Warming in the Agulhas Current system since the 1980's

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[1] Since the 1980's, the sea surface temperature of the Agulhas Current system has increased significantly. The warming is due to an augmentation of its transport in response to an increase in wind stress curl in the South Indian Ocean at relevant latitudes. This causes an increase in the fluxes of salt and heat into the Atlantic Ocean and in the transfer of energy from the ocean to the atmosphere. Therefore, the changes we are witnessing in the region could have far reaching consequences on top of the regional impacts on ecosystem and climate. The increase in wind stress curl is consistent with a poleward shift of westerly wind in the Southern Hemisphere reported by others. **Citation:** Rouault, M., P. Penven, and B. Pohl (2009), Warming in the Agulhas Current system since the 1980's, *Geophys. Res. Lett.*, *36*, L12602, doi:10.1029/2009GL037987.

1. Introduction

[2] Western boundary currents such as the Gulf Stream and the Agulhas Current are energetic currents driven by the wind field over the neighboring basins. Substantial transfer of energy takes place at the surface [*Yu*, 2007]. This is due to a sea surface temperature contrast between western boundary currents and their surroundings, leading to a high evaporation rate, and important turbulent latent and sensible heat fluxes. The Agulhas Current system has a profound impact on regional weather and climate and on the marine ecosystem [*Lutjeharms*, 2006]. It creates a coastal dynamic upwelling. Agulhas water leakage around South Africa controls the exchange of heat and salt between the Indian and Atlantic Oceans and has a role in the Atlantic meridional overturning circulation [*Biastoch et al.*, 2008; *Weijer et al.*, 2001].

2. Observations

[3] Sea surface temperature (SST) and turbulent heat fluxes have increased significantly in the Agulhas Current system south of Africa since the 1980's. Figure 1a shows the linear trend in the 4 km by 4 km resolution AVHRR SST in °C per decade from 1985 to 2006 in that region. Superimposed on that graph is a mean observed sea surface height [*Rio and Hernandez*, 2004] showing the major elements of the Agulhas Current system. The main loop is found south of the continent; the Retroflection is located in the domain delimited by 10°E to 20°E and 36°S to 41°S; eddies shed from the Agulhas Current are usually formed in the Retroflection region and move northwestwards in the Eddy Corridor [*Garzoli and Gordon*, 1996]; the Agulhas Return Current flows eastwards and meanders between 36°S to 41°S. All those areas have warmed since the 1980's (up to 0.7 °C per decade) in spite of an increase in the already large loss of energy due to air sea interaction. We note a cooling in the coastal Port Alfred dynamic upwelling at 25°E encroaching into the Agulhas Current suggesting that the Agulhas Current has intensified there. The warming is stronger to the west.

[4] There is a good correspondence in Figure 1b between trends in SST and the sum of the Optimally Adapted (OA) latent and sensible heat fluxes [*Yu*, 2007]. This represents an increase in the loss of energy at the surface of the region of up to 20 $W.m^{-2}$/decade. The increase in latent and sensible heat fluxes should have cooled the ocean surface, meaning that local air-sea interaction did not lead to the warming. The warming and higher latent and sensible heat fluxes trends occur at all months of the year. We observe an increase in eddy kinetic energy derived from altimetry in the Retroflection since 1993 (Figure 2).

[5] Extending our observations to the 1960's, in Figure 2 we plot yearly means of Hadley [*Rayner et al.*, 2003] and Reynolds SST, the sum of OA latent and sensible heat fluxes, *in situ* temperature measurements obtained from the World Ocean Database 2005, binned on 5 years periods and between 450 m and 550 m depth, NCEP [*Kistler et al.*, 2001] and ERA40 [*Uppala et al.*, 2005] surface wind speeds all averaged in the Retroflection area (36°S to 41°S; 10°E to 20°E). After a rather flat period from the 1960's to the 1980's, all time series but NCEP and ERA40 wind speed show an increase. This refines a recent analysis [*Yu*, 2007] showing that latent heat fluxes in western boundary currents (Gulf Stream, Kuroshio, and Agulhas Current) increased from 1958 to 2006. Averaging data in a larger domain representing most of the Agulhas Current system (36°S to 45°S; 10°E to 35°E, Figure S1 of the auxiliary material) leads to the same significance in trend.[1]

