

Mechanisms for the Indian Ocean warming during the 1997-98 El Niño

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Abstract. This study examines primary mechanisms that gave rise to the basin-wide variations of the sea surface temperature (SST) in the Indian Ocean during the 1997-98 El Niño by using multi-source data sets. The evolution of some key atmosphere-ocean variables indicated that the SST variability in the Indian Ocean was largely attributable to the ENSO impact on the large-scale atmospheric circulation. During June-December 1997, when the El Niño in the Pacific was maturing, the Indian Ocean experienced the reversal of the Walker Circulation and the prolonged equatorward displacement of the southeast trades. The resultant changes in surface wind influenced the SST through the following means. In the equatorial region, the easterly winds associated with the reversed Walker Circulation forced equatorial Kelvin/Rossby waves, which then affected the equatorial ocean heat balance (mainly through upwelling/downwelling) and led to the reversal of the zonal SST gradient in the fall of 1997. The negative SST anomalies in the east and positive anomalies in the west in turn helped maintain and prolong the equatorial easterlies, a clear indication of coupled atmosphere-ocean interactions in operation. Outside of the equatorial waveguide, changes of latent heat flux induced by wind speed variations played a major role in the broad-scale warming. The effect was most significant during the summer/fall of 1997 when the southeasterly trade winds weakened considerably, leading to a dramatic reduction of latent heat release and subsequently a rapid surface warming in the southern ocean.

1. Introduction

Several statistical studies have indicated that the dominant mode of interannual variability in the Indian Ocean is closely related to ENSO [Cadet 1985; Nigam and Shen 1993; Tourre and White 1995; Nicholson 1997; Chambers and Tapley 1998]. Such a relationship was best displayed during 1997-98 when the greatest El Niño event of the century took place in the Pacific and a record-breaking basin-scale warming occurred in the Indian Ocean [e.g. Webster *et al.* 1999]. Thanks to the expanded satellite and in situ observing capability and the improved quality of model re-analyses, a more detailed examination and advanced understanding of the physical mechanisms that govern the Indo-Pacific interaction can be made. In this study we present an analysis of multi-source data sets to delineate key processes that were responsible for the Indian Ocean warming during the evolution of the 1997-98 El Niño event. The data used

in the study include the SST from the NCEP objective analyses [Reynolds and Smith 1995], sea surface height (SSH) from the TOPEX/Poseidon altimeter, surface wind derived from the FSU pseudo-stress analyses, and the diagnosed heat fluxes from the reanalyses of National Center for Environmental Prediction (NCEP).

2. Variability of surface fields in the Indian Ocean during 1997-98

The Indian Ocean north of 10°S is influenced by the semi-annually reversing Indian Monsoon, while the southern ocean is dominated by the southeast trade winds all year round. It is known that the ENSO-related changes in the atmospheric circulation over the Indian Ocean is primarily related to the large-scale climate fluctuations of the Southern Oscillation, a seesaw in sea level pressures between the southeast Pacific and north Australia-Indonesian regions [Bjerknes 1969; Rasmusson and Wallace 1982]. During an El Niño, the Walker Circulation reverses in both the Pacific and Indian Oceans [e.g., Webster *et al.* 1999]. This is clearly illustrated in Figure 1a: easterly anomalies started to develop along the equator in early June 1997, about three months after the onset of the 1997-98 El Niño event [Climate Diagnostic Bulletin 1997; Yu and Rienecker 1998]. When the El Niño condition was maturing in the Pacific during the summer/fall of 1997, easterly wind anomalies strengthened significantly. Meanwhile, intense and localized negative SST anomalies (<-2°C) (Figure 1b), accompanied by a drop of the sea level of about 30cm (Figures 1c,d), appeared in the eastern basin. These anomalies were of sufficient magnitude to reverse the climatological east-west SST gradient in the equatorial region (Figures 2a,b). As easterly anomalies weakened rapidly with the decay of the El Niño since late December 1997, the abnormal warming extended to the entire basin, with the maximum SST anomalies reaching more than 2°C in the west.

