MAUSAM, 52, 1 (January 2001), 151 - 162

551.526.6 : 551.553.21 : 551.509.313.4 (540)

The effect of Indian Ocean warming on the Indian Monsoon: An atmospheric model study

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सार - फ्लोरिडा राज्य विश्वविद्यालय के भूमंडलीय स्पेक्ट्रल मॉडल का उपयोग करते हुए वायुमंडलीय मॉडलिंग के अध्ययन से प्राप्त परिणामों से यह पता चलता है कि कुछ वर्षों जैसे 1997 में जब हिंद महासागर का समुद्र सतह तापमान प्रचुर मात्रा में होता है जब भारतीय मानसून वर्षा ऋतु के विशिष्ट प्रकार के लक्षण दिखाई देते हैं। 1997 में उष्णकटिबंधीय अभिसरण क्षेत्र के उत्तर की ओर दूर तक बढ़ने से प्रादेशिक हैडले सेल में विसंगतियाँ उत्पन्न हुई थी। हिन्द महासागर के उत्तर पश्चिम में स्थानीय उष्ण परिसीमा स्थितियाँ उत्पन्न होने से मॉडल अनुकरणों के दौरान पश्चिमी भारत में अधिक वर्षा की विसंगतियाँ पाई गई हैं। बड़े पैमाने पर दृष्टिगोचर होने वाली उपरि सतह द्रुतगति संरचना 1997 में सही ढंग से प्रच्छन्न रूप से कुछ कुछ पूर्व दिशा की ओर बढ़ जाती है। इस संरचना से इंडोनेशिया के अभिसरण के क्षेत्रों का पता चलता है जहाँ पर भीषण अकाल पड़ा था मॉडल के अनुसार भूमध्यरेखीय हिन्द महासागर की वर्षा की जिन अवधियों के निष्पादन का अध्ययन किया गया है उनमें से अधिकांश अवधियों में वर्षा में विलक्षणता पाई गई है। कुल मिलाकर महासागरीय क्षेत्रों में मॉडल का निष्पादन बहुत ही अच्छा रहा है।

ABSTRACT . The results from an atmospheric modeling study using the Florida State University Global Spectral Model indicate that, in years such as 1997 when the Indian Ocean SSTs are large, the Indian monsoon exhibits a typical behaviour. During that year, an extended shift of the tropical convergence zone towards the north played a role in the regional Hadley cell anomalies. The local warm boundary conditions in the northwestern Indian Ocean aided the high rainfall anomaly in Western India during the model simulations. The upper level structure, exhibited in terms of the global velocity potential is slightly shifted east for 1997, but with the correct sign. This structure shows regions of convergence over Indonesia where severe drought had occurred. The performance of the model rainfall over the equatorial Indian Ocean was uncanny for most seasons studied. Overall, the model performed best over the oceanic regions.

Key words – Spectral model, Indian ocean SST, Indian monsoon, Rainfall simulation.

1. Introduction

The skillful forecast of the impending summer monsoon over Indian region and its intraseasonal variability has the potential of alleviating some of the societal and agricultural concern for anomalous monsoon rain. Some progress has been made in Indian monsoon forecasting by using both the anticipated states of the ENSO cycle and the SSTs (Sea Surface Temperatures) of the Indian Ocean. Most recently, Sadhuram (1997), Harzallah and Sadourny (1997) and Clark *et al.* (1999) offer some hope for forecasting Asian-Australian summer monsoon rainfall with reasonable skill using Indian Ocean SST distributions during the previous winter and spring. In addition, major operational research centers such as ECMWF and NCEP issue seasonal forecasts using complex coupled ocean-atmosphere models. They have shown some success in forecasting the evolution of the 1997-1998 El Niño (*e.g* Webster and Palmer 1997, McPhaden 1999, Barnston *et al.* 1999 and Krishnamurti *et al.* 1999). These same models (global in nature) have potential to help forecast the intraseasonal variability of rainfall in the monsoon regions.

The 1997-1998 SSTs were anomalous in both the Pacific and Indian Oceans. During this period, the strongest El Niño of this century occurred in the Pacific Ocean. During the middle of 1998, the El Niño weakened and a moderate La Niña developed. The El Niño was unique because of the absence of remote Indian monsoon events normally associated with a strong Pacific Ocean warming. The rainfall over India was close to normal during the 1997-1998 El Niño compared to the 1871-1998 mean, despite the statistics that suggest that drought is normally associated with El Niño and flood with La Niña (*e.g.* Rasmusson and Carpenter, 1983). Furthermore, Indonesia is typically dry during an El Niño but the drought in 1997 was the strongest on record. Also, East African rainfall was very much wetter than average although the canonical association of rainfall with El Niño calls for only slightly above normal precipitation (Rasmusson and Carpenter, 1983 and Nicholson and Kim,

TABLE 1

SST anomalies (K) for various regions of the Pacific and Indian Oceans averaged over the summer season defined by June, July, August, and September. The regions are defined (from left to right) by (5N°-5°S; 170°W-120°W), (5°N-5°S; 150°W-90°W), (5°N-5°S; 160°E-150°W), (5°N-5°S; 55°E-95°E), (15°N-5°N; 55°E-72.5°E), (15°N-5°N;82.5°E-95°E). The lower row indicates the standard deviation for the respective column