[6] Since the transport in the Agulhas Current is a function of the integral of the wind stress curl over the South Indian Ocean, the wind stress curl calculated from ERA 40 and NCEP averaged over the Indian Ocean (50°E to 100°E; 20°S to 40°S) is plotted on Figure 2f. The change in SST and fluxes, are all statistically significant at the 95 % level since the 1960's according to Spearman's rank correlation test.

3. Modelling the Warming in the Agulhas Current System

[7] A Regional Oceanic Modeling System (ROMS) [*Shchepetkin and McWilliams*, 2005] configuration (SAfE,

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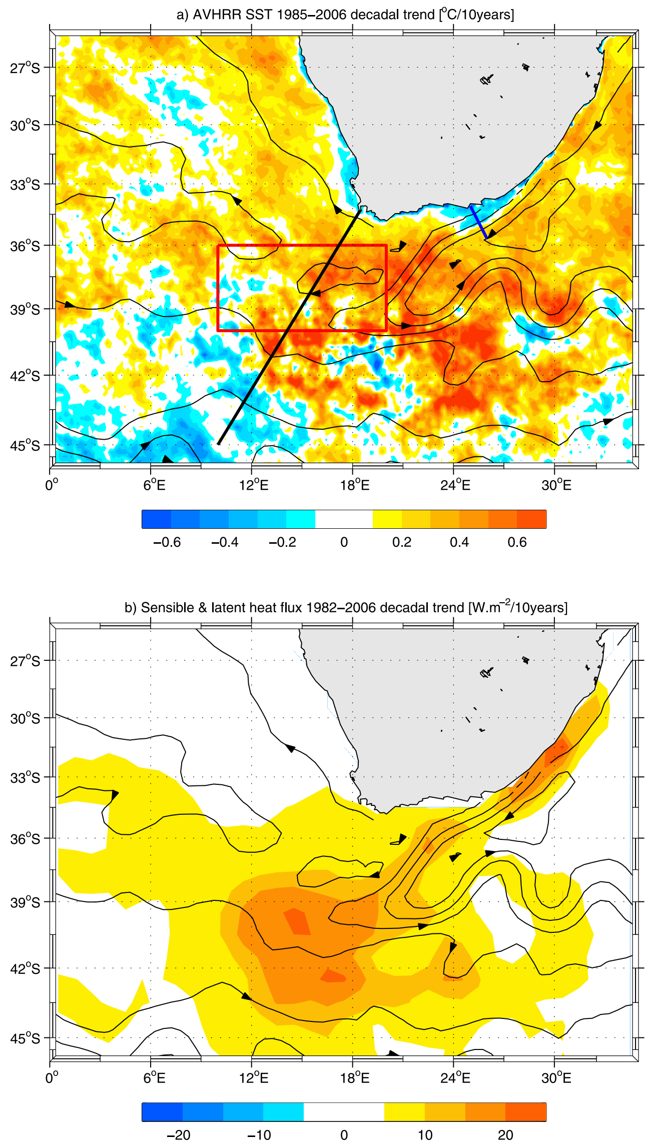

Figure 1. Observations of the recent warming in the Agulhas Current system. (a) Linear trend in AVHRR SST from 1985 to 2006 [°C/decade] showing a warming of up to 0.7 °C/decade. (b) Linear trend in sensible and latent heat flux [W.m^{-2}/decade] for the same period (positive values represent a loss of energy for the ocean). The black contours represent an observed mean dynamic topography [*Rio and Hernandez*, 2004] (1 contour per 20 cm) accounting for the mean surface currents. Arrows indicate the direction of the flow. The red box represents the region in which variables are averaged for Figure 2. The blue and black lines are relevant sections for Figure 4.

