

Seasonal variability in the Agulhas Retroflexion region

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Abstract.

The objective of this article is to present evidence for the existence of seasonal variability in sea surface height (SSH) anomaly in the Agulhas Retroflexion region. TOPEX/POSEIDON altimeter data are used to estimate seasonal changes in the mesoscale SSH variability. There is a seasonal oscillation of SSH variability characterized by a maximum during the austral summer and a minimum during the austral winter. The amplitude of this seasonal change is approximately 30% of its mean value. During the winter season the spatial distribution of SSH variability resembles that of the annual mean variability, with relative maxima centered at approximately 18°E, 27°E and 38°E. During the summer there is an additional maximum which extends from approximately 20°E to 25°E and from 40° to 42°S. Analysis of longitude-time diagrams reveals that at low latitudes planetary waves propagate freely throughout the basin. Along the latitude of the Agulhas Retroflexion region, the East Madagascar Ridge hampers the westward propagation of planetary waves. It is speculated that the difference between summer and winter patterns is caused by an inertially driven bifurcation of the Agulhas Current.

Introduction and background

The oceanic circulation of the southwestern Indian Ocean is dominated by the poleward flow of the Agulhas Current which, after separating from the continental slope of the African continent, makes an abrupt turn (the Agulhas Retroflexion) and flows back into the Indian ocean as the Agulhas Return Current. The retroflexion region has been characterized as one of the most energetic areas of the World Ocean [Chelton *et al.*, 1993] but little is known about its seasonal variations. The objective of this study is to investigate the

seasonal variability in the Agulhas Retroflexion region (ARR) from three years of TOPEX/POSEIDON measurements of sea surface elevation (SSH).

Although calculations based on the curl of the wind stress indicate that the volume transport of the Agulhas Current should be $20 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ higher during the austral winter than during the austral summer [Hellerman and Rosenstein, 1983], in-situ observations have failed to show any significant seasonal variation in its path along the continental slope of the African continent [Pearce and Gründlingh, 1982]. From a model of the wind-driven circulation of the South Indian Ocean, Matano *et al.* [1998] argued that the absence of seasonal variations of the Agulhas transport is the result of topographic barriers that isolate the western boundary current from the wind driven signal in the interior Indian Ocean. They also argued that, as the Agulhas Current leaves the continental slope and disperses over the ARR, local winds convey their distinctive seasonal cycle to the underlying ocean circulation. There are very few observational descriptions of this region to confirm this hypothesis. Lutjeharms and van Ballegooyen [1984] observed that satellite-derived streamlines indicated a westward penetration of the Agulhas flow into the South Atlantic for the summer months but noted that their observations were severely limited by cloud cover. Zlotnicki *et al.* [1989] computed the mean mesoscale variability in the region from the first one and a half years of data from the GEOSAT mission, finding a minimum for July–September and a less well defined maximum during November–December. Quartly and Srokosz [1993] compared the results of a numerical experiment with two years of GEOSAT data and concluded that, although it was not possible to establish an unambiguous picture of seasonal variations in the ARR, the observations suggested that the ARR variability is higher during the austral summer than during the winter. The objective of this article is to investigate seasonal variations in the ARR, from three years of SSH data collected by the TOPEX/POSEIDON altimeter.

Data analysis

The SSH data studied here comprise cycles 2–197 of the TOPEX/POSEIDON mission, spanning the time period from October 1992 to April 1996. These data are a processed version of the Merged Geophysical Data Records obtained from V. Zlotnicki and A. Hyashi of the Jet Propulsion Laboratory. Standard procedures were applied to reduce errors arising from the sea state bias,

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ionospheric range delay, wet and dry tropospheric range delays, inverse barometer effect, and TOPEX oscillator drift. The SSH data was used to check the two hypotheses proposed by *Matano et al.* [1988], namely: (1) there is a seasonal cycle in the ARR with a maximum during the austral summer and a minimum during the austral winter; (2) bottom topography arrests the propagation of wind driven signals from the Indian Ocean interior to the ARR. To address the first hypothesis, we calculated the standard deviation of the SSH for: (a) the three-year data span, (b) each individual year, (c) composite months, and (d) composite seasons. To address the second hypothesis, we constructed longitude-time diagrams of the South Indian basin from the equatorial region to the Southern Ocean.