While the evolution of the atmosphere-ocean system in the equatorial Indian Ocean mirror-imaged the El Niño condition in the equatorial Pacific, the changes in the extratropics were more complicated. These changes also took place mostly from June 1997 to May 1998. Our analyses in the following will be focused on this period. To characterize the basin-scale variations, we show in Figures 2a&c the monthly-averaged SST and surface wind fields in July, November 1997 and March 1998. For a better comparison, the corresponding climatological states for these three months are also presented (Figures 2b,d). The most dramatic change in SST appeared in the fall of 1997 when the zonal gradient of the equatorial SST was reversed completely. During this time, the climatological westerly wind along the equator was replaced by an easterly wind in association with the reversal of the Walker Circulation and the

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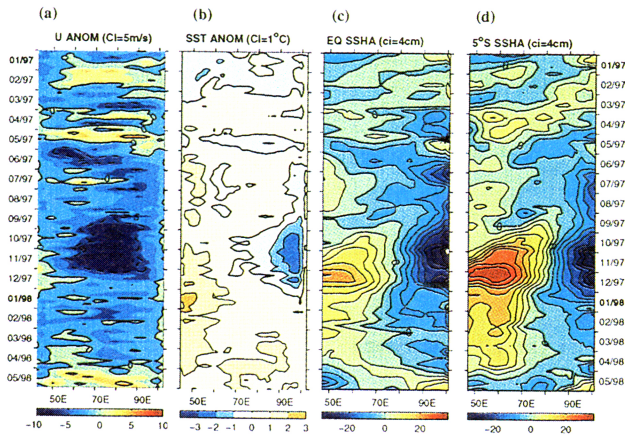


Figure 1. Time-longitude sections (an average over 2°S - 2°N) of anomalous (a) zonal winds (5-day means) from NCEP reanalyses and (b) weekly-mean SST from Reynolds analyses; and time-longitude sections of anomalous SSH from TOPEX/Poseidon altimeter (10-day average) along (c) the equator and (d) 5°S. In this and the following figures, the anomalies are all derived from the 1981-96 base period monthly means except the SSH anomalies which are deviations from the 1993-96 base period monthly means.

prolonged equatorward displacement of the southeast trades. The winds in the equatorial region had basically resumed their climatological state as of March 1998, but the SST in the whole basin was still anomalously high.

The atmospheric circulation in the tropics is thermally driven: air converges to warm areas where convection takes place. The warmest water in the Indian Ocean is typically located in the equatorial and northern regions (Figure 2b). During the boreal spring of 1997, the transition period to the southwest monsoon, the SST was abnormally warmer in these areas (not shown). The anomalous sea surface heating drove a greater convergence of surface winds toward these hot spots. As a result, the cross-equatorial wind components were enhanced, leading to intensified southwesterlies in the Arabian Sea during July-September 1997 (Figure 3). Meanwhile, the southeast trades, which were undergoing seasonal equatorward migration, were displaced even closer to the equator than normal. This movement, along

with the reversed Walker Circulation, produced strong easterly anomalies in the equatorial region. During the boreal fall of 1997, the transition period to the northeast monsoon, the anomalous equatorial easterlies were considerably intensified largely due to the enhancement of high sea-level pressures over the Pacific Maritime associated with the maturing of the El Niño in the Pacific [*Climate Diagnostic Bulletin* 1997]. The zonal gradient of SST in the equatorial Indian Ocean further helped maintain the equatorial easterlies (Figure 4a). In fact, the southeast trades remained near the equator in November 1997 and did not proceed on their seasonal retreat. At the same time, the associated southeasterlies in the broad southern basin (south of 10°S) were significantly weakened (Figure 3). The alteration in the surface wind fields, as will be shown in the following, influenced both oceanic dynamical processes and the latent heat flux.

3. Causes of the broad-scale surface warming

As in the Pacific, the changes in the equatorial zonal winds in the Indian Ocean have a profound impact on the equatorial ocean circulation and eventually on the SST itself [*Cane and Sarachik* 1979]. The study by *Webster et al.* [1999] suggests the existence of strong coupled atmosphere-ocean interactions in the equatorial Indian Ocean that are potentially unstable, involving positive feedbacks between the two systems in a manner similar to the El Niño of the equatorial Pacific Ocean. This can be seen from Figures 1, 3 and 4. The easterly anomalies in June-December 1997 forced upwelling Kelvin waves and downwelling Rossby waves in the equatorial waveguide. Kelvin waves can cross the whole equatorial Indian basin in about a month while Rossby waves take about three months. Eastward propagation of free Kelvin waves (Figure 1c) and westward propagation of the first baroclinic Rossby waves (Figure 1d) were observed before the period between. During July-December 1997, when persistent, strong easterly wind forcing prevailed, the waves were no longer free but were coupled atmosphere-ocean waves, migrating westward in response to the westward extension and amplification of the easterly wind anomalies (Figure 1a).

