ABSTRACT-A reduced gravity, primitive equation, sigma coordinate OGCM coupled to an advective atmospheric mixed layer is employed to study the period of 1980-1995. The spin up with climatological winds produces the seasonal dynamics and thermodynamics of the tropical Indian Ocean that are in excellent agreement with observations and other model results. Model experiments clearly demonstrate that the wind forcing plays a large role in determining interannual SST anomalies (SSTA) in the tropical Indian Ocean. However, lack of solar radiation and cloudiness data are shown to be a major handicap in reproducing observed SSTA. ENSO related equatorial winds drive SSTA south of the equator along the coast of Sumatra. Ekman pumping in the western STIO (Southern Tropical Indian Ocean) where the thermocline is close to the surface leads to SSTA of opposite sign. A significant correlation is found between the SST gradient along about 10°S and the strength of the Somali Jet. A joint EOF analyses of COADS data was carried out to determine whether SSTs are passive or if they could feedback onto wind variations. Composites of strong and weak monsoons seem to indicate that winds drive SST variability with little evidence of an active role for Indian Ocean SSTs in driving monsoons at interannual time-scales. The observed wind variability in the tropical Indian Ocean appears to be primarily driven by monsoon precipitation variability.

2. INTRODUCTION- The role of the Indian Ocean SST in the interannual variability of the summer monsoon over India has been explored before but no definitive causal or mechanistic relation has been established. The results of previous studies are rather contradictory and no clear picture exists for the relation between Indian Ocean air-sea interaction and Indian summer monsoon variability. Recent analyses by Goswami et al. (1997) with their broad scale circulation index for the interannual variability of the Indian summer monsoon (EIMR: Extended Indian Monsoon Rainfall) shows that for 1989-1994 period, the largest correlations between SST and EIMR is in the southern tropical Indian Ocean (STIO). Our OGCM studies had previously pointed to the fact that the thermocline in the western STIO is close to the surface due to Ekman pumping and along the same latitude in the eastern STIO, the thermocline is deeper (Murtugudde and Busalacchi 1998). Based on model simulations and analyses of observational sea level and SST, we have also demonstrated previously that the thermocline along 10S experiences a wind-driven quasi-biennial oscillation. As expected at these latitudes, the thermocline variations have a large-scale surface expression which is seen as a quasi-biennial oscillation in sea-level and SST between the western and eastern STIO. The OGCM is coupled to an advective atmospheric mixed layer model (AML) in order to compute the thermodynamic response of the lowest layer of the atmosphere and allow SST evolution without any feedbacks to observed quantities (Murtugudde et al. 1996). A joint EOF analyses of COADS winds and SST together with monsoon rainfall is also carried out to investigate whether SST variations drive wind and hence, monsoon variations or the other way around. to demonstrate that the SSTA do not seem to have a significant role in determining monsoon variability.

2. RESULTS- A simple representation of the Indonesian throughflow (ITF) is included in the model by treating the eastern boundary between Australia and Indonesia as a sponge layer. The climatological cycle of the ITF is in remarkable agreement with global OGCM simulations and estimates based on observations. The annual mean differences between model and Reynolds SST are typically of order 1°C or less. Model results reproduce the reversal of the surface and subsurface flows with core velocities which are comparable to observations. The seasonal cycle of heat budget in
the Arabian Sea shows that the entrainment cooling is maximum in May due to shallow mixed layer during the transition from northeast to southwest monsoon. The meridional advection brings cold water into the Arabian Sea from the upwelling region off Somalia in August. As expected, the entrainment cooling to be important in western STIO since the thermocline is close to the surface. Despite the nearly identical seasonal variation of SST and MLD in the eastern and western STIO, the interannual anomalies are typically out of phase in the two regions.

The initial conditions for the interannual simulations are provided by the climatological spin up. The control run was forced with the FSU winds for the period of 1980-1995 with the wind-speeds for latent heat loss computed from the wind-stresses. We employed climatological solar radiation (ERBE) and cloudiness (ISCCP) data due to a lack of reliable data for the entire period of simulation. This is our control run. The ISCCP climatology can be larger than ERBE by as much as 20 W/m² resulting in SST that are warmer by up to 0.5°C. It is thus evident that the differences among satellite products for radiation themselves can introduce SST errors that are as large as observed SST. A simulation was carried out with interannual wind stresses and climatological radiation and cloudiness as in the control run except that the wind-speeds in computing the latent heat losses are held to their climatological values (EXPLH). This removes the interannual variability of the latent heat loss and allows only the wind driven variability. Another experiment, EXPCI is conducted by holding the wind stresses to their climatological values while the wind speeds for computing latent heat losses were allowed to vary interannually. When the wind-stresses are held to their climatological monthly mean values, the variability of SST is reduced over the entire basin, especially in the Somali Current region. Thus a large part of the SST variability in the model is due to wind-stress forcing. The results for EXPLH where interannual variability of wind-speeds was eliminated in the latent heating, show a reduction in SST variability in the Arabian Sea and the Bay of Bengal in addition to the Somali Current region. The thermocline variability in the STIO remains nearly unchanged since it is mainly determined by the wind-forced model dynamics. Thus the SST and thermocline anomalies along the Somali coast, in the Arabian Sea and the Bay of Bengal depend both on wind-stresses and surface heat fluxes.

