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Seasonal circulation in the South Indian Ocean

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Abstract. Two World Ocean Circulation Experiment hydrographic cruises in March and June 1995, along with Topex-Poseidon altimeter data and National Meteorological Center wind data are used to estimate seasonal changes in the South Indian Ocean subtropical gyre. Mean annual curves derived from the altimeter and wind data reveal strengthening of the anticyclonic gyre in March and September, and weakening in June and December. The seasonal changes correspond to variations in the wind field south of 30 °S at the equinoxes and solstices. In addition, the wind-driven gyre is further north in July, and further south in March. These variations in strength and location of the South Indian Ocean gyre may influence inter-ocean transports south of Africa. Despite the inferred mean annual seasonal variations in the South Indian Ocean gyre, volume transports estimated in 1995 from the hydrographic data are close to mean values. Apparently, a mesoscale eddy in March disrupts the stronger fall gyre, whereas in June the weaker winter gyre is delayed by 1 month.

Introduction

Wind analyses from the European Centre for Medium Range Weather Forecasts (ECMWF) reveal the anticyclonic forcing in the South Indian Ocean. The annual mean wind stress is westward between 10 and 35 °S, and eastward between 35 and 60 °S [*Trenberth et al.*, 1990]. The anticyclonic forcing drives the subtropical gyre of the South Indian Ocean defined by the strong Agulhas western boundary current flowing south near the coast of Africa, and relatively weak northward interior flow east to Australia [*Toole and Warren*, 1993]. Away from the equator the curl of wind stress is used in the Sverdrup relation to describe the depth-averaged, wind-driven, ocean circulation. The 1980 to 1986 ECMWF winds force an annual mean Sverdrup transport in the South Indian Ocean reaching 100 Sv (1 Sv = 1 x 10^6 m^3/s) at the tip of Africa [*Trenberth et al.*, 1990]. The integrated Sverdrup transport value is assumed to be closed by a western boundary current, in this case the Agulhas Current.

At the southern tip of Africa, *Gordon et al.* [1987] estimated the baroclinic Agulhas Current transport relative to the sea floor to be 95 Sv, close to the amount needed to balance the Sverdrup circulation. Much of this flow is located in the upper ocean. *Stramma and Lutjeharms* [1997], using historical hydrographic data, estimated an average Agulhas Current volume transport in the upper 1000 m of 65 Sv. Efforts to estimate the seasonality of the Agulhas Current have produced conflicting results [*Pearce and Gründlingh*, 1982] in part due to different criteria and methods.

As part of the World Ocean Circulation Experiment, high quality, high resolution hydrographic surveys of the Indian Ocean were obtained in 1995 with repetition of certain sections to capture the variability. In March 1995 the NOAA Ship MALCOLM BALDRIGE obtained "repeat" hydrographic data across the zonal I5W section, nominally along 33 °S, crossing the Agulhas Current south of Durban and continuing eastward to 55 °E (Figure 1). In June 1995, the RV Knorr occupied the same section obtaining "one-time" hydrographic coverage of the I5W line. In this letter, the two I5W cruises along with Topex-Poseidon altimeter data and National Meteorological Center wind data are used to estimate seasonal changes in the subtropical gyre of the South Indian Ocean.

Circulation Inferred From Hydrographic Data

Two potential temperature sections across the southwestern Indian Ocean reveal downward sloping isotherms from the coast of South Africa to 32 °E associated with the strong southward flowing Agulhas Current (Figure 2). East of 32 °E the isotherms generally slope upwards in June indicating possible northward interior flow into the Indian Ocean. However in March the

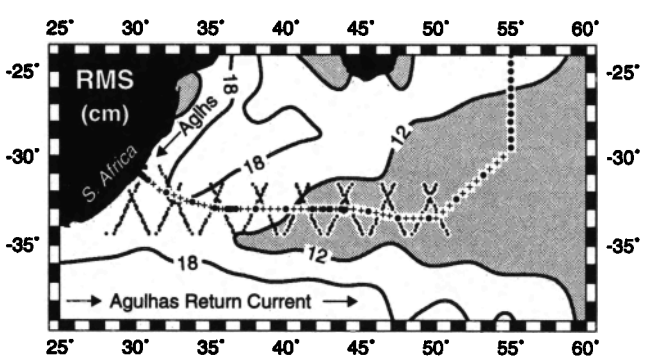

Figure 1. Root-mean-squared sea surface height anomalies in the southwest Indian Ocean smoothed by a 5° by 5° gaussian filter. The contour interval is 6 cm. CTD (circles) and XBT (crosses) station locations for the March 1995 cruise are shown, along with a subset of the criss-crossing tracks of the altimeter data. (CTD station locations for the June 1995 cruise are at both circle and cross locations.)