Year	Nino 3.4	Nino 3	Nino 4	Indo 1	Indo 2	Indo 3
85	-0.6	-0.9	-0.5	-0.5	-0.6	-0.5
86	0.1	-0.1	0.1	-0.3	-0.4	-0.3
87	1.2	1.2	0.5	0.3	0.3	0.3
88	-1.4	-1.5	-0.8	0.1	0.1	0.1
89	-0.6	-0.4	-0.6	-0.5	-0.4	-0.5
90	0.0	-0.1	0.2	0.0	-0.3	-0.2
91	0.5	0.5	0.4	0.1	0.1	0.2
92	0.2	0.0	0.3	0.0	-0.1	0.0
93	0.3	0.2	0.2	-0.1	-0.1	0.0
94	0.2	-0.2	0.4	0.0	-0.3	-0.2
95	-0.3	-0.4	-0.1	0.1	0.3	0.1
96	-0.3	-0.3	-0.3	0.0	0.0	0.0
97	1.3	2.0	0.4	0.3	0.6	0.2
98	-0.7	0.0	-0.5	0.6	0.7	0.7
σ	0.7	0.8	0.4	0.3	0.4	0.3

1997). Each ENSO event is different in both spatial and temporal structure. We could say that no two ENSOs are alike, not the ocean or atmospheric state from which the ENSO is derived. There are an infinite amount of atmospheric or ocean features which could result in varying response in the atmosphere. Here we focus on some model interpretations of the Indian Monsoon response to Pacific and Indian Ocean forcing.

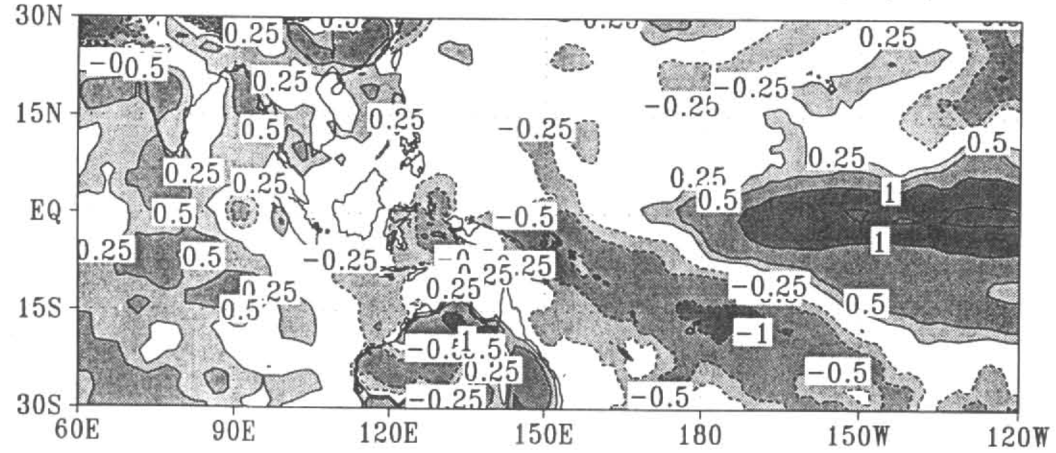
This paper presents the results of an atmospheric model representation of the Indian monsoon for various years over the last couple of decades, particularly the monsoon seasons of 1997 and 1998. Observed SSTs are used as boundary conditions for the model response. Section 2 discusses the model used for the work, and is followed by a brief discussion of the state of the Indian and Pacific Oceans in section 3. Section 4 discusses the model results, while section 5 is a summary of the results.

2. Model

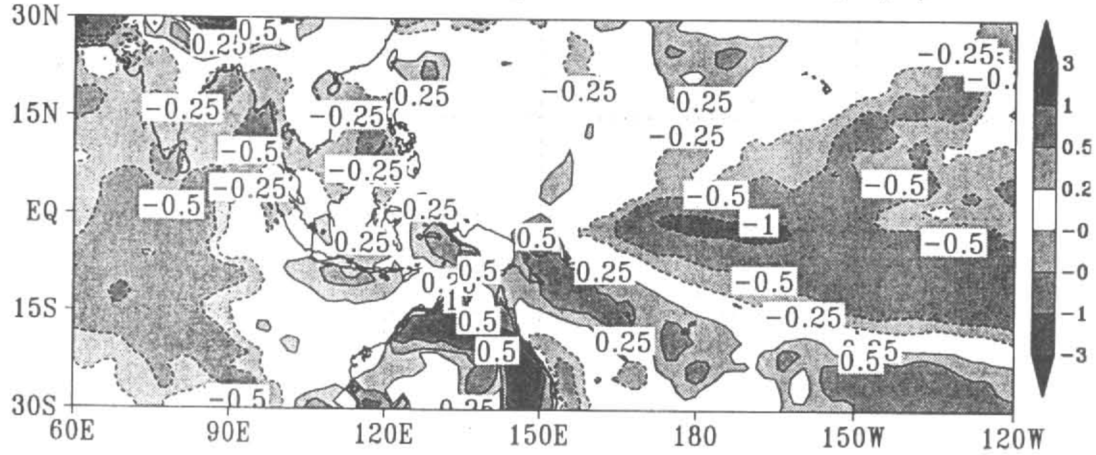
The model used for this work is the FSU global spectral model (Cocke and LaRow 1999). The model was run with a horizontal, spectral resolution T63, using 14 sigma layers in the vertical (approximately between 30 and 1000 hPa). A similar version of the FSU model has been utilized for winter seasonal cases (Cocke and LaRow 1999) as well as various other global studies.

