8.2 A STUDY OF THE INDIAN OCEAN DIPOLE MODE DYNAMICS USING SATELLITE OBSERVATIONS AND MICOM SIMULATIONS

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Abstract The Dipole Mode (DM) in the Indian Ocean is a new interannual feature and little exists in the literature detailing its behavior. The intention here is to characterize the oceanic behavior associated with the DM and make comparisons with existing hypotheses of DM evolution. The specific mechanisms involved in the generation and demise of the DM remain the subject of investigation. In this study we will examine and diagnose the thermodynamic oceanic processes associated with the DM cycle using Miami Isopycnal Coordinate Ocean Model (MICOM) and satellite observations.

1. Introduction

The Indian Ocean DM, only recently discovered (Yu and Rienecker, 1999; Saji *et al*., 1999; Webster *et al*., 1999; Murtugudde *et al*., 2000), is understood to be a coupled air-sea interaction within the Indian Ocean. It has been identified in previous years 1961, 1967, 1972, 1982, and 1994 (Saji *et al*., 1999). In fact there has already been some discussion of this Indian Ocean DM in earlier literature based on a large event that occurred in 1961/62 (Kapala *et al*., 1994). It did not attract much attention because the amplitude of typical events are weak. Indeed, there have only been three major events during the past 40 years, during 1961/62, 1993/94 and 1997/98. The two recent events are occurrences coincided with Pacific ENSO events, the first one with weak El Niño and the 97/98 one with a strong El Niño, but the earlier one did not. The fact that some (but not all) of the DM events occur during El Niño years suggests a weak ENSO DM link (Webster *et al*., 1999; Murtugudde *et al*., 2000). A basic description of the DM has already been developed. Initiation involves a change in the surface winds off Sumatra to a southeasterly state which enhances the local upwelling, raises the thermocline, and reduces the SST. Cooler waters in the eastern Indian Ocean gives rise to easterly winds along the equator (these winds are normally westerly) enhancing the cooling in the eastern equatorial Indian Ocean and promoting warming in the western equatorial Indian Ocean. The western warming involves the generation of an Ekman ridge around 10°S which then propagates westward (Webster *et al.,* 1999). Planetary waves appear to play a role in the formation of the DM. Westward propagating Rossby waves contribute to the warming process in the west by suppressing local upwelling (W*ebster et al*., 1999) and upwelling Kelvin waves are speculated to play a role in the initial elevation of the eastern thermocline (Murtugudde *et al*., 2000).

2. Heat transport

2.1 MICOM Simulations

A global version of the MICOM is used in this study. MICOM is a three-dimensional primitive equation global ocean general circulation model (OGCM) with 15-isopycnic layers and a mixed layer on top. A major modification is the implementation of a variable resolution horizontal grid (Figure 1). The grid is designed such that the resolution gradually increases while approaching the East African coast, the Indian subcontinent and the Indonesian Through flow (ITF) region. The grid is generated by conformal mapping the North and South Poles to arbitrary locations on the Earth, in this case to one location near the coast of Africa (5°N, 38°E) and one on an island of Indonesia (0°N, 110°E). The resulting grid will always have enhanced resolution between the new "poles" and is inherently orthogonal. For this application we have chosen a grid which maintains relatively high (20-60 km) resolution in the northern Indian Ocean model domain to represent

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the transport by major current systems, equatorial phenomenon and the ITF. This hybrid mixed isopycnic layer configuration allows for convenient implementation of the entrainment or detrainment process in the mixed-layer that plays an important role in determining the SST. In this study the MICOM has been adapted to simulate the circulation in the Indian Ocean. The model description is given in Manghanani *et al.* (2000). The model was spun up from rest, using climatological forcing from COADS for 6 years, by which time the top seven layers (*i.e.*, a depth of ~ 500m) of the model ocean had reached quasi-steady state. The model was then forced using monthly wind stress, radiation, wind speed, specific humidity and air temperature from the NCEP/NCAR reanalysis for the 20-year period from January 1980 to December 1999. The model latent and sensible heat fluxes were calculated using wind speed dependent heat transfer coefficients. These fluxes are used along with the radiation fields to calculate the net oceanic heat gain. Since most of the variability on seasonal to inter-annual scales is in the top 500 m of the ocean, the model heat content is derived by integrating top seven layers. The monthly heat storage was estimated as the rate of change of heat content using a 2nd order centered time differencing scheme. Finally, the heat storage was subtracted from the model surface heat flux to yield the divergence of upper-ocean heat content.