To characterize the general mesoscale variability of the region, we first calculated the standard deviation of the SSH relative to the 1993–1996 mean for the entire observational period (Figure 1). The regional distribution of anomalies shown in Figure 1 has three distinct peaks: centered at approximately 18°E, 28°E and 38°E. The peak at 18°E coincides with the approximate location of the Agulhas Retroflection and is probably indicative of the shedding of Agulhas rings. The peak located at 28°E appears to be related to the interaction between the Agulhas Retroflection and the Agulhas Plateau. The relative maximum at 38°E is likely associated with the interaction between the Agulhas Return Current and the East Madagascar Ridge [e.g., *Stramma and Lutjeharms*, 1996; *Lutjeharms and Ansoorge*, 1997]. The standard deviation for each individual year (not shown) showed no significant differences compared with Figure 1, indicating the absence of significant interannual variability.

To estimate the amplitude of the seasonal signal in the ARR, we divided all the available data by month, calculated the standard deviation for each grid point and spatially averaged over the region between 44°S and 35°S and 5°E and 40°E. The resulting time series, shown as the solid line in Figure 2, shows a clear seasonal cycle with higher values during the austral summer and fall than during the winter and spring. There is

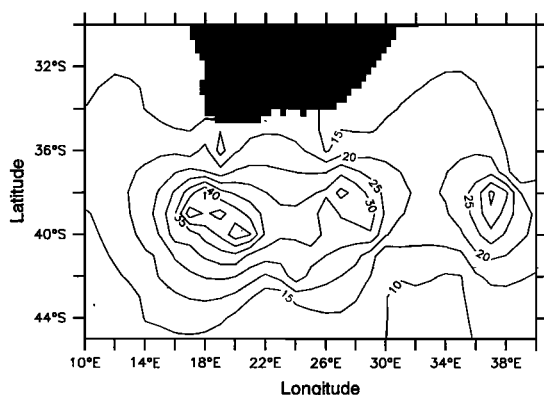


Figure 1. Standard deviation of sea surface height observed by the TOPEX/POSEIDON altimeter for years 1993–1995.

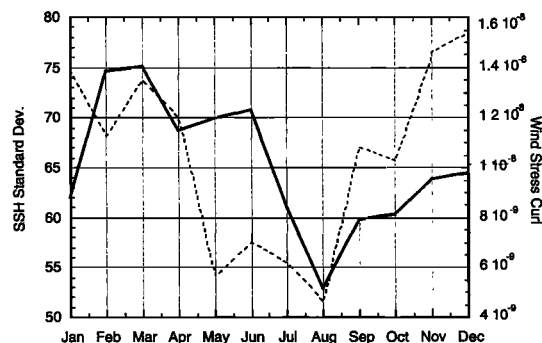


Figure 2. Time series of the standard deviations of the wind stress curl (solid line) and the standard deviation of the sea surface height anomalies (dotted line) averaged over the Agulhas Retroflection region.

an absolute maximum during the month of March and a minimum during August. The amplitude of the change is approximately 30% of its mean value. The dotted line in Figure 2 shows the wind stress curl computed from *Hellerman and Rosenstein* [1983] over the same geographical region. *Matano et al.* [1998] argued that seasonal changes in the ARR are mostly related to local wind forcing. In agreement with the model results, the altimeter data shows a close correspondence between oceanic and atmospheric variabilities; both having a maximum during the summer and a minimum during the winter.

Figure 3 shows the spatial distribution of the standard deviation for the peak seasons, i.e., the austral summer (January–March) and austral winter (July–August), relative to the three-year mean. It is apparent that the summer maximum anomaly is associated with an extension of the high variability regions rather than to an increase in amplitude. In fact, the most conspicuous difference between the opposing seasons is the summertime appearance of an additional maximum centered at 41°S, 24°E on the western side of the Agulhas Plateau. Examination of the standard deviation of the SSH anomalies relative to the seasonal mean instead of the three-year mean (not shown) indicates that, although the seasonal differences decreased substantially, the eddy-variability is still higher during the austral summer than during the austral winter. This result agrees with the observations of *Goñi et al.* [1997] who concluded from analysis of TOPEX/POSEIDON data over the Benguela region that ring formation associated to the Agulhas Current usually starts during the Southern Hemisphere summer and that the formation of those rings seems to be linked to large increases in the Agulhas transport.