The upwelling in the eastern basin lifted the thermocline, brought the colder deep water into the surface and depressed the sea level. Downwelling in the west had the opposite effect on the thermocline. The corresponding set-up of the thermocline is evident in the reversed equatorial SSH gradient: the sea level tilted toward the west and, in late 1997,

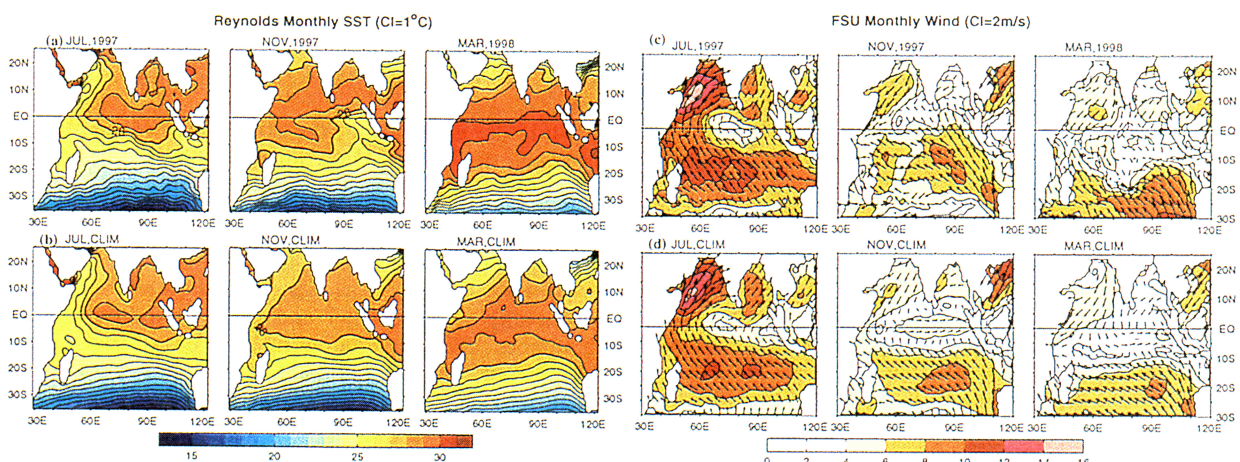


Figure 2. Monthly mean conditions in July, November and March. (a) SST during 1997-98; (b) climatological SST; (c) FSU wind during 1997-98; and (d) FSU climatological wind. Wind speeds are shaded.

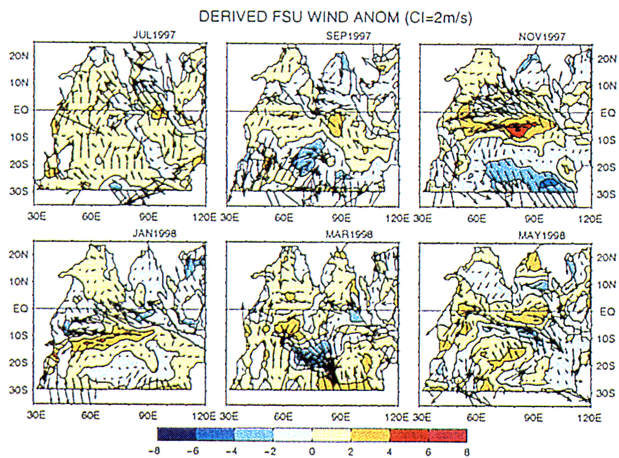


Figure 3. Monthly-mean wind anomalies during 1997-98. Wind speed anomalies are superimposed.