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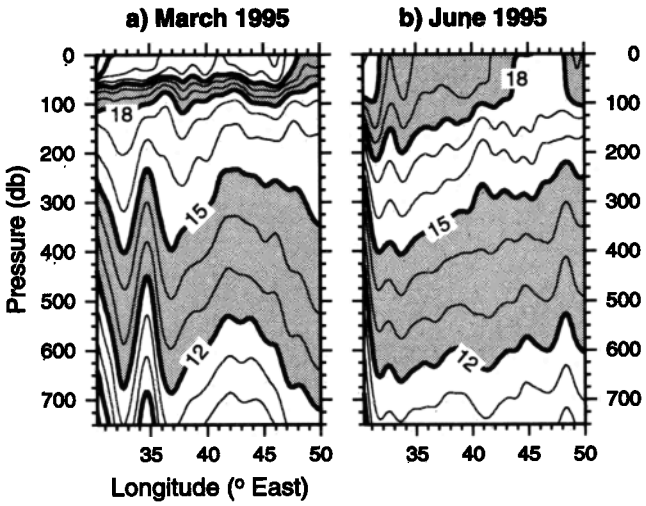

Figure 2. Potential temperature sections nominally along 33 °S for the a) March 1995 and b) June 1995 cruises. The contour interval is 1 °C. CTD and XBT data are used in a), and CTD data are used in b).

situation is more complicated with the isotherms below 200 db revealing a cyclonic mesoscale eddy centered at 34.5 °E, and possible northward then southward flows centered at 42 °E. Both these features are centered over shallow 1000 m topography: the Mozambique Ridge at 35 °E and the Madagascar Ridge at 44 °E. Cyclonic eddies have been previously observed in this region [*Gründlingh et al.*, 1991; *Gründlingh*, 1988].

To compare volume transports across the zonal sections, geostrophic velocities are estimated. Rather than attempt to determine the absolute transport across the sections, the calculations are performed in a way to insure good comparisons between the different occupations. In this way baroclinic transports can be directly compared to each other, and errors due to bottom topography, station spacing, and small velocities are reduced: 1) the integration starts slightly offshore Africa where the bottom depth is greater than 1000 m, 2) only stations occupied during both cruises are included, 3) a level of no motion at 2000 dbars or the deepest common depth is selected, and 4) the transports are integrated for the upper 1000 m (only near the Madagascar Ridge at 44 °E does the bottom topography rise slightly above 1000 m).

The cumulative geostropic transports (Figure 3) quantify the flow patterns implied by the potential temperature sections (Figure 2). In June the Agulhas Current flows swiftly southward with 61 Sv in the upper 1000 m, similar to the historical average value of 64 Sv reported by *Stramma and Lutjeharms* [1997]. In March the eddy obscures the offshore edge of the Agulhas Current. Integrated to 32 °E - the western edge of the cyclonic eddy - the cumulative transport is 7 Sv less in March (54 Sv) than in June (61 Sv). However, when integrated to 36.7 °E - the eastern edge of the cyclonic eddy - the cumulative transport is 3 Sv more in March (60 Sv) than in June (57 Sv). In the interior, between 32 and 50 °E, the flow is weak with 0 Sv net transport in March, and 4 Sv net northward transport in June. These net interior flows are not significantly different from each other.

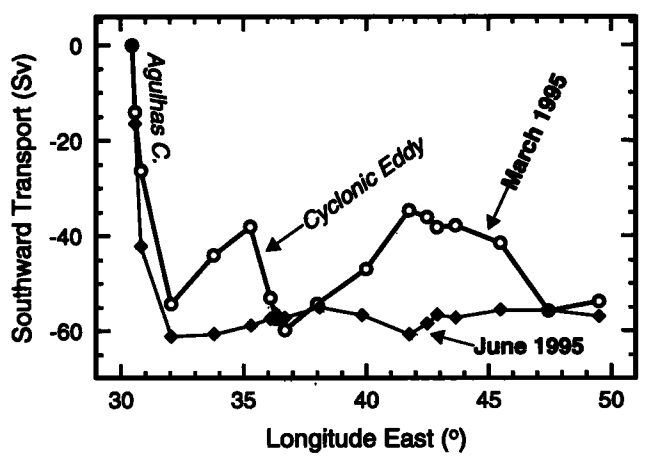

Figure 3. Cumulative geostrophic transport in the upper 1000 m using a subset of the March 1995 (open circles) and June 1995 (solid diamonds) station data nominally along 33 °S.