The current work requires a brief discussion of some of the model physics pertaining to the radiation and lower atmosphere. The model contains a wide-band radiation code used to calculate shortwave solar, near-infrared solar and thermal longwave radiation separately (Chang 1979). Multiple Rayleigh scattering is applied to the shortwave radiation and an emissivity method is used for longwave fluxes. The near-infrared radiation accounts for water vapour absorption, while the solar zenith angle includes seasonal and diurnal variations. The low, middle and high clouds are based on threshold relative humidity following Slingo (1980). Surface flux of heat, moisture, and momentum is estimated using Monin-Obukhov similarity theory (Businger *et al.* 1971). A local, first-order closure scheme is used for the vertical mixing of heat, moisture, and momentum (Louis 1981). The turbulent mixing coefficient is a function of mixing length, local wind shear, and local stability. The vertical profile of momentum, heat, and moisture for stable and unstable boundary layers

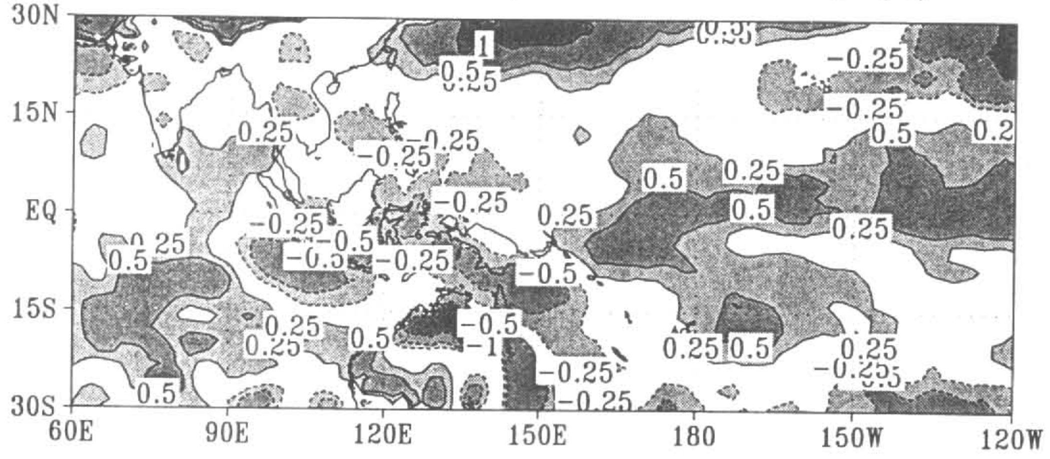
a) 1987 Surface Temperature Anomaly (K)



b) 1989 Surface Temperature Anomaly (K)

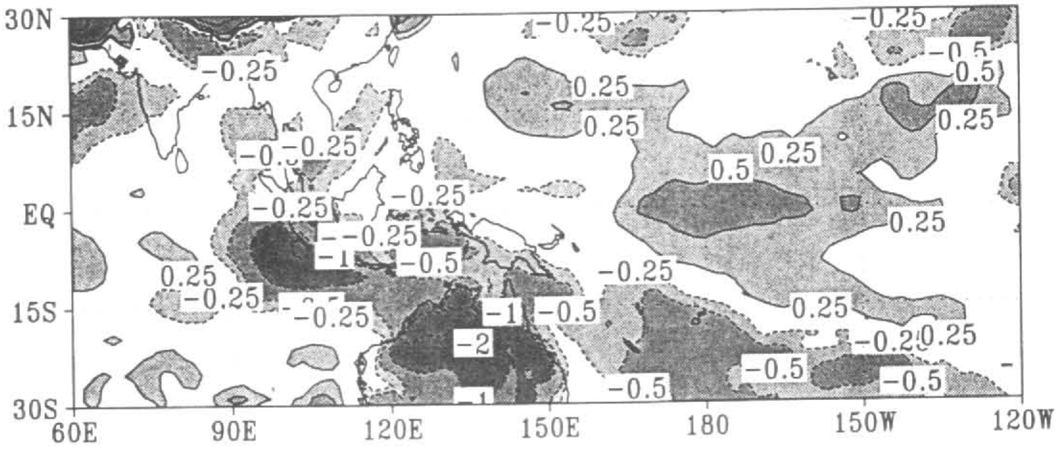


c) 1991 Surface Temperature Anomaly (K)