the SSH dropped as much as 30 cm in the eastern equatorial region and rose more than 20 cm in the western basin. The negative SST anomalies associated with the shallowed thermocline (negative SSH anomalies) in the eastern basin are clearly shown (Figures 1,4). However, the effects of upwelling and downwelling on the SST are not symmetrical. Upwelling brings cooler water to the surface and directly lowers the SST. Downwelling converges warm surface water, pumps it into the ocean interior, but does not necessarily increase the SST. Figures 4a-b show that the deepened thermocline coincided with the general warming of the sea surface, but the locations of maximum SST anomalies were not correlated well with those of maximum SSH anomalies. For example, the large SSH changes induced by the equatorial Rossby waves were centered at about 5° in latitude in both hemispheres, roughly symmetric about the equator. However, the warm SST anomalies in the southern ocean extended across the basin in a banded structure, aligned away from the equatorial waveguide, and the evolution of the SST anomalies was distinctly different from that of SSH. Webster *et al.* [1999] argue that the SSH anomaly south of the equator was associated with anomalous Ekman convergence.

The SST and SSH anomalies were less correlated outside of the equatorial waveguide. As is known, direct air-sea heat fluxes are also a major factor in causing SST changes. Their influence is more significant in extratropical regions and off coasts where ocean dynamics are less dominant [Liu *et al.* 1994; Gautier *et al.* 1998; Yang *et al.* 1998]. To examine this mechanism, we first plot in Figure 5a the anomalous SST monthly tendency (defined as the differences between the first-week SST anomalies of two consecutive months). Two features stand out. First, positive SST tendency did not occur uniformly in space (Figure 5a). Instead, warming in one area was often accompanied by cooling in some other areas. However, warming clearly dominated cooling over the whole period. Second, the most intensive warming was located in the Southern Ocean in 1997 but shifted to the eastern and central equatorial region in the first few months of 1998. Therefore, by March 1998, nearly the entire Indian Ocean was considerably warmer than its climatological condition. The heat fluxes used in the study are diagnosed from the output of NCEP reanalyses. Examination of all four flux components (latent, solar, longwave and sensible) shows that variations of the total heat flux during this period were dominated by the latent heat flux since anomalies for the other components were generally less than 20 W/m^2 . Quite remarkably, the variations of latent flux (Figure 5b) corresponded well with the month-to-month SST tendency. For example, the broad-scale warming in the southern basin in the fall of 1997 occurred when the latent heat release was considerably reduced in that area. The high correlation be-

tween the SST tendency and the changes of latent flux in most areas indicates the latent flux is the leading cause of the extratropical warming.

Since the NCEP heat fluxes are derived from the reanalyses of a model which itself is forced by the observed SST, one might wonder whether the latent heat flux anomalies from NCEP are the direct response to the SST anomalies. This is not the case because higher (lower) SST would lead to a greater (weaker) latent heat release if other physical parameters are kept unchanged. Here exactly the opposite occurred – the SST was higher due to the weaker latent heat release. In other words, *the latent flux drove the SST tendency*. Our analyses show that the changes of latent flux were primarily controlled by the changes of surface wind speed. The surface wind fields of 1997-98 from the NCEP reanalyses are found to be consistent with those from the FSU analyses of ship observations (not shown). A comparison of the latent flux variability (Figure 5b) with that of the FSU winds (Figure 3) shows that, on the broad scale, stronger (weaker) wind speed was mostly coincident with greater (weaker) latent heat release. The most notable discrepancy appeared in the southern Indian Ocean in January 1998. The band of positive heat flux anomaly extending across the basin seems to be directly related to the strong positive SST anomaly. The average pattern correlation between the anomalous latent heat flux and the anomalous SST tendency for the regions outside of the equatorial waveguide ($10^\circ\text{S} - 10^\circ\text{N}$) and away from the coasts is 0.503 and is statistically significant at the 95% confidence level. Obviously, the broad-scale warming in the extratropical Indian Ocean was due primarily to the variations of latent flux, and ultimately to the changes of wind speed.