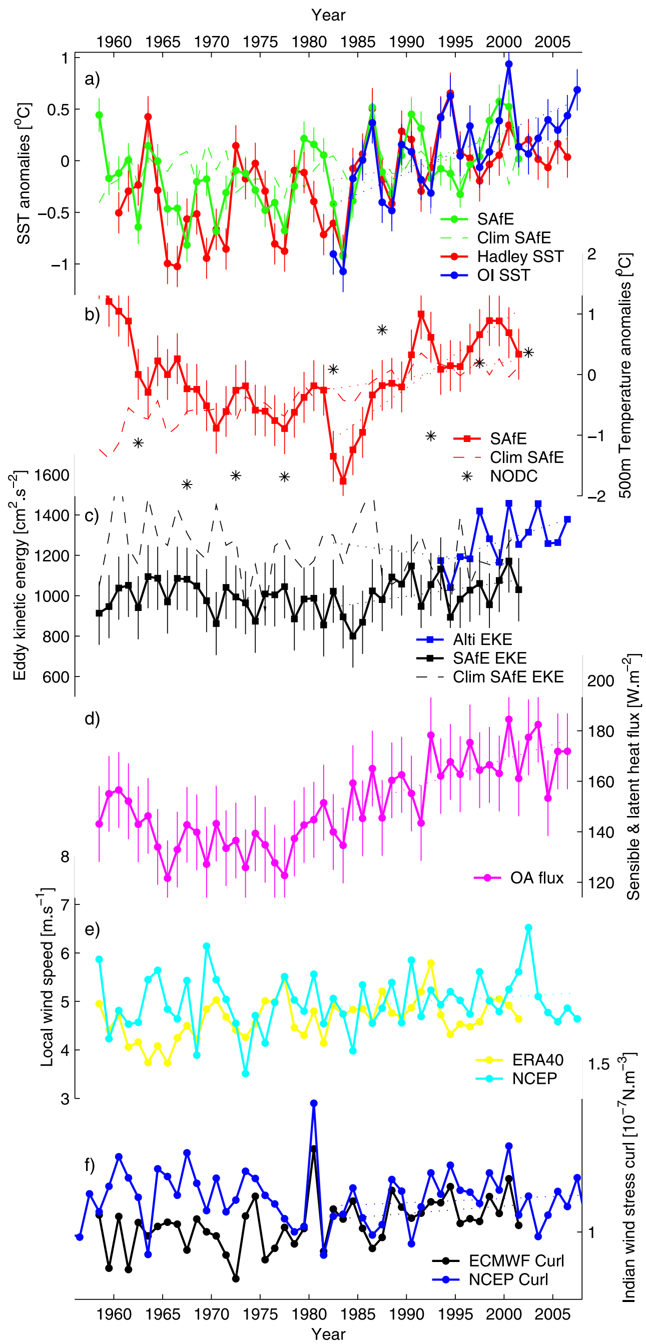

Figure 2. Changes in the Agulhas Retroflection region (36°S to 41°S and 10°E to 20°E) from 1960 to 2006. Dashed lines represent a model run forced by monthly climatology. Interannual variability RMSs in this climatological simulation are used as model error bars. (a) Observed (red and blue + error bars: ±0.2°C) and modeled (green) SST anomalies [°C]. (b) Modeled (red) and observed (black stars) temperature anomalies [°C] at 500 m. (c) Modeled (black) and observed (blue) geostrophic eddy kinetic energy [cm^2/s^{-2}] derived from sea surface height. (d) Observed latent plus sensible heat fluxes (purple) [W.m^{-2}] and error bars (±15 W.m^{-2}). (e) ERA 40 (yellow) and NCEP (cyan) surface wind speed [m.s^{-1}]. (f) Wind stress curl [10^{-7}N.m^{-3}] calculated from NCEP (blue) and from ERA40 (black) for the whole South Indian Ocean (20°S to 40°S and 50°E to 100°E). Dotted lines are linear fits to data from 1980 onwards.