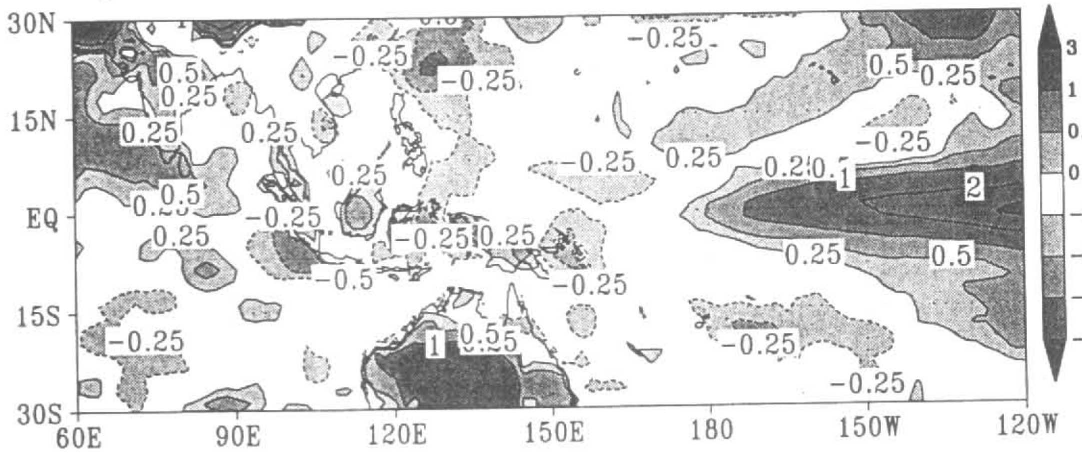


Figs. 1 (a-c). Seasonal mean (JJAS) SST anomaly over the Indian and Pacific Ocean based on Reynolds and Smith (1994) for the years (a) 1987, (b) 1989 and (c) 1991

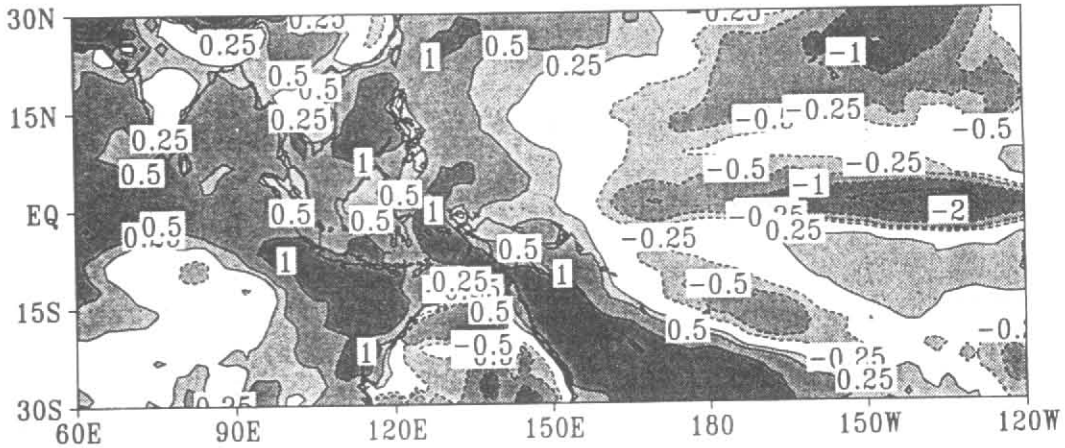
d) 1994 Surface Temperature Anomaly (K)



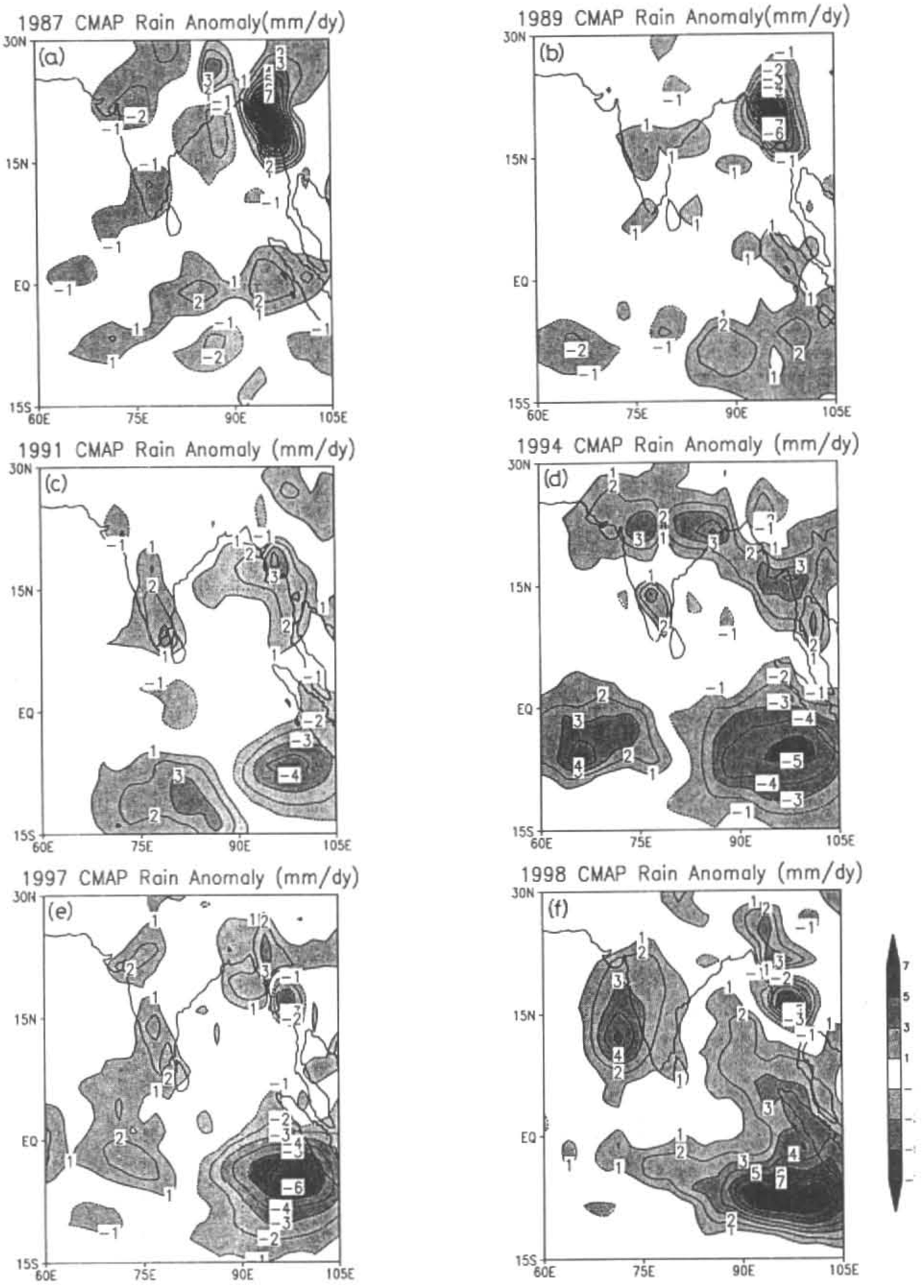
e) 1997 Surface Temperature Anomaly (K)