The large-scale variations in the surface wind were induced by ENSO. During June-December 1997, the southeast trades were displaced abnormally nearer to the equator and their northern edge actually crossed the equator into the northern hemisphere in November (Figure 2c). This movement increased the wind speed in the equatorial region and reduced the wind speed over the vast area south of 10°S . Meanwhile, the southwest monsoonal winds were abnormally stronger in the west of Arabian Sea and yet weaker in the Bay of Bengal. Such variations of wind speed enhanced the latent heat release in areas along the equator and off the African coast but reduced it elsewhere. The effect was particularly dramatic in the southern Indian Ocean where winds were significantly weaker. This explains why there was a rapid warming in the southern basin during September-December 1997 (Figure 5a). Starting from January 1998,

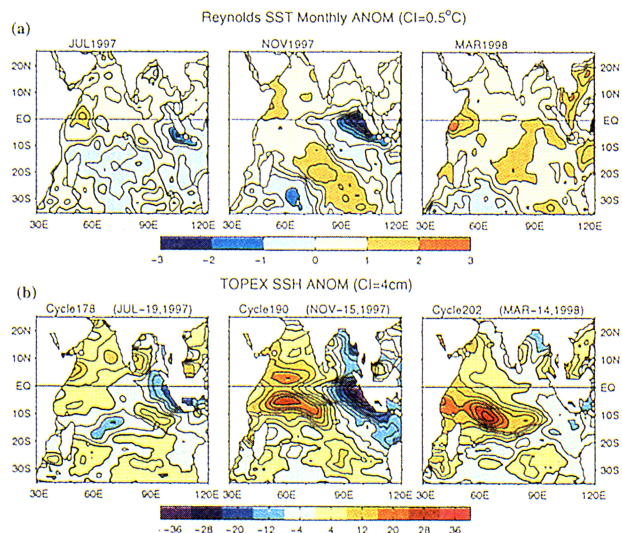


Figure 4. (a) Monthly-mean SST anomalies, and (b) 10-day-mean SSH anomalies in July, November 1997 and March 1998.

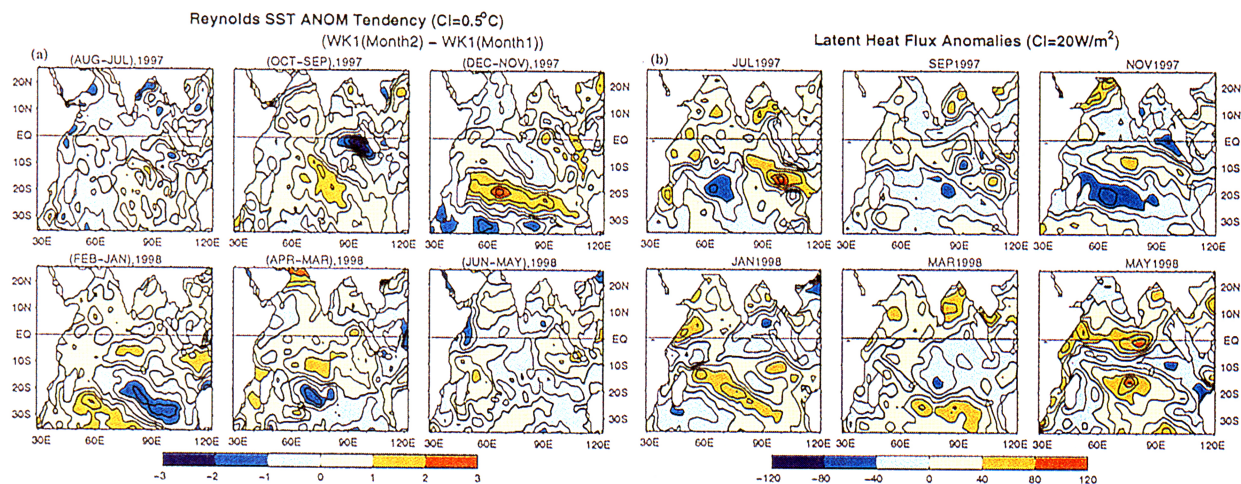


Figure 5. (a) Monthly tendency of SST anomalies, and (b) monthly-mean latent heat flux anomalies diagnosed from the NCEP reanalyses, where the positive (negative) sign denotes more (less) latent heat release from the sea surface.

the equatorial easterly anomalies associated with the reversal of the Walker Circulation weakened as El Niño waned. This reduced the upwelling in the eastern Indian Ocean and helped warm up the sea surface there. The remnant easterly anomalies counteracted the climatological equatorial westerly components, reducing the total wind speed and consequently the latent heat release in the region. The diminished upwelling and reduced latent heat release all contributed to the surface warming in the central and eastern equatorial regions, resulting in anomalously high SSTs in the entire Indian Ocean in 1998.