Southern African Experiments [*Penven et al.*, 2006]) has been designed to explore the causes and possible consequences of this warming. ROMS is a split-explicit, free-surface oceanic model discretized in coastline- and terrain-following curvilinear coordinates using higher order numerics. The Southern Africa Experiment (SAfE) is a 1/4° resolution regional ROMS configuration designed for the simulation of the greater Agulhas Current system [*Penven et al.*, 2006]. Previous SAfE evaluations show its abilities in reproducing

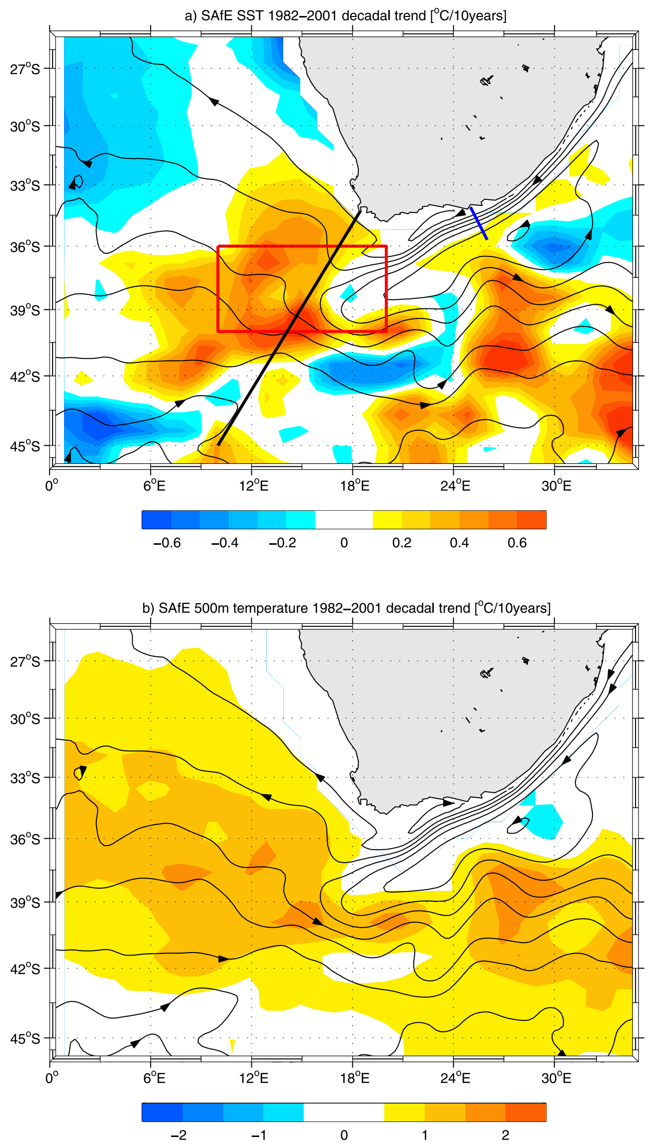

Figure 3. Modeling the recent warming in the Agulhas Current system. (a) Linear trend in modeled SST from 1982 to 2001 [°C/decade]. (b) Linear trend in modeled temperature [°C/decade] at 500 m for the same period. The black contours represent the model sea surface elevation (1 contour per 20cm) accounting for the mean surface currents for the same period. Arrows indicate the direction of the flow.