f) 1998 Surface Temperature Anomaly (K)



Figs. 1 (d-f). Seasonal mean (JJAS) SST anomaly over the Indian and Pacific Ocean based on Reynolds and Smith (1994) for the years (d) 1994, (e) 1997 and (f) 1998


1987 CMAP Rain Anomaly(mm/dy)

1989 CMAP Rain Anomaly(mm/dy)

1991 CMAP Rain Anomaly (mm/dy)

1994 CMAP Rain Anomaly (mm/dy)

1997 CMAP Rain Anomaly (mm/dy)

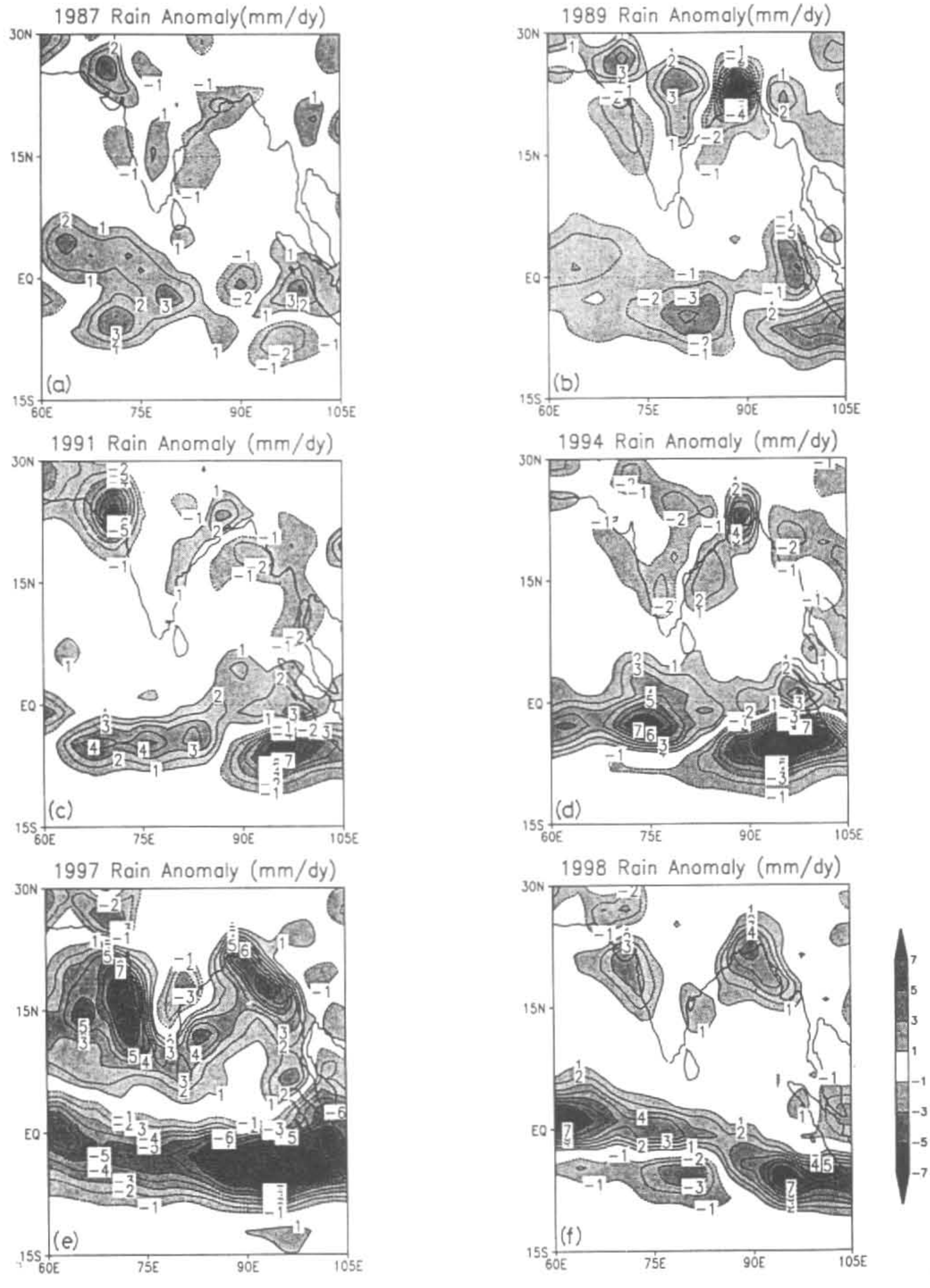
1998 CMAP Rain Anomaly (mm/dy)