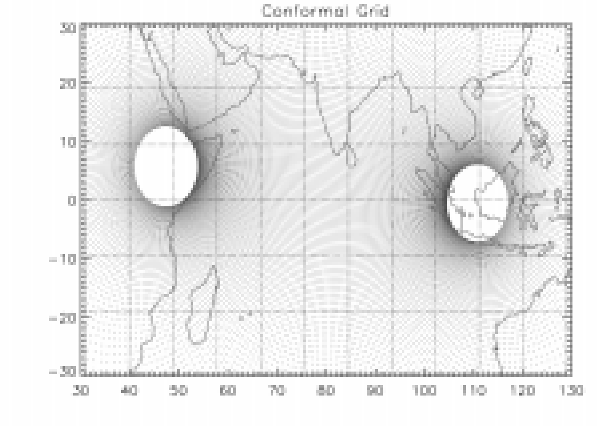

Figure 1. MICOM model grid

2.2. TOPEX/Poseidon altimetry

The sea-level anomalies (SLA) from the T/P altimeter are used to derive the heat transports. Manghanani *et al.* (2000) presented a method for deriving the heat content anomalies of the ocean from the SLA. The monthly heat storage anomalies were estimated using centered time differencing of the heat content anomalies. The value of heat storage thus obtained was subtracted from the net oceanic heat gain to yield an estimate of the oceanic heat divergence.

3. Results

During the 1997/98 El Niño (perhaps the strongest in the modern record) the Indian Ocean experienced a large perturbation from its normal state. The sea level in the eastern equatorial region dropped by 20-30 cm, and the western equatorial region rose a similar amount (Figure 2). This was associated with a reversal of the usual SST gradient, producing abnormally cool water in the east and warm water in the west (Yu and Rienecker, 2000). The Indian Ocean DM is detectable in the T/P SLA's along 4°S (Figure 3) during 1997/98 El Niño. Negative SLA'S eastern basin and positive SLA'S in the in the western basin showed the existence of the DM and its slowly demise during May 1998.

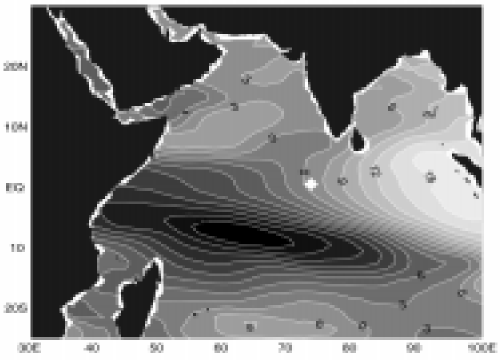

Figure 2. T/P Sea level anomalies (cm) during December, 97.

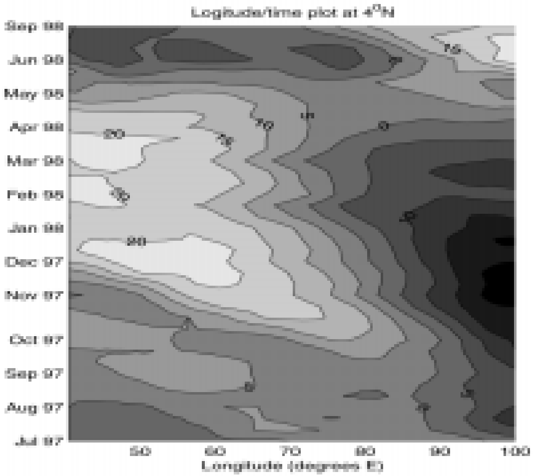

Figure 3. T/P Sea level anomalies (cm) along 4°S.