The second hypothesis to be tested in this study is that bottom topography arrests the propagation of wind driven signals from the Indian Ocean interior to the ARR. *Matano et al.* [1998] argued that seasonal changes in the ARR appear to be mostly related to local wind forcing because the East Madagascar Ridge acts as a barrier to the westward propagation of the seasonal signal from the interior of the Indian Ocean

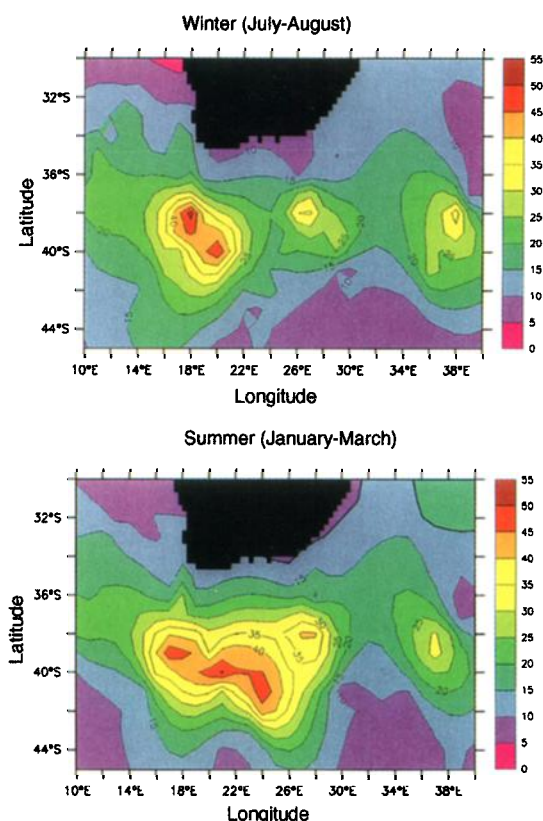


Figure 3. Standard deviation of sea surface height anomalies corresponding to the austral summer (January–March) and austral winter (July–September). To construct this figure we used TOPEX/POSEIDON data for the period October 1992 through April 1996.

basin. To investigate this hypothesis we constructed a set of time-longitude diagrams of residual SSH. Figure 4 shows examples at 20°S and 40°S, which were chosen to illustrate the differences between tropical and subtropical regimes. Although the oceanic adjustment along both latitudes is dominated by the westward propagation of planetary waves (characterized by the negative slopes of the SSH contours in Figure 4) perturbations along 20°S have a higher phase speed and an obvious basin-wide coherence. Along 40°S, waves propagate at a much slower rate, approximately 5 cm s^{-1} , which implies that in the course of a year such perturbations do not cross the South Indian basin and therefore cannot contribute to the seasonal adjustment of the ARR.

The coherent structure of the signal along 40°S is interrupted near 45°E, the approximate location of the Madagascar Ridge. The topographic effect is clearly seen in Figure 4 as a series of stationary oscillations between 40°E and 50°E. West of the ridge, the Agulhas Return Current flows more or less due east at this latitude, while east of the ridge it turns toward the southeast. Furthermore, the variability to the west of the ridge is much higher and there is evidence of enhanced wave generation. As pointed out in the discussion of Figure 1, these higher variability levels are likely to be associated to the interaction between the East Madagascar Ridge and the Agulhas Return Current. The

westward propagating perturbations generated by this interaction have higher amplitude than those propagating from the interior of the basin do. Time-longitude plots show that the effect of the East Madagascar Ridge is obvious as far north as 30°S; this is probably related to baroclinic wave energy arising from the interaction of barotropic waves from the interior of the Indian Ocean and the ridge, and to the presence of the southwest Indian subgyre [Stramma and Lutjeharms, 1997].

Summary and discussion

Although the statistical analysis discussed above does not allow the identification of the physical mechanisms responsible for the seasonal cycle shown in Figures 2 and 3, Figure 5 illustrates a dynamical scenario that is consistent with our observations and previous regional descriptions [e.g., Quartly and Srokosz, 1993; Field et al., 1997]. We hypothesize that the seasonal differences in variability are the result of displacements of the mean path of the Agulhas Current. The circulation characteristic of the winter months, and perhaps most of the year, is schematically shown in the lower panel of Figure 5. After flowing along the eastern coast of Africa, the Agulhas Current turns offshore and, at approximately 15°E, retroflects and turns back to the South Indian Ocean as a meandering eastward jet. During the summer months, the altimeter data suggest that there is an early retroflexion or bifurcation of the current at approximately 25°E. The portion of the flow that moves off the continental slope and onto the Agulhas Plateau gets trapped by topographic effects creating the