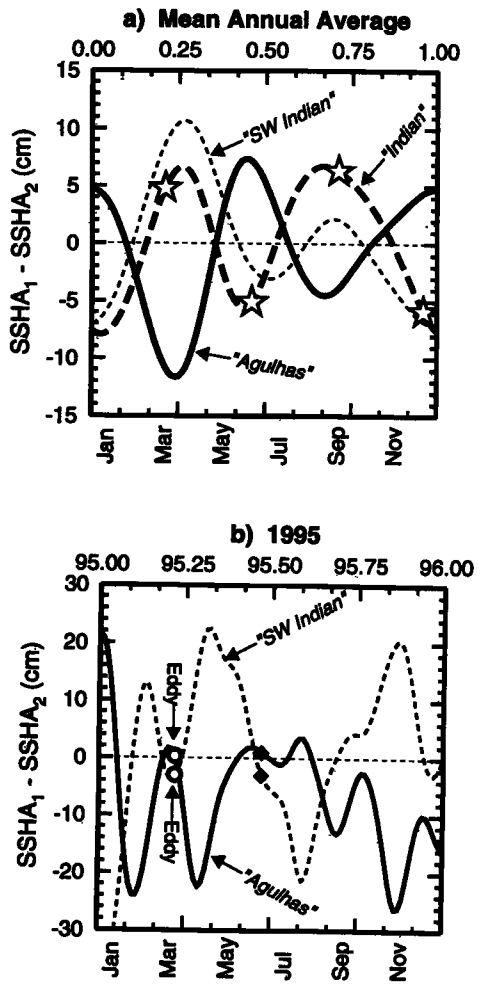

Figure 4. Sea surface height anomaly (SSHA) difference across the "Agulhas" (31.1 °S, 30.4 °E - 32.2 °S, 32.5 °E, solid line), "Indian" (32.2 °S, 32.5 °E - 33.2 °S, 112.4 °E, thick dashed line), and "Southwest Indian" (32.2 °S, 32.5 °E - 33.2 °S, 50.0 °E, thin dashed line). In a) the mean annual average SSHA differences are smoothed by a 6 month gaussian filter, with stars marking the solstices and equinoxes, and in b) the 1995 SSHA differences are smoothed by a 2 month gaussian filter with the occurrences of the March (open circle) and June (solid diamond) cruises indicated.

However, the energetic +/- 20 Sv flows centered over the Mozambique Ridge at 35 °E and the Madagascar Ridge at 44 °E in March contrast with the +/- 5 Sv amplitude flows observed in June.

Circulation Inferred From Altimeter Data

Fully processed Topex/Poseidon sea level height data were obtained from the NASA Ocean Altimeter Pathfinder Data Project for the period, October 1992 through April 1996. The data are averaged to 0.2 degrees spatial resolution along each satellite track and the three year, 1993 to 1996, mean subtracted. Consequently, the contribution of the geoid and the mean ocean circulation to the sea level height values is effectively removed. The remaining data are time series of sea surface height anomalies (SSHA) at approximately 10 day intervals. The root-mean-square (RMS) of the SSHA data illustrates the high variability (> 12 cm) of the southwestern Indian Ocean associated with the Agulhas Return Current, the eastern edge of the Agulhas Current, and numerous mesoscale eddies (Figure 1).