Figs. 2(a-f). Observed rainfall anomaly based on CMAP data over the monsoon region for the same years as Fig. 1

are linear and functions of PBL height. Cumulus convection is parameterized by a simplified Arakawa Schubert scheme (Moorthi and Suarez, 1992). The model is integrated with 15-minute time steps and calls to radiation every 3 hours. The land-surface scheme for this version of the model is very simple, and is a likely source of error in the results here as will be discussed later. Further model development will include a more elaborate land-surface scheme, as well as a higher vertical resolution and improved low-level clouds.

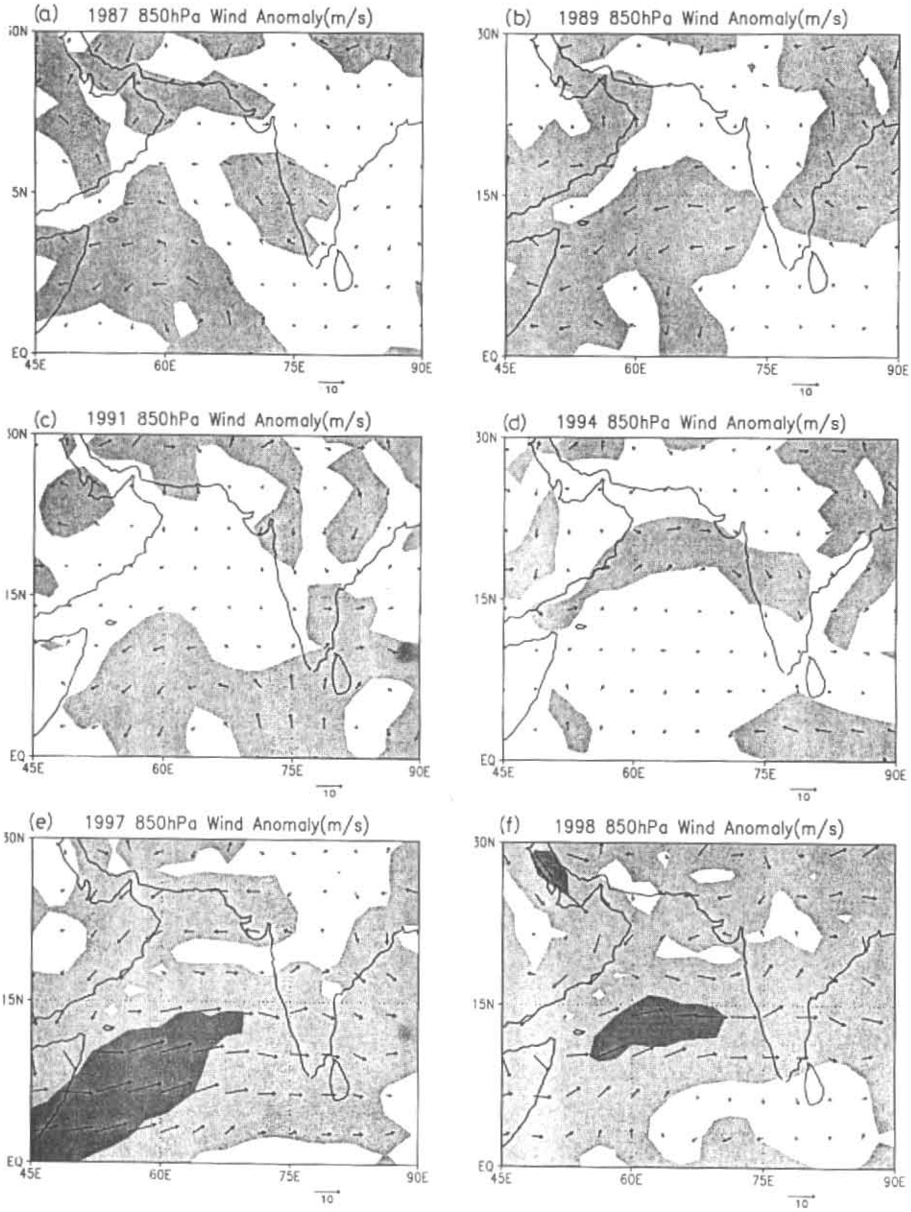
3. The State of the Indian and Pacific Oceans

The equatorial Pacific Ocean surface temperatures have been quite variable over the last two decades. Beginning with the large El Niño event in 1983 and



Figs. 3(a-f). Model-based rainfall anomaly over the monsoon region for the same years as Fig. 1