the Agulhas Current, the Agulhas Retroflection, the Agulhas Return Current, the generation of Agulhas Rings and their drift into the South Atlantic [*Penven et al.*, 2006]. For this inter-annual simulation, the model is forced by the 1958–2001 SODA ocean reanalysis [*Carton et al.*, 2005] with a temporal sampling of 1 month at its open boundaries and by the NCEP reanalysis with a temporal sampling of 6 hours for the surface. We are using a bulk formula for the surface heat fluxes and no restoring towards observed SST is performed. SAfE is therefore not forced by observed SST. After a spin-up of 2 years, the model is run from 1958 to 2001. To test eventual model drifts, a mirror SAfE experiment is designed in which lateral and surface boundary conditions are kept as monthly climatology. Inter-annual variations of this climatology experiment are used as a level of noise for the model in Figures 2 and 3. Figures 2 and S1 show the ability of the model in reproducing the observed SST variations in this region. The modeled SST trend for the period 1982–2001 is presented in Figure 3a, showing a warming pattern comparable to Figure 1a. Patches of cooling are also visible but they concern small areas compared to the overall domain and they are mostly confined to the surface. Figure 1a also shows patches of cooling offshore in the Agulhas Current system.

[8] At 500 m depth (Figures 2b, 3b, and 4c), the modeled temperature trend for the period 1982–2001 is much larger (1.1°C per decade). Note that at this depth, the warming trend is mostly downstream of the Agulhas Current. To test if this is caused by model drifts, we conducted a control experiment in which both surface and lateral forcing are taken as monthly climatology. Although negligible for model SST, a warming drift of 0.25°C per decade is present at 500m. Hence, at least 75% of the increase in temperature for the 1982–2001 period is not related to a spurious drift of our model. *In situ* temperature measurements present variations comparable to SAfE (Figure 2b; the mean observed temperature for 1982–2001 is 9.4°C while it is 9.7°C for SAfE). A global study [*Palmer et al.*, 2007] of ocean temperature profiles from 1954 to 2004 averaged from 200 m to the surface indicates also a warming trend at depth in the region, especially in the Eddy Corridor.

[9] An analysis of the heat budget over the domain (36°S to 41°S; 10°E to 20°E) shows that the incoming lateral fluxes are more than 40 times larger than the loss across the sea surface, demonstrating that the increase in temperature is driven by lateral advection. The effect of the increased warm Agulhas Current transport largely offsets the cooling effect of air-sea heat fluxes increase and associated turbulent mixing. This is confirmed in Figure 4a, which represents the modeled transports from 1000 m to the surface, in conjunction with the modeled SST downstream of the Retroflection. The short section off Port Elizabeth from 26°E 35.7°S to 25°E 34.1°S is representative of the core of the Agulhas Current. The modeled transport varies from about 52 Sv ($10^6 m^3.s^{-1}$) to 71 Sv and has increased since the 1980's. Farther upstream, in the regions feeding the Agulhas Current, there is no increase in the transport across the Mozambique Channel at 20°S around a mean value of 21 Sv. However, the transport across a meridional section South of Madagascar (at 45°E and from 35.7°S to 25.6°S) is significantly increasing and is correlated with the SST of the Retroflection region (r = 0.6), almost 3000 km downstream. The transport derived from integrating a Sverdrup relation from 120°E to 45°E and from 33°S to 21°S (green line in Figure 4a) illustrates how an increase in the wind stress curl over the Indian Ocean induces a significant increase in the Agulhas Current transport.

4. Causes and Consequences

[10] Figure S3 shows the linear trend in observed sea level pressure [*Allan and Ansell*, 2006] in the region from 1979 to 2006. It shows an increase in both the South