The dipole structure is an anomalous structure in the equatorial Indian Ocean, wherein warmer than normal waters are found in the western Indian Ocean and cooler than normal water in the eastern equatorial ocean (Webster *et al.,* 1999; Mutturgude *et al.,* 2000; Saji *et al.,* 1999). The DM is significant because it is usually a precursor to heavy rainfall over east Africa and a weak monsoon over the Indian subcontinent. A Dipole Mode Index (DMI) was used by Saji *et al.* (1999) to study the processes associated with this anomalous mode in the equatorial Indian Ocean. The DMI is essentially the difference in average SST anomaly between the west (5° S - 5° N, 55° E - 75° E) and east (10° S - Equator, 85° E - 95° E) in the Equatorial Indian Ocean. Figure 4 shows the DMI derived from the MICOM model simulations. This time series is remarkably similar to the time series shown by Saji *et al.* (1999) which they derived from Reynolds SST. The two main periods when this anomalous dipole is significant in the given time series are in 1994 and 1997. This implies that the anomalous nature of the dipole structure leads to significantly different readjustment processes in the equatorial region than those for non-ENSO years. These readjustment processes were studied by Murtugudde *et al.* (2000), and they found that the processes involved were indeed quite different, and were related to the anomalously strong equatorial easterlies resulting in significant weakening of the fall Wyrtki Jet. This weakening of the Wyrtki Jet results in a shallowing of the thermocline in the eastern Indian Ocean and thereby enhanced anomalous cooling of the region. Further, the strengthened easterlies help generate westward propagating downwelling Rossby waves that aid the anomalous warming of the western Indian Ocean.

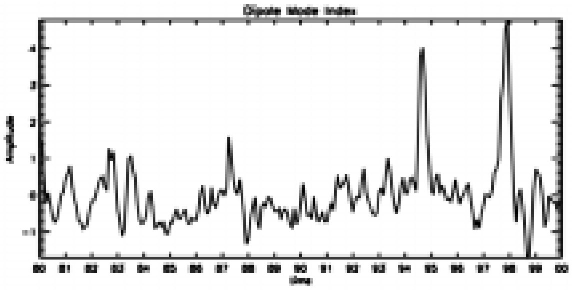

Figure 4. The Dipole Mode Index in the equatorial Indian Ocean.

It is interesting to compare the net oceanic heat stored (Figure 5) and the heat gain (Figure 6) in the Indian Ocean. The net oceanic heat gain shows that in the boreal summer (winter) there is a net heat gain (loss) by the North Indian Ocean (NIO) and heat loss (gain) by the south Indian Ocean. In this paper we showed only for winter (December, 1997) in figures 5 & 6. The distribution is almost zonal with the north and south Indian Ocean being out of phase. On the other hand, the spatial distributions of the heat stored is much more complicated and are not directly explained by net oceanic heat gain. Heat depletion in the NIO occurs in spite of a net oceanic heat gain from the surface. The oceanic surface heat gain in spring and early boreal summer coincides with an increase in heat storage in the NIO; however, as soon as the monsoon winds affect ocean dynamics in the NIO, the ocean looses heat, even while there is surface oceanic heat gain. On the other hand, during December 1997 there is net surface oceanic heat loss in the NIO (Figure 6) and this corresponds to depletion in the local heat stored (Figure 5), but in the later half of the winter, heat is stored in the ocean even as the surface loses heat. In the central Arabian Sea, heat is gained as a result of convergence of the surface waters and downwelling due to the easterly wind stress on the southern side of the Findlater Jet. This leads to a scenario where, during the summer, while there is cooling off the coasts, heat is stored in the central Arabian Sea. This intensified summer time depletion in the Northern Hemisphere occurs at a time when there is an increased heat flux into the ocean from the atmosphere. It is clear from the heat budget calculations that the net oceanic heat gain (even from the MICOM simulations as shown in Figure 7) from the atmosphere plays a secondary role to ocean dynamics in the redistribution of heat content in the Indian Ocean during the DM.

