PROCESS STUDIES IN THE INDIAN OCEAN FROM ALTIMETRY AND MODEL SIMULATIONS

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Abstract

Estimates of the heat budget of the Indian Ocean computed using TOPEX/Poseidon (T/P) Sea Level Anomalies (SLA) and the Miami Isopycnic Coordinate Ocean Model (MICOM) are compared in order to look at the redistribution of heat in the Indian Ocean. The results show that T/P derived heat storage is weaker than that derived from the model but has similar spatial structure and temporal evolution.

Complex Principal Component Analysis (CPCA) shows that there are two main modes of heat content redistribution in the Indian Ocean. The most dominant mode has an annual signal peaking in the boreal summer, and depicts the response to strong southwest monsoon winds. This involves offshore propagation of heat in the north Indian Ocean and southward propagation of heat across the equator.

The other main mode of heat content redistribution in the Indian Ocean results from westward propagating equatorial Rossby waves. This process is prominent in the boreal fall to spring, and represents the dynamic readjustment of the Indian Ocean to near-equatorial wind forcing. This mode indirectly relates to the Dipole Mode Index (DMI) in the Indian Ocean. The minima of this time series coincide with the occurrence of the anomalous dipole structure in the equatorial Indian Ocean.

Heat transports calculated from altimetry

The 10-day repeat T/P altimeter data used in this study span 1993 - 1997 in the Indian Ocean between 30-140° E and 30S - 30°N. Chambers *et al.* (1997) present a method for deriving the heat content anomalies of the ocean from the SLA. This method assumes a linear relationship between the heat content anomalies and the SLA's. To the first order, a temperature change in the water column will cause a change in density according to,

$$\Delta\rho=\rho\alpha\Delta T_a \qquad (1)$$

where ρ is the density, is the thermal expansion coefficient of seawater and is strongly dependent on the temperature (T_a) and pressure level of the water parcel. A change in density due to heating will cause a change in sea level, Δ η as

$$\Delta r=\frac{-r\Delta h}{h+\Delta h}=\frac{-r\Delta h}{h} \qquad (2)$$

assuming Δ η is much smaller than *h* (the sea level height). This is true, since the change in sea level is only a few centimeters, while the depth of the upper mixed layer is of the order of tens or hundreds of meters. Therefore a change in heat content (ΔH) can be related to a change in sea level through the above equations as,

$$\Delta H=\frac{rc_p}{a}\Delta h \qquad (3)$$

where c_p is the specific heat at constant pressure. Thus we can relate thermal sea level changes from mean sea level to heat storage anomalies via the coefficients α, ρ and c_p. These coefficients are estimated from monthly mean climatological data (NCEP) and an equation of state (*e.g. Gill, 1982, Table A.3.1*). The sea level change due to heating can be approximated from the sea level anomaly measured by the TOPEX altimeter as,

$$\Delta h=\Delta h^{TOPEX}+\epsilon \qquad (4)$$

where ε is the error introduced by neglecting salinity and barotropic effects, as well as errors in altimetric measurement.

The other issue involving the use of (3) is the accuracy of the coefficients α, ρ, and c_p. Over most of the ocean, and c_p change by less than 1%, therefore assuming that they are constant introduces little relative error. α is a function of pressure level and temperature so the error in is more at higher latitudes than in the tropics. For this study, surface values, based on monthly and annual mean temperature data, will be used for the thermal expansion coefficient. Subsurface temperature data to a depth of 400m were obtained from Levitus climatology.

Monthly surface flux data for net radiation (R_{sfc}) for 1993-1996 were obtained from NCEP re-analysis. The latent heat flux (LHF) and sensible heat flux (SHF) for 1993-1995 were derived from the model simulations. These data were used to calculate the net oceanic heat gain (Q_{sfc}) from the atmosphere, using the relation

$$Q_{sfc}=R_{sfc}-LHF-SHF \qquad (5)$$

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.

Heat Content from Model Simulations

A global version of the Miami Isopycnic Coordinate Ocean Model (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. The uppermost layer in MICOM is an explicit, Kraus and Turner mixed layer. A major modification is the implementation of a variable resolution horizontal grid (Figure 1).

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 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 (*Xie et al., 2000; Liu et al., 1979*). These fluxes along with the radiation fields to calculate the net oceanic heat gain using equation (5).

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 the top seven layers. The monthly heat storage was estimated as the rate of change of heat content using a 2nd order centered time difference scheme. Finally, the heat storage was subtracted from the model surface heat flux to yield the divergence of upper-ocean heat content. T/P and model derived heat transports are shown in figures 2-8.

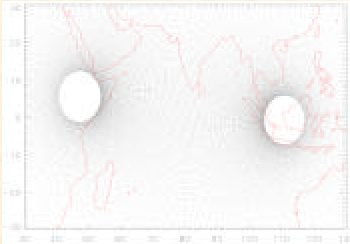

Figure 1. The model horizontal grid.

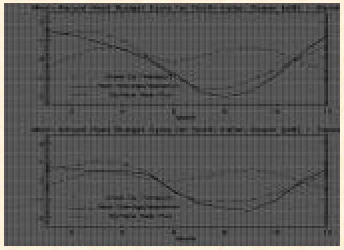

Figure 2. The mean annual cycle of the heat budget terms in the North Indian Ocean.

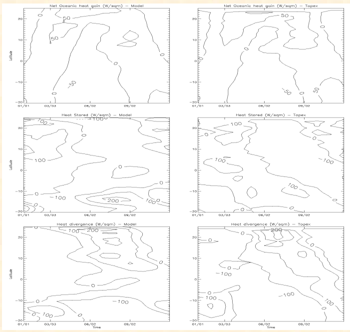

Figure 3. Latitudinal and annual variation of oceanic heat budget components for the Indian Ocean in Wm-2 . Net Ocean Heat Gain –model simulation and T/P derived (Top panel); Heat Storage - model derived and T/P derived (middle panel); Heat Divergence –model derived and T/P derived (bottom panel).