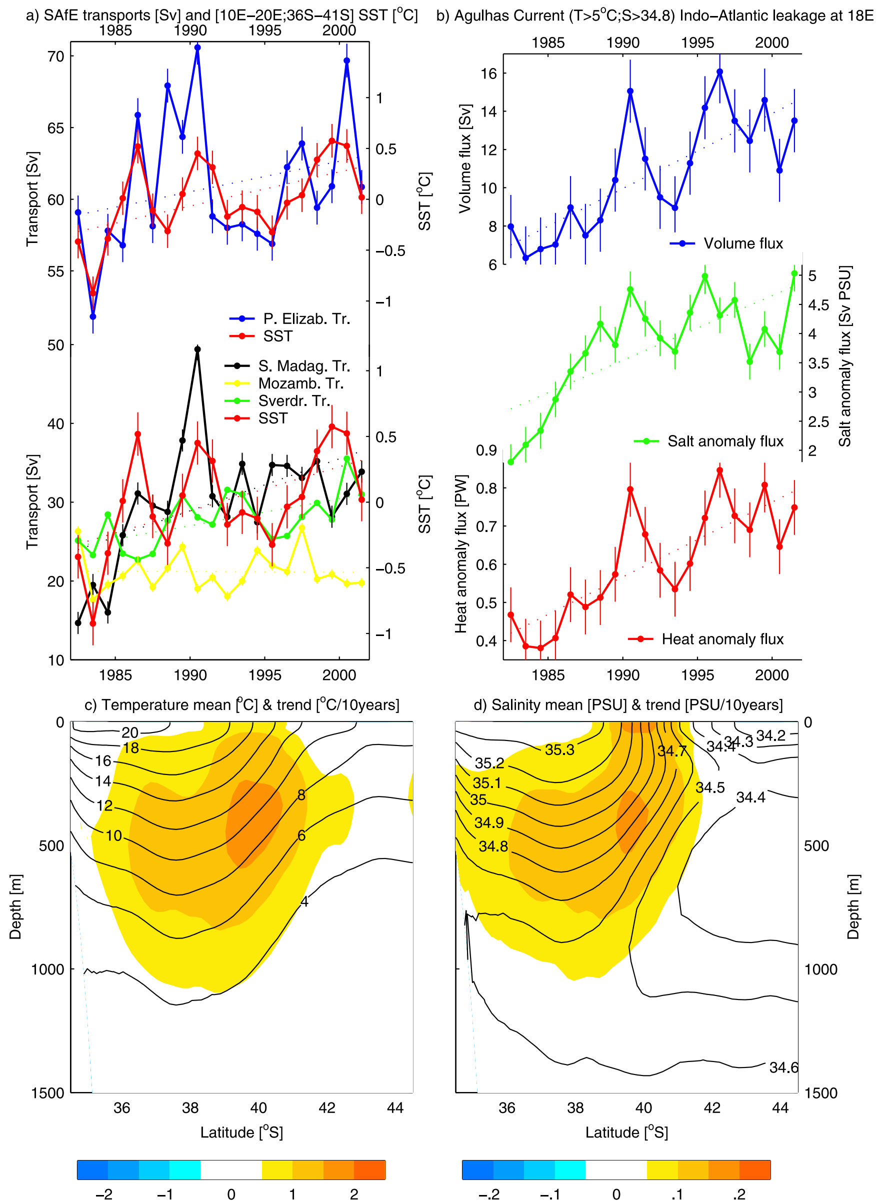

Figure 4. Causes and consequences of the recent changes in the Agulhas Current system: (a) Modeled ocean transport [Sv] from 1000m to the surface: across a coastal section off South Africa (Port Elizabeth) from 26°E 35.7°S to 25°E 34.1°S (blue), across a meridional section south of Madagascar at 45°E from 35.7°S to 25.6°S (black) and across a zonal section in the Mozambique Channel at 20°S (yellow). The green line represents the transport [Sv] obtained by integrating a Sverdrup relation forced by ERA40 winds in domain 120°E to 45°E; 33°S to 21°S. The red line represents the modeled SST over the Figure 2 Retroflection domain. (b) Net westward transport [Sv] (blue), salt anomaly flux [Sv PSU] (green) and heat anomaly flux [PW] (red) for waters with temperatures above 5°C and salinities above 34.8 PSU across a meridional section at 18°E. (c) Linear trend in modeled temperature [°C/decade] from 1982 to 2001 along a vertical section going from the Cape of Good Hope to 10°E 42°S. (d) Linear trend in modeled salinity [PSU/decade] from 1982–2001 along the same vertical section.