The anomalies of SST and depth of 20°C isotherm (D20) are highly correlated in the eastern Indian Ocean along the coast of Sumatra. Most of the significant SSTA in the eastern STIO are typically associated with SSTA of the opposite sign in the western STIO. The anomalous SST, sea level and D20 are shown in Fig. 1 for eastern and western STIO (88°E-72°E and 98°E-102°E over 2°S-6°S). Note the quasi-biennial nature of all the quantities and the generally out of phase relation between the eastern and western STIO. Since the STIO supplies a significant fraction of the moisture for the Indian Summer monsoon (Reverdin et al. 1986), the interannual variability of the winds over this region must have some bearing on the interannual variability of the Indian summer monsoon. The zonal wind-stress anomaly over 78°E-88°E × 2°S-2°N has a correlation of 0.69 with the SOI over 1980-1995 (see Fig. 2). The region of high correlation between SST and D20 anomalies off Sumatra is driven by these wind-stress anomalies. The SST gradient between eastern and western STIO has a correlation of -0.88 with the zonal wind-stress anomalies above with a lag of about one month. This SST gradient change in the STIO leads the Somali Jet (averaged zonal wind stress over 50°E-70°E × 5°N-15°N) by two months with a correlation of -0.34. The correlation between the SST gradient and the Somali Jet is rather low over this short period. Hence a joint EOF analysis was carried out with the COADS data to see if air-sea interaction plays an active role in determining wind variability over the tropical Indian Ocean.

The analyses of COADS (1950-1987) can be briefly summarized as follows. Joint EOFs of SST, and zonal and meridional surface winds show that the first joint EOF (12.1 %) is ENSO related, the third EOF (8.2 %) represents the biennial mode and the second EOF (9.9 %) has contributions from both ENSO and the biennial modes (Fig. 3). A characteristic feature of SST patterns associated with both ENSO and the QBO mode is an east west dipole similar to the one seen in OGCM simulations. Zonal winds (UEQ) averaged over 70°E-110°E × 10°S-Eq have a correlation of -0.71 with SST gradient defined as SSTD=SSTA ave (50°E-80°E,20°S-5°S)-SSTA ave (85°E-120°E,10°S-Eq). An index of the Somali Jet, USOM = unamov ave (50°E-80°E,5°N-15°N), has a correlation of -0.53 with SSTD defined above. These observed relations between the east-west SST gradient and the winds over the equatorial Indian Ocean and the Somali region are well simulated by the OGCM. Composites were computed from 12 months before to 12 months after strong and weak monsoons. The differences between these composites for zonal wind and SSTA are shown in Fig. 4. Among the
Figure 1. Anomalies of SST (top), sea level (middle) and thermocline depth for the western (solid) and eastern STIO (dashed). Note the quasi-biennial nature of the variability in the STIO and the out of phase variation between the easter and western STIO.

Figure 2. Top: Zonal wind-stress anomalies over 78°E-88°E x 2°S-2°N are correlated with the SOI. Middle: These wind-stress anomalies lead to SST gradient changes in the STIO with a lag of about 1 month. Bottom: The SST gradient changes in the STIO are correlated with the Somali Jet with a lead of about two months. See text for definitions of SST gradient and Somali Jet.
many interesting features such as eastward propagation of anomalies, the most notable feature is that wind anomalies lead SST anomalies by nearly a month. This seems to indicate that the SST variability is forced by winds and there is no feedback from SST anomalies to wind anomalies.

It is obviously important to understand the origin of the wind anomalies. For this, precipitation (P) data is needed over the tropical Indian Ocean. Due to a lack of long time-series for P, we used the Xie and Arkin (1996) precipitation analysis over 1979-1995 to compute differences in P between strong (1983 and 1994) and weak monsoons (1982 and 1989). This P was used along with observed SST differences in a series of experiments with a linear atmospheric model (Saji and Goswami 1996) to separate the wind response to forcing due to P and SST differences between strong and weak monsoons. The results show that the wind response to SST differences is about 1/3 of that due to precipitation differences. Even though this is a short (16 years) experiment, it supports the conclusion above, i.e., SST anomalies associated with the strong and weak monsoons cannot by themselves explain the accompanying wind changes.

3. Summary- A reduced gravity, primitive equation, sigma coordinate OGCM coupled to an advective atmospheric mixed layer model is used to study the seasonal and interannual air-sea interactions in the tropical Indian Ocean. The biggest drawback for the interannual simulations is the lack of solar radiation and cloudiness data. Our sensitivity experiment with climatological wind-stresses but interannual wind-speeds in the computation of latent heat fluxes show a noticeable reduction in standard deviation of the SSTA over much of the basin. The parallel experiment with climatological wind-speeds, but interannual wind-stresses demonstrates that the variability of SSTA in the Arabian Sea, the Somali Current and the STIO depend on surface heat fluxes as well as wind forcing.

Interannual sea level anomalies of over 10 cm and SSTA of over 1°C are caused by changes in wind-stress curl in the western STIO where the thermocline is close to the surface. Interannual SSTA in the western and eastern STIO tend to be of opposite sign. The zonal wind stresses along the equator between about 80°E-90°E are correlated with the SOI and these winds drive thermocline
and SST variations off Sumatra through coastal wave dynamics. The SSTA in the western STIO where the thermocline is close to the surface are typically opposite in sign to those in the eastern STIO. The resultant change in SST gradient across the basin is correlated with the Somali Jet which in turn is highly correlated with the rainfall over India. This connection between the SOI and the Indian monsoon through the STIO was further investigated with COADS data and a linear atmospheric model. The results seem to indicate that SSTA are generated by wind forcing but there is no feedback from SSTA to wind anomalies. A composite analyses showed that precipitation changes associated with strong and weak monsoons can explain 2/3 of the wind response.

REFERENCES