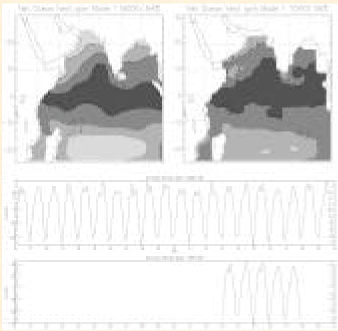

Figure 5. The first mode PCA of net oceanic heat accounts for 64% and 56% of the variance for the fields associated with the Model and T/P respectively. Spatial structure of Model and T/P derived fields (top panel) and amplitude time series (bottom panel).

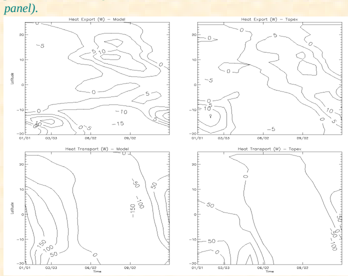

Figure 4 The seasonal and meridional variation of heat export and heat transport (10^{13} W). Heat Export– model simulation and T/P derived (top panel); Heat Transport –model derived and T/P derived (bottom panel)

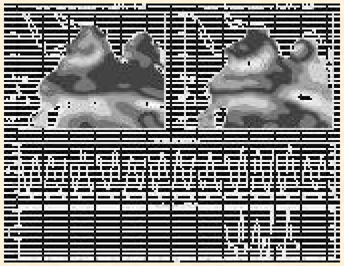

Figure 6. The first mode PCA of oceanic heat stored derived from model and T/P data. Spatial structure of Model and T/P derived fields (top panel) and amplitude time series (bottom panel).

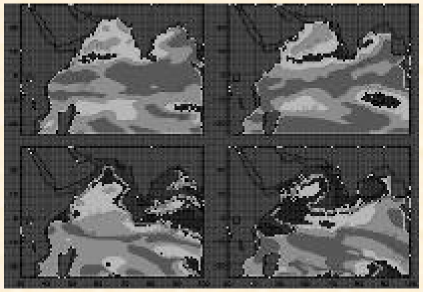

Figure 7. The spatial distribution of first mode CPCA of oceanic heat divergence for model and T/P derived data. This mode accounts for 34% and 27% of the variance for the fields associated with the model and T/P SLA, respectively. Spatial structure of Model and T/P SLA derived amplitude fields (top panel) and phase fields (bottom panel).

Figure 8. Amplitude and phase time series of the first mode CPCA of oceanic heat divergence for model and T/P derived data. Amplitude of model and T/P SLA (Top panel), and the phase of the model and T/P SLA fields (bottom panel).

Indian Ocean Dipole Mode

Recent studies using historical data analysis, new observations and modeling, have focused on interannual variability in the monsoon circulation, noting the existence prominent ocean-atmosphere events in the Indian Ocean region. One such event was happened in 1993/94. It consisted of the anomalously low eastward surface currents along the equator in spring 1994 (Vinaychandran *et al.*, 1999) and causing anomalously cool surface waters and low sea level in the east, and increased throughflow from Pacific (Potemra *et al.*, 1997). The strong event of 1997/98 was marked by easterlies on the equator and the cold wedge in the east, similar to the equatorial upwelling regimes of the other oceans, suggesting a possible mode of ocean-atmosphere interaction local to the Indian Ocean (Webster et al., 1999; Saji et al., 1999; Murtugudde et al., 2000). An interpretation of the coupled event in terms of Indian Ocean internal dynamics was given in Webster et al., (1999) described in the schematic representation (Figure. 9). This 1997/98 Dipole Mode is clear in the T/P altimetric observations (Figure 10) and in the Dipole Mode Index derived from the SST field in MICOM (Figure 11).

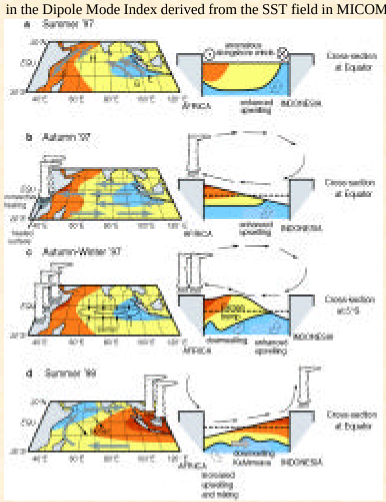

Figure 9 The development of the Indian Ocean Mode according to Webster et al., 1999 (their Fig. 4 see text for details).

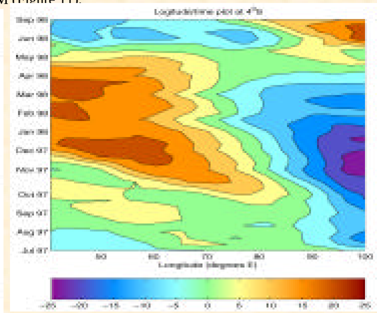

Figure 10. Indian Ocean Dipole Mode during 1997/98 El Niño from T/P altimetry.

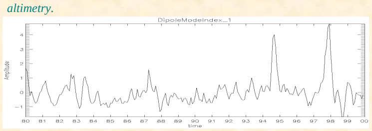

Figure11. The Dipole Mode Index for the variability in the equatorial Indian Ocean. The Index is estimated from the SST fields in the MICOM model simulations. It is the difference between the average temperature anomaly between the west (5° S-5° N, 55° E-75° E) and east (10° S - Equator, 85°E - 95° E) in the Equatorial Indian Ocean.

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