Atlantic and South Indian Ocean. NCEP and ERA40 have the same trend. The change in SLP leads to an increase in the easterly wind in the subtropics (Figure S4) effectively increasing the wind stress curl in the South Indian Ocean. The wind stress curl calculated from ERA40 and NCEP shows an increase in the South Indian Ocean (Figure 2f) at relevant latitudes. The observed change in SLP and wind speed is consistent with a poleward shift of the westerly wind system in the South Hemisphere and an increase of the South Atlantic and South Indian Ocean high pressure systems reported by others and thought to be influenced by humans [*Thompson and Solomon*, 2002; *Gillet et al.*, 2003; *Seidel et al.*, 2008]. However, variations of similar magnitude happened in the past [*Rayner et al.*, 2003] and could be linked to multidecadal variability [*Allan et al.*, 1995].

[11] In agreement with theory [*Pichevin and Nof*, 1997; *Pichevin et al.*, 1999], but in disagreement with *van Sebille*

et al. [2009], the increase in Agulhas Current transport in SAfE is associated with an increase in the leakage of warm and salty waters from the Indian to the Atlantic Oceans (Figures 4b, 4c, and 4d). Following Agulhas waters with a salinity above 34.8 PSU and a temperature above 5°C (i.e., excluding explicitly the Antarctic Circumpolar Current, see Figures 4c and 4d) across a meridional section at 18°E for the period 1982–2001, we obtain, for a mean incoming Agulhas transport of 79 Sv, a mean interocean leakage of 11 Sv (Figure 4b), which is close to the 15 Sv recently observed [*Richardson*, 2007]. For the associated mean heat and salt fluxes, we obtain 0.8 PW and 400 Sv.PSU (1 Sv.PSU = 10^6 kg.s^{-1}), in agreement with other models [*Matano and Beier*, 2003; *Reason et al.*, 2003]. The significant increase in Agulhas Water leakage is 3.9 Sv/decade (Figure 4b) and occurs in conjunction with a significant increase in eddy kinetic energy (70 cm^2.s^{-2}/decade (Figure 2c, correlation 0.4). This confirms the key role of Agulhas Rings for Indo-Atlantic exchanges [*Biastoch et al.*, 2008]. The important increase from 1993 to 2007 in observed eddy kinetic energy calculated from 7-days mean merged altimetry [*Ducet et al.*, 2000] for the Agulhas Retroflection Region (Figure 2c) is in agreement with SAfE results.

[12] Using 3.86°C and 34.94 PSU for the mean Atlantic temperature and salinity [*Weijer et al.*, 2001], we obtain 0.6 PW and 3.8 Sv.PSU for the mean flux of heat and salt anomalies associated with the Agulhas Current leakage (Figure 4b). Based on SAfE outputs, we estimate that the recent increase in Agulhas Current transport induces an interocean heat anomaly exchange increase of about 0.2 PW/decade and a salt anomaly exchange increase of about 1.1 Sv.PSU/decade. These two large values should have a significant effect on the Atlantic Overturning Circulation [*Biastoch et al.*, 2008; *Weijer et al.*, 2001].

5. Conclusion

[13] The Agulhas Current system has warmed up since the 1980's in spite of a substantial increase in latent and sensible heat fluxes that should have cooled the region. The warming increases from East to West and is more important in the Retroflection area. The warming spreads into the Eddy Corridor and the Agulhas Return Current. We observe an increase in eddy kinetic energy in the Retroflection. The model reproduces the interannual variations in sea surface temperature and suggests that the changes in the region are linked to an increase in transport south of Madagascar, consistent with an increase in wind stress curl to the east. Both observations and model outputs suggest that the Agulhas Current leakage to the Atlantic has increased since the 1980's.

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