An oceanic teleconnection between the equatorial and southern Indian Ocean

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Sequences of Kelvin and Rossby waves are found to rapidly carry sea surface height anomalies across the Indian Ocean, and have an impact on Indian to Atlantic interocean exchange. Satellite altimeter data reveal an oceanic teleconnection between equatorial waves and variability of the interocean exchange. Four times per year, we observe an equatorial Kelvin wave that hit Indonesia, forced by monsoon variability. The signal then propagates southward along the Indonesian coast and triggers Rossby waves that propagate westward across the subtropical Indian Ocean. On reaching the Madagascar and Mozambique Channel regions, large rings form at the same four per year frequency. These drift towards the Agulhas retroflection where they control the shedding of Agulhas rings. Disturbances of this pin-ball-like propagating signal can be traced from Indian Ocean Dipole/El Niño events in 1994 and 1997/1998, to decreases of Indian-Atlantic ocean exchange by Agulhas rings over two years later.

INDEX TERMS: 4599 Oceanography: Physical: General or miscellaneous; 4576 Oceanography: Physical: Western boundary currents; 4520 Oceanography: Physical: Eddies and mesoscale processes; 4227 Oceanography: General: Diurnal, seasonal, and annual cycles

1. Introduction

On average, 4–5 Agulhas rings drift into the Atlantic Ocean each year, delivering large amounts of warm and saline water into this relatively cold and fresh region [Byrne et al., 1995; Schouten et al., 2000]. This largely feeds the warm upper limb of the northward thermohaline transport in the South Atlantic [Gordon, 1986; De Ruijter et al., 1999]. Model studies suggest that this exchange stabilizes the Northern Atlantic meridional overturning circulation and thus promotes our present relatively stable climate [Weijer et al., 2001]. Connections between Indian monsoon strength and climate fluctuations over the Northern Hemisphere have been shown in paleoclimatological data [Zonneweld et al., 1997]. Because of the instantaneous appearance (on paleoclimatological timescales) of these variations, they are generally attributed to large-scale changes in the atmospheric circulation. This study shows that an active role may be played by the Indian Ocean equatorial regime in the sustenance and change of these global connections in the climate system. An increase in Agulhas leakage to the Southern Atlantic may lead to enhanced meridional overturning and northward heat transport within decades [Weijer et al., 2002]. This lag is too short to enable paleoclimatological data to distinguish between the different causal chains.

By analysis of Topex/Poseidon (T/P) altimeter data (1992–2000) we follow the propagation of the signal generated by the equatorial winds, downstream to the interocean link formed by Agulhas rings drifting into the Atlantic. Patterns of propagating anomalies in the sea surface height measured by the altimeter are extracted using Multi-channel Singular Spectrum Analysis (MSSA) [Plaut and Vautard, 1994]. Selected patterns from the extracted modes of variability are spatially correlated with the original along-track data to avoid smoothing or regularization of the signal by statistical procedures. This allows the full temporal spectrum of the signal to be conserved.

2. The Equatorial Region

The atmospheric circulation over the equatorial Indian Ocean is dominated by the monsoon winds (Figure 1) that force strong semi-annual downwelling equatorial Kelvin waves during the transitions between the monsoons [Wyrtki, 1973]. This enforced oceanic signal is primarily semi-annual, as observed in-situ [Luyten et al., 1980; Schott and McCreary Jr., 2001] and in ocean circulation models [Visbeck and Schott, 1992; Han et al., 1999].

Besides this strong semi-annual component, we found from the altimeter data that sea surface height (SSH) variability in the eastern half of the equatorial basin also has a peak on the double frequency of four per year (Figure 2). This is also supported by tide gauge observations on the Maldives island Gan (73°E, 0°30’S), where in an eight year record of SSH daily SSH measurements obtained from the University of Hawaii, (http://ilikai.soest.hawaii.edu/uhsic/), the first three spectral peaks lie at frequencies of 1, 4 and 2 cycles per year (in order of decreasing power).