4. Summary and Discussion

Our analyses indicate that the SST variability in the Indian Ocean during the 1997-98 El Niño was mainly attributable to two key processes: coupled atmosphere-ocean interactions in the equatorial region and the local SST response to changes of surface heat flux in the extratropics. We have identified the variations of latent heat flux as the main cause of the extratropical surface warming. We should point out that the change of surface wind affects not only latent heat flux but also dynamical processes in the ocean such as mixing. The latter effect is being investigated in an ocean model study. We have analyzed other flux terms and found their contribution to the SST variations was small. Solar radiation was important in areas where the cloud distribution was changed by the ENSO-induced anomalous convection. The magnitude of solar radiation anomalies diagnosed from the NCEP reanalyses was, however, around 20W/m^2 , about three times smaller than that of latent flux anomalies. In addition, the changes of cloud pattern also affected the long-wave radiation, whose effect on SST is opposite to that of the solar flux. Due to the cancellation of these two fluxes, the total radiative impact on the SST was small. Finally, the fluxes diagnosed from the NCEP reanalyses are currently the only data available for describing the basin-wide variability of air-sea flux exchanges in the Indian Ocean for the targeted period. The data quality is inevitably affected by model errors even though the NCEP model assimilates observed data. More direct observations will help to calibrate the NCEP reanalyses.

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References

- Bjerknes, J., Atmospheric teleconnections from the equatorial Pacific. *Mon. Wea. Rev.* 97, 163-172, 1969.
- Cadet, D.L., The Southern Oscillation over the Indian Ocean. *J. Climatol.*, 5, 189-212, 1985.
- Chambers, D.P., and B.D. Tapley, Anomalous warming in the Indian Ocean coincident with El Niño. *J. Geophys. Res.*, In press, 1998.
- Climate Diagnostic Bulletin, published by the Climate Prediction Center, U.S. Department of Commerce, NOAA/NWS/NCEP, 1997.
- Gautier, C., P. Peterson, and C. Jones, Variability of air-sea interactions over the Indian Ocean derived from satellite observations. *J. Clim.*, 11, 1859-1873, 1998.
- Liu, T.W., A. Zhang, and J.K.B. Bishop, Evaporation and solar irradiance as regulators of sea surface temperature in annual and interannual changes. *J. Geophys. Res.*, 99, 12623-12637, 1994.
- Nicholson, S.E., An analysis of the ENSO signal in the tropical Atlantic and western Indian Oceans. *Intl. J. Climatol.*, 17, 345-375, 1997.
- Nigam, S., and H.S. Shen, Structure of atmospheric low-frequency variability over the tropical Pacific and Indian Oceans. Part I: COADS Observations. *J. Clim.*, 6, 657-676, 1993.
- Rasmusson, E.M., and J.M. Wallace, Meteorological aspects of the El Niño/Southern Oscillation. *Science*, 222, 1195-1202, 1983.
- Reynolds, R.W., and T.M. Smith, A high resolution global sea surface temperature climatology. *J. Clim.*, 8, 1572-1583, 1995.
- Tourre, Y.M., and W.B. White, ENSO signals in global upper-ocean temperature. *J. Phys. Oceanogr.*, 25, 1317-1332, 1995.
- Webster, P.J., J.P. Loschnigg, A.M. Moore, and R.R. Leben, The Great Indian Ocean warming of 1997-1998: Evidence of coupled oceanic-atmospheric instabilities. Submitted to *Nature*, 1999.
- Yang, J., L. Yu, C. Koblinsky, D. Adamec, Dynamics of the seasonal variations in the Indian Ocean from TOPEX/POSEIDON sea surface height and an ocean model. *Geophys. Res. Lett.*, 22(11), 1915-1918, 1998.
- Yu, L., and M. Rienecker, Evidence of an extratropical atmospheric influence during the onset of the 1997-98 El Niño. *Geophys. Res. Lett.*, 25(18), 3537-3540, 1998.

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