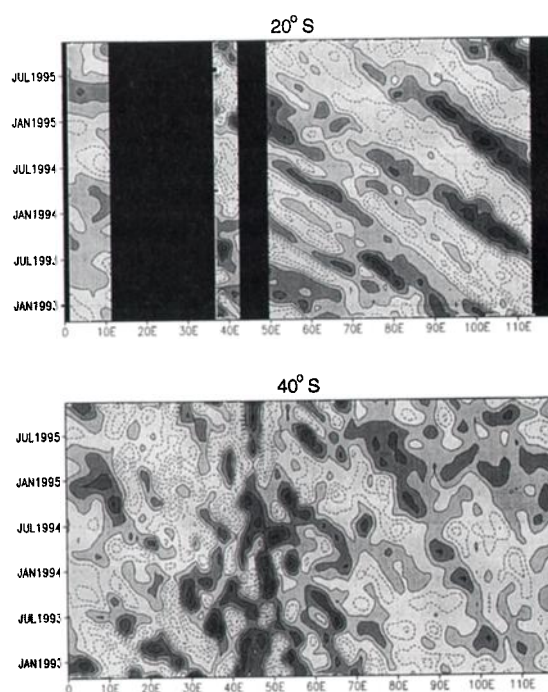


Figure 4. Time-longitude plots of sea surface height anomalies at 20°S (upper panel) and at 40°S (lower panel). The black rectangles in the upper panel indicate the location of continental land masses.

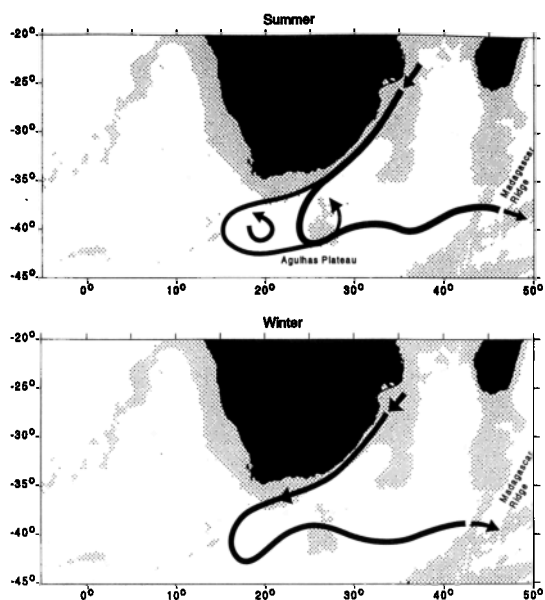


Figure 5. Schematic representation of the circulation patterns responsible for the seasonal differences: (a) Winter, (b) Summer.

high variability region located between 22°E and 26° (Fig. 2). Although a seasonal change of the retroflection mode has not been previously noted in the literature, *Lutjeharms and Van Ballegooyen* [1988b] observed, in satellite imagery and drifter tracks, that anomalous reversals of the current, like the one depicted in Figure 5, occur near Port Elizabeth (~25°E) and can last for more than two months.

While the generation mechanisms for the proposed circulation patterns cannot be deduced from the TOPEX/POSEIDON data, a plausible explanation is that a weaker transport of the Agulhas Current during the winter months allows most of the incoming flow to penetrate as far west as 18°E before retroflecting. During the summer, local winds might cause an increase in the intensity of the inertial re-circulation cell and force an earlier retroflection at 20°E because of a reduced advection of planetary vorticity [e.g., *Ou and de Ruijter*, 1986]; The inshore portion of the Agulhas Current might still flow as far west as 18°E while the offshore portion of the current is inertially forced to leave the coast sooner, thereafter becoming trapped by the Agulhas Plateau. Westward progressions of the retroflecting loop might lead to the shedding of an Agulhas ring, thus filling in the area of variability between the Agulhas Plateau and the winter maximum.

This description is consistent with the observations of *Ffield et al.* [1997] that argued that the Agulhas transport might have a relative maximum at the end of the summer and a minimum during the winter. *Garzoli and Gordon* [1996] analyzed time series of inverted echo sounders and conductivity-temperature-depth profiles collected in the Benguela region and reported that, during the 16 months of observations, the Agulhas inflow was stronger during the fall and weaker during the

summer. It is possible that early retroflection of the Agulhas Current during the summer period would decrease a direct linkage with the Benguela system.

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