The semi-annual and four per year modes of variability are very well reproduced in an MSSA analysis of the equatorial SSH data. A snapshot from the four per year MSSA mode (Figure 3) shows how the Equatorial Kelvin waves that hit the Indonesian coast four times per year split up into north- and southward traveling coastal Kelvin waves, and are partially reflected as an equatorial Rossby wave which has started to propagate westward. Sea level changes associated with this Kelvin wave signal are on the order of 10 cm. We have correlated the eastern part of the snapshot of Figure 3 with the original along-track T/P altimeter data, to obtain a timeseries that shows the occurrence of these coastal Kelvin waves independent of the statistical filtering techniques. The resulting timeseries of the spatial correlation is plotted in Figure 4b. Although this is a rather irregular signal, four Kelvin waves per year...
appear in most years except for the years 1994 and 1997. For 1996/1997 this time series is in good agreement with observed throughflow through Lombok strait [Chong et al., 2000]. The observed zonally averaged wind over the equator between 60–90E (Figure 4a) shows strong semiannual winds. These non-sinusoidal windbursts may lead to four Kelvin waves per year due to the excitation of a four per year equatorial basin mode [Cane and Moore, 1981]. The presence of the Maldives island chain in the middle of the basin may lead to a preference of this mode, which is resonant for the sub-basins east and west of the Maldives. During the anomalous years 1994 and 1997 strong easterlies prevailed over the Indian Ocean equatorial basin, connected to the IOD/ENSO events of those years [Saji et al., 1999; Chambers et al., 1999]. The upwelling Kelvin wave forced by these winds may have interfered destructively with the eastward propagating downwelling Kelvin wave signal.

3. Connection to the South Indian Ocean

Individual Kelvin waves have been observed to travel southward along the Indonesian coast [Sprintall et al., 2000]. Their appearance at frequencies higher than the semi-annual is also supported by throughflow measurements at the Lombok and Sumba passages, and less so further south [Chong et al., 2000]. There, around 10–12°S the Kelvin waves seem to induce Rossby waves at the same

Figure 1. Seasonal cycle of equatorial winds over the Indian Ocean from the NCEP reanalysis data. West of 65E, the circulation is dominated by the annual monsoon cycle. Further east, the semi-annual westerlies are present in April/May and October/November.

Figure 2. SSH variability (over 1995–2000) in (a) the semi-annual and (b) the four per year frequency bands.

Figure 3. Snapshot from the reconstructed component of the dominant four per year MSSA mode. Solid (dashed) lines denote positive (negative) contours. An equatorial Kelvin wave has hit the Indonesian coast, and coastal Kelvin waves propagate poleward. Also, an equatorial Rossby wave leaves in westward direction.

Figure 4. (a) Mean zonal wind along the equator between 60–90 E (m/s). The westerly windbursts occur semi-annually, but are missing in the second half of 1994 and 1997. (b) Spatial correlation between the snapshot of Figure 3 and the original T/P altimeter measurements, showing the occurrence of the coastal Kelvin waves along the coast of Indonesia. (c) Mean SSH anomaly (cm) along the characteristic path of the first baroclinic Rossby wave along 12°S, starting at 115°E. (d) Spatial correlation of a snapshot of the four per year MSSA mode in the Mozambique Channel, showing the generation of a Mozambique Eddy, and the altimeter measurements. A significant (0.35) correlation exists between the generation of the coastal Kelvin waves (b) and this timeseries, at a lag of 1.25 year. This is in agreement with the propagation of Rossby waves across the basin.
90-days periodicity (Figure 5). These observations provide strong evidence for the Kelvin waves to originate in the equatorial Indian Ocean. There may also be some remote influence from the Pacific, as suggested by Potemra [2001]. Rossby waves at (semi-)annual frequencies had already been identified in the southern Indian Ocean [Périgaud and Delecluse, 1992; Morrow and Birol, 1998]. Here we identify for the first time the strong four per year mode. The train of Rossby waves travels westward along 12°S with speeds of ~20 cm/s, in agreement with modern theory for Rossby wave propagation [Killworth et al., 1997]. The mean sea surface height averaged along the characteristic path of the Rossby wave between 120°E and 50°E (the radon transform) (Figure 4c) shows these waves. Average amplitudes here are low compared to the individual waves, due to variable strength of the background South Equatorial Current and the influence of other signals. The forcing time series of the Rossby waves (Figure 4c) is correlated significantly with the arrival of the equatorial Kelvin waves at Indonesia (the maximum correlation of 0.35 is at a lag of 1.25 year). According to theory [Killworth et al., 1997], a first mode baroclinic Rossby wave at 12°S needs 1.1 year to cross the South Indian Ocean. Added to the one month it takes a coastal Kelvin wave to propagate from the equator to 12°S, this explains the observed lag. The Mozambique eddies have been measured hydrographically, and extend over the full depth and width of the channel [De Ruijter et al., 2002]. These eddies, and probably also simultaneously shed eddies from the southern limb of the East Madagascar Current, propagate southward into the Agulhas Retroreflection region where they arrive about a year after their generation, and provide a large disturbance that may cut the retroreflection loop [Schouten et al., 2002]. This results in the shedding of large Agulhas rings that move into the South Atlantic.

