10] The inter-annual variability of the transport of the Agulhas Current in our experiment is almost entirely controlled by the wind stress forcing over the South Indian Ocean (Figure 2). The first PEP between meridional velocities at 32°S and the wind stress curl over the South Indian Ocean in the Indian experiment, shows that most of this variability is concentrated in the upper 2000 m of the water column (Figure 5a). This PEP also shows that the variations of the Agulhas Current transport are associated with two maxima of the wind stress curl, one in the northwest and the other in the southeast (Figure 5b). The northwest maximum is the most influential on the Agulhas Current variability on account of its proximity and the fact that bottom topography shields the current from anomalies generated in the southeastern sector of the basin. Note, in fact, that winds on the northwest are in phase with changes in the Agulhas transport. The comparison between the amplitude time series of the first PEP and the inter-annual anomalies of the transport of the Agulhas Current (in the control experiment) show a good match, with a correlation coefficient of 0.84, which indicates that this mode is indeed responsible for the inter-annual variability of the Agulhas Current (Figure 5c).

4. Conclusions

[11] These model experiments show that the influence of the wind stress forcing on the seasonal variability of the Agulhas Current transport is relatively small, considering

the total transport of the current. Nevertheless, they are quite specific, with the South Atlantic and South Indian oceans contributing with approximately half of the seasonal variations. The variability originated in the South Atlantic propagates as a coastally trapped wave along the east coast of southern Africa. Our experiments indicate that interannual variations of the Agulhas Current transport are almost entirely controlled by the wind forcing over the Indian Ocean. This variability in the Agulhas Current is likely to influence the dynamical processes that control the inter-ocean leakage, but this influence cannot be ascertained at the spatial resolution used in this study.

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References

Beal, L. M., and H. L. Bryden (1999), The velocity and vorticity structure of the Agulhas Current at 32°S, *J. Geophys. Res.*, *104*, 5151–5176.

Biastoch, A., C. J. C. Reason, J. R. E. Lutjeharms, and O. Boebel (1999), The importance of flow in the Mozambique Channel to seasonality in the greater Agulhas Current system, *Geophys. Res. Lett.*, *26*, 3321–3324.

Bryden, H. L., L. M. Beal, and L. M. Duncan (2005), Structure and transport of the Agulhas Current and its temporal variability, *J. Oceanogr.*, *61*, 479–492.

Davis, R. E. (1977), Techniques for statistical analysis and prediction of geophysical fluid systems, *Geophys. Astrophys. Fluid Dyn.*, *8*, 245–277.

De Ruijter, W. P. M., A. Biastoch, S. S. Drijfhout, J. R. E. Lutjeharms, R. P. Matano, T. Pichevin, P. J. van Leeuwen, and W. Weijer (1999), Indian-Atlantic interocean exchange: Dynamics, estimation and impact, *J. Geophys. Res.*, *104*, 20,885–20,911.

Donohue, K. A., E. Firing, and L. Beal (2000), Comparison of three velocity sections of the Agulhas Current and Agulhas Undercurrent, *J. Geophys. Res.*, *105*, 28,585–28,594.

Ducet, N., P. Y. Le Traon, and G. Reverdin (2000), Global high-resolution mapping of ocean circulation from the combination of TOPEX/Poseidon and ERS-1/2, *J. Geophys. Res.*, *105*, 19,477–19,498.

Ffield, A., J. M. Toole, and W. D. Wilson (1997), Seasonal circulation in the south Indian Ocean, *Geophys. Res. Lett.*, *24*, 2773–2776.

Garzoli, S. L., G. J. Goñi, A. J. Mariano, and D. B. Olson (1997), Monitoring the upper southeastern Atlantic transports using altimeter data, *J. Mar. Res.*, *55*, 453–481.

Jacobs, S. S., and D. T. Georgi (1977), Observations on the southwest Indian/Antarctic Ocean, *Deep Sea Res.*, *24*, supplement, 43–84.

Levitus, S. (1982), Climatological atlas of the world ocean, *NOAA Prof. Pap. 13*, 173 pp., U. S. Gov. Print. Off., Washington, D. C.

Lutjeharms, J. R. E., and R. C. van Ballegooyen (1984), Topographic control in the Agulhas Current system, *Deep Sea Res., Part A*, *31*, 1321–1337.

Matano, R. P., M. G. Shilax, and D. B. Chelton (1993), Seasonal variability in the southwestern Atlantic, *J. Geophys. Res.*, *98*, 18,027–18,035.

Matano, R. P., C. G. Simionato, and P. T. Strub (1999), Modeling the wind-driven variability of the south Indian Ocean, *J. Phys. Oceanogr.*, *29*, 217–230.

Matano, R. P., E. J. Beier, P. T. Strub, and R. Tokmakian (2002), Large-scale forcing of the Agulhas variability: The seasonal cycle, *J. Phys. Oceanogr.*, *32*, 1228–1241.

Ou, H. W., and W. P. M. de Ruijter (1986), Separation of an inertial boundary current from a curved coastline, *J. Phys. Oceanogr.*, *16*, 280–289.

Pacanowski, R. C. (1995), MOM 2 documentation, user's guide and reference manual, *GFDL Ocean Tech. Rep. 3*, 232 pp., Geophys. Fluid Dyn. Lab., Princeton, N. J.

Reason, C. J. C., J. R. E. Lutjeharms, J. Hermes, A. Biastoch, and R. E. Roman (2003), Inter-ocean fluxes south of Africa in an eddy-permitting model, *Deep Sea Res., Part II*, *50*, 281–298.

Schumann, E. H., and K. H. Brink (1990), Coastal-trapped waves off the coast of South Africa: Generation, propagation and current structure, *J. Phys. Oceanogr.*, *20*, 1206–1218.

Toole, J. M., and B. A. Warren (1993), A hydrographic section across the subtropical south Indian Ocean, *Deep Sea Res., Part I*, *40*, 1973–2019.

Weijer, W., W. P. M. de Ruijter, H. A. Dijkstra, and P. J. van Leeuwen (1999), Impact of interbasin exchange on the Atlantic overturning circulation, *J. Phys. Oceanogr.*, *29*, 2266–2284.

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