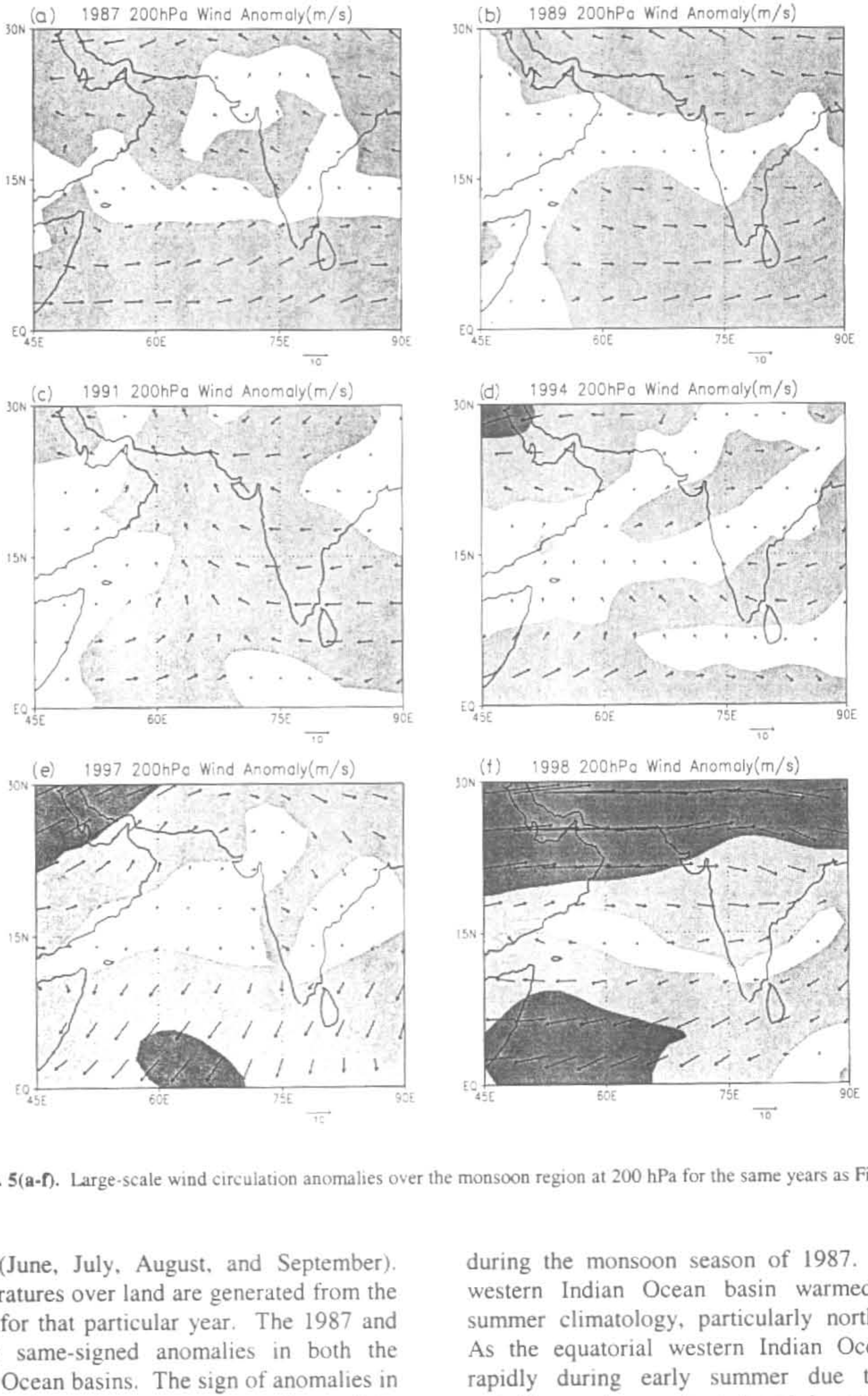
followed by strong events in 1986/1987 and 1997, with a weaker event in 1991. Furthermore, there was significant cold SST events in 1988 and 1998, continuing into 1999. The impact of such events on the global large-scale anomalies of rainfall and temperatures has been documented in the literature in various studies (Rasmusson and Carpenter 1983). Significant anomalous SSTs are not only found in the Pacific Ocean, but also in the Atlantic Ocean and Indian Ocean, but to a lesser extent. The anomalies in the Indian Ocean could be very instrumental in development and strength of the Indian and Asian Monsoons. A reduction or increase in local surface temperatures can alter the sign of the development of convection through boundary destabilization. Table 1 illustrates SST anomalies for a number of regions in the Pacific and Indian Oceans over the period between 1985



Figs. 4(a-f). Large-scale wind circulation anomalies over the monsoon region at 850 hPa for the same years as Fig. 1

and 1998 averaged from June through September for each year. Highlighted boxes indicate years where the anomalies exceed one standard deviation (shown in the bottom row of the table). Quite clearly, most years when there is a large anomaly (positive and negative) in the Pacific Ocean basin there is also a significant SST anomaly in the Indian Ocean. The reason for this is not clear, but may be a combination of global scale oceanic wave propagation into the Indian Ocean from the Pacific in response to the anomalies in the Pacific and secondary impact due to the atmosphere's remote response to the Pacific Ocean anomalies. Yulaeva and Wallace (1994) found the Indian Ocean SST variability correlated to the ENSO signal, albeit a lagged correlation.