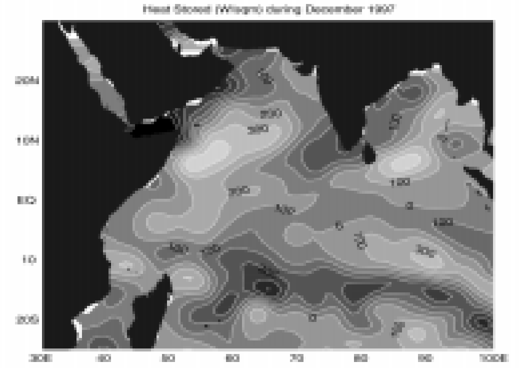

Figure 5. Heat stored (W/sqm) derived from the MICOM simulations during December, 1997.

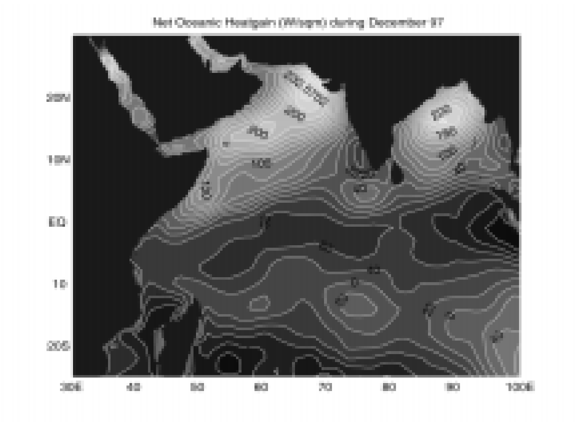

Figure 6. Net oceanic heat gain (W/sqm) derived from the T/P altimetry during December, 1997.

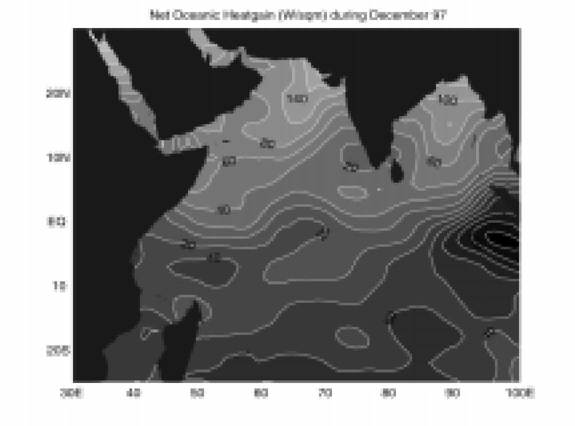

Figure 7. Net oceanic heat gain (W/sqm) derived from the T/P altimetry during December, 1997.

4. Conclusions

The comparison of model output with the altimetry derived heat budget fields demonstrates the potential to study variability of the Indian Ocean DM. The 1997 DM altered the local atmospheric circulation, resulting in changes in regional rainfall, precipitation increased over eastern Africa, and drought conditions ensued over Indonesia. It is important to know that the mechanism(s) triggering the DM and demise of the DM is even less clear. It may be that seasonal increased insolation acting on the relatively thin thermocline in eastern Indian Ocean returns the temperature to a more normal state (*Saji et al.*, 1999). Or, the advent of the winter monsoon may cool the western Indian Ocean through increased evaporation and upwelling (W*ebster et al.*, 1999). A third possibility is that the end of the 1997/98 El Niño relaxed the Indian Ocean winds to a more normal state, generating downwelling Kelvin waves which would lower the thermocline in the east, decrease the upwelling in that region, and increase the ocean temperature (*Webster et al.*, 1999). The relationship between oceanic planetary waves and the DM is suggested, but poorly understood. What is the role of these waves in the initiation, growth, longevity, or demise of the DM? How are they generated? What is their phase relation to the DM? How do they differ from the planetary waves normally occurring during the seasonal cycle or during and ENSO event? Do they behave consistently in every DM event? Are they responsible for the differences in the DM? Are they predictable? These are among the issues to be investigated in future.

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