5. Discussion and Conclusion

The timeseries plotted in Figure 4 show inter-annual variability in the above described sequence of events. In particular, the strong 1994 IOD/ENSO event clearly resulted in the absence of a Kelvin wave reaching Indonesia in late 1994. At this phase, the IOD is characterized by anomalously strong equatorial easterlies that inhibit the Kelvin wave signal (Figures 4a and 4b). This results in the temporary absence of the Rossby wave trigger to the south and leads to half a year without a Rossby wave along 12°S (Figure 4c) and no Mozambique rings shed between November 1995 and May 1996 (Figure 4d). The same happened in response to the IOD/ENSO in 1997/1998: no Kelvin wave arriving at Indonesia in late 1997 (Figure 4b) and reduced eddy formation in early 1999 (Figure 4d). Subsequently, between January and September 2000 no Agulhas rings were shed into the Atlantic [Quartly and Srokosz, 2002].

By analyzing altimetric data, we have identified a large-scale oceanic teleconnection system, originating in the equatorial Indian Ocean. The signal generated by equatorial wind variations propagates through the Indian Ocean, accelerating eastward or southward as an equatorial or coastal Kelvin wave, picking up energy and amplifying in regions of convergence and high shear zones, eventually influencing the eddy shedding in the Mozambique Channel, and subsequently that from the Agulhas Retroreflection (Figure 5). These Agulhas rings then drift into the Atlantic Ocean and establish part of the conveyor belt connection [Gordon, 1986; De Ruijter et al., 1999] between the Indian and Atlantic Oceans. Weakening or strengthening of the equatorial wind regime might thus result in a decrease or increase of the warm and salty link between the two oceans. Model studies have shown that the meridional overturning circulation of the Atlantic weakens (strengthens) with decreasing (increasing) Agulhas leakage and that the signal takes only several decades to propagate to the polar North Atlantic [Weijer et al., 2002]. In this way, an oceanic teleconnection may exist between the tropical Indian Ocean and the North Atlantic region. This could provide a relatively fast oceanic link between climate variations over the two regions.

4. Mozambique Channel Eddy Formation

The interaction of the Rossby waves with Madagascar leads to the formation of large anticyclonic eddies in the Mozambique Channel at the same 90-day periodicity. The formation of these eddies appears as maxima in the correlation timeseries of the original altimeter data with a snapshot of the 90-days MSSA-mode in the Channel (Figure 4d). This timeseries is significantly correlated to the arrival of the equatorial Kelvin waves at Indonesia (the maximum correlation of 0.35 is at a lag of 1.25 year). According to theory [Killworth et al., 1997], a first mode baroclinic Rossby wave at 12°S needs 1.1 year to cross the South Indian Ocean. Added to the one month it takes a coastal Kelvin wave to propagate from the equator to 12°S, this explains the observed lag. The Mozambique eddies have been measured hydrographically, and extend over the full depth and width of the channel [De Ruijter et al., 2002]. These eddies, and probably also simultaneously shed eddies from the southern limb of the East Madagascar Current, propagate southward into the Agulhas Retroreflection region where they arrive about a year after their generation, and provide a large disturbance that may cut the retroreflection loop [Schouten et al., 2002]. This results in the shedding of large Agulhas rings that move into the South Atlantic.
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