The slope of the sea surface - which can be calculated using SSHA data - is proportional to geostrophic flow at the sea surface. Geopotential topography at the sea surface, 500 m, and 1000 m all reveal an anticyclonic gyre in the South Indian Ocean west of 80 °E [*Wyrtki*, 1971, plates 388, 389, 390]. This suggests that circulation revealed by SSHA data at the sea surface mirrors deeper circulation patterns. In order to directly compare the SSHA data to the results of the two hydrographic sections, SSHA data intersecting the sections are examined. The largest RMS variability along the sections is at 32.5 °E, which is also approximately the transition point between the southward flowing Agulhas Current and the eventual northward interior flow to the east. To investigate the variability of the current flows, the differences in SSHA across three longitude intervals are estimated: the "Agulhas" (31.1 °S, 30.4 °E to 32.2 °S, 32.5 °E), the "Southwest Indian" (32.2 °S, 32.5 °E to 33.2 °S, 50.0 °E; eastern edge of the hydrographic sections), and the "Indian" (32.2 °S, 32.5 °E to 33.2 °S, 112.4 °E, eastern edge of the South Indian Ocean).

Mean annual curves constructed for the SSHA differences clearly reveal a seasonal circulation in the South Indian Ocean (Figure 4). On Figure 4 negative values imply anomalous southward flow (or reduced northward flow if the mean flow is larger and northward) and positive values imply anomalous northward flow (or reduced southward flow if the mean flow is larger and southward). The seasonal circulation is maximum with stronger southward "Agulhas" and stronger northward "Indian" flows implied during March and September (stars on Figure 4a). In other words a stronger gyre. In contrast during June and December, the opposite situation is observed: weaker southward "Agulhas" and weaker northward "Indian" flows. The same seasonality is found in the mean-annual curve constructed for the "Southwest Indian".

This strengthening and weakening of the South Indian Ocean gyre may be driven by seasonal variations in wind, because the strengthenings correspond to equinoxes (March and September), and weakenings correspond to solstices (June and December). The monthly mean position of the center of the subtropical high reaches maximum southerly positions in March (35 °S) and September (32 °S), and maximum northerly positions in June (30 °S) and November (30 °S) [*Van Loon*, 1971, Fig. 7]. At 90 °E, 50 °S, the annual cycle of mean zonal wind stress also reveals maximums in March (3.5 dyn cm^{-2}) and September (3.7 dyn cm^{-2}), and minimums in May (2.6 dyn cm^{-2}) and December (1.9 dyn cm^{-2}) [*Trenberth et al.*, 1989, Fig. 23]. One report of geostrophic volume transport of the Agulhas Current relative to 1000 m suggests this seasonality: 23 Sv in January-February, 38 Sv in April, 32 Sv in July-August-September, 27 Sv in October-November. However, when the geostrophic velocities are referenced to observed surface currents the seasonality disappeared [*Gründlingh*, 1980, averages compiled from his Fig. 6].

Despite the mean annual seasonality, at the times of the hydrographic cruises in March and June, 1995, the SSHA differences are all within 3 cm of the mean (Figure 4b). In March 1995 the expected strengthening of the gyre appears disrupted by the mesoscale eddy crossing the section, whose circular SSHA depression signature can be traced from March 9 to April 20. In June 1995 the expected weakening of the gyre seems to be delayed 1 month.

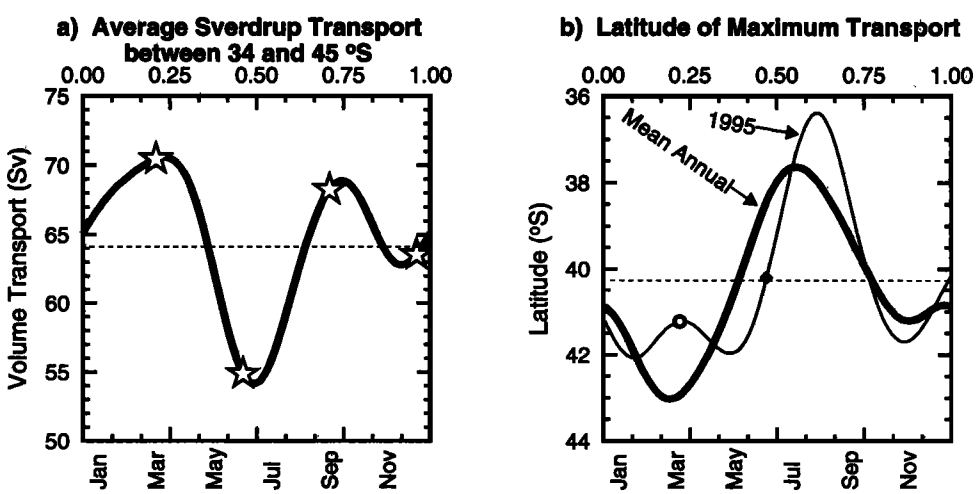

Figure 5. In a) the mean annual curve of the average Sverdrup transport between 34 and 45 °S along 32.5 °E is drawn for the South Indian Ocean gyre, with stars marking the solstices and equinoxes. In b) the mean annual curve of the latitude of maximum Sverdrup transport along 32.5 °E is drawn, along with the 1995 curve showing the occurrences of the March (open circle) and June (solid diamond) cruises. The data are smoothed by a 6 month gaussian filter, and the means are indicated by dashed lines.

Circulation Inferred From Wind Data

The data-assimilating, operational, T-62 model wind field from the National Meteorological Center is used with a drag coefficient of 1.4, to compute the Sverdrup relation at ~1.5 degree spatial resolution and weekly averaged temporal resolution. The Sverdrup circulation is estimated every week from 1991 through 1995, by integrating volume transports calculated from the Sverdrup relation westward from the Australian and New Zealand's coasts between 20 and 50 °S.

The Agulhas Return Current is located between 34 and 45 °S, and feeds the northward interior circulation of the South Indian gyre. The mean annual curve of the average Sverdrup transport between 34 and 45 °S, at 32.5 °E is constructed for the South Indian gyre (Figure 5a). The average Agulhas Return Current is estimated to be 65 Sv. Seasonally, the wind-driven Agulhas Return Current follows the same semi-annual seasonality revealed by the altimeter data. For example, in both the altimeter data and the wind data, March (70 Sv) and September (70 Sv) correspond to maximum gyres, and June (55 Sv) and December (65 Sv) to minimum gyres (stars on Figures 4a and 5a). The center of the subtropical anticyclonic circulation also varies with season (Figure 5b). The latitude of maximum Sverdrup transport along 32.5 °E is furthest north in July (38 °S) and furthest south in March (43 °S). This meridional movement of the gyre is partially resolved by historical hydrographic sections crossing 30 °S, 65 °E, that show a shift in the circulation southward between January and March, and northward during June and July [*Stramma and Lutjeharms*, 1997].

In March 1995 the position of the wind-driven South Indian Ocean gyre is anomalously north relative to the mean annual curve (Figure 5b). Whereas, in June 1995 the northward movement of the gyre appears delayed one month.

Discussion and Conclusions

Altimeter and wind data used to estimate seasonal changes in the anticyclonic subtropical gyre of the South Indian Ocean reveal a stronger gyre in March and September, and a weaker gyre in June and December. The Sverdrup transport of the Agulhas Return Current suggests that seasonal variations range between +5 to -10 Sv about the 65 Sv mean. In addition, the meridional position of the gyre is furthest north in July (38 °S), and furthest south (43 °S) in March. The meridional movement and strength of the wind-driven gyre may have important implications for inter-ocean transports, by possibly influencing the water mass sources drawn into the South Indian Ocean subtropical gyre and by modulating volume transports south of Africa.

Despite the inferred seasonal changes, baroclinic volume transports estimated from the March and June 1995 hydrographic data are close to the historical mean. In March 1995 a mesoscale eddy disrupts the expected stronger fall anticyclonic circulation and the South Indian gyre moves unusually far north during the same time interval. In June 1995, the expected weaker winter anticyclonic circulation and northward movement of the gyre is delayed by 1 month. These results mask the far more complicated reality indicated by the large sea level height RMS in the southwest Indian Ocean. For example, even though the integrated transport values across the hydrographic sections are similar in March and June, energetic +/- 20 Sv flows were observed in March centered over the Mozambique Ridge at 35 °E and the Madagascar Ridge at 44 °E. No notable transport features were seen there in June.

The response of the southwestern Indian Ocean to seasonal variation in wind forcing is clearly complicated by the major ridge systems of this basin that attain depths shallower than 1000 m. Only barotropic wave motions propagate sufficiently fast to transmit information about seasonally varying wind stress across mid-latitude oceans. Baroclinic waves are too slow. Yet, barotropic motions can be reflected and/or scattered into baroclinic modes at tall bathymetry. Better understanding of these processes may help explain the high SSH variability of the southwestern Indian Ocean, and shed light on the seasonal transport field of the Agulhas Current and its associated interbasin exchanges.

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