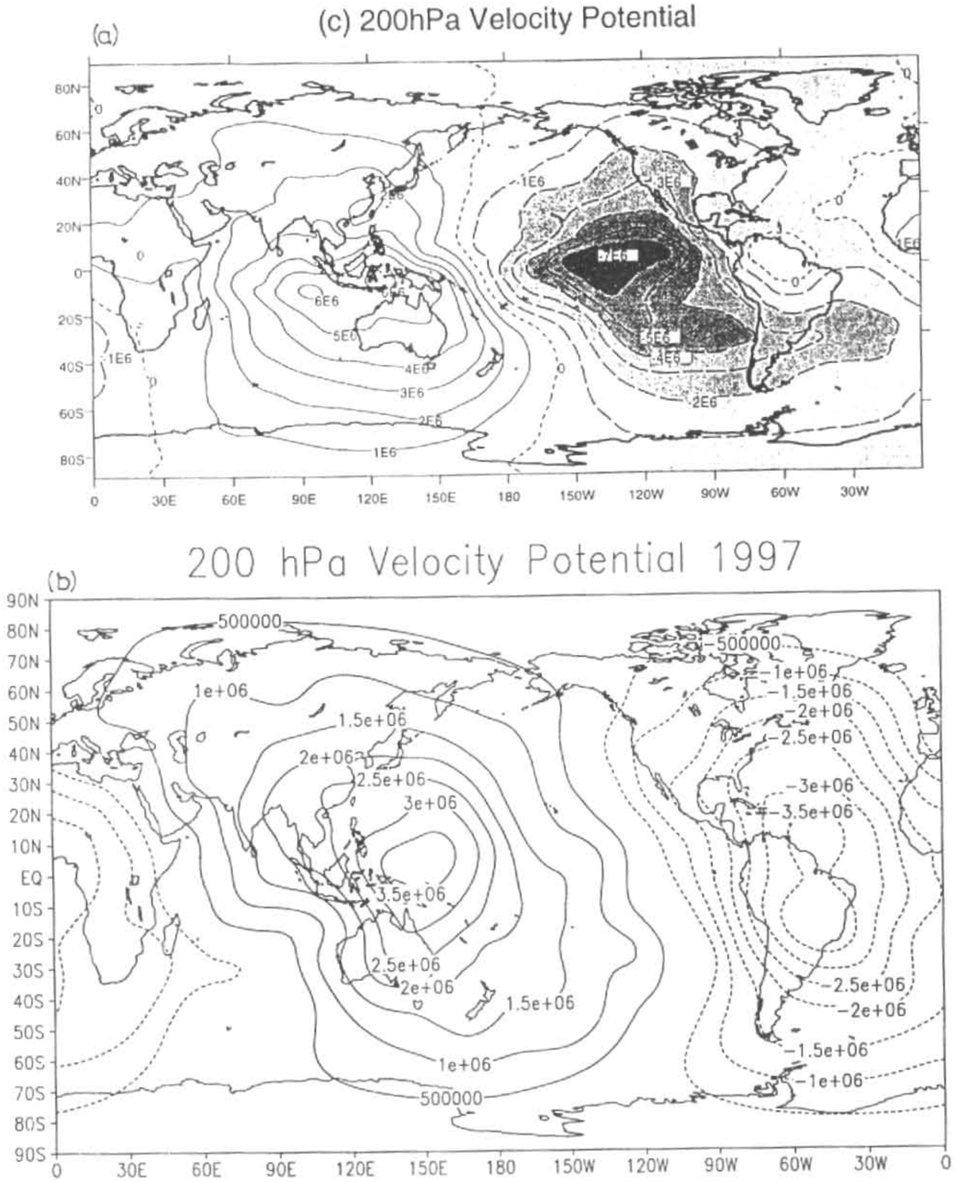
The spatial distributions of surface temperatures (Reynolds and Smith, 1994 over the Indian and Pacific Ocean domains are plotted in Fig. 1 for selected years considered ENSO years, or years with large Indian Ocean SST anomalies (based on Table 1). Averages are for the



Figs. 5(a-f). Large-scale wind circulation anomalies over the monsoon region at 200 hPa for the same years as Fig. 1

monsoon season (June, July, August, and September). The surface temperatures over land are generated from the model integration for that particular year. The 1987 and 1989 years show same-signed anomalies in both the Pacific and Indian Ocean basins. The sign of anomalies in the Indian Ocean is fairly homogeneous as observed by Weare (1979). The anomalies in both basins during 1991 and 1994 are not excessively large and have rather incoherent spatial structure.

A very strong El Niño event was in its mature/decaying phase in the Eastern Pacific Ocean during the monsoon season of 1987. The SST in the western Indian Ocean basin warmed relative to the summer climatology, particularly north of the equator. As the equatorial western Indian Ocean usually cools rapidly during early summer due to strong mixing and Ekman transports induced by monsoon winds, in absolute terms, the anomalous warming can be thought of as a reduced cooling. Beginning in July 1997, strong cooling approached in the eastern Indian Ocean, reaching a minimum (<-2 K) in November 1997. Towards the end of the year, the cooling in the eastern basin decreased but the relative warming in the west increased


(a) (c) 200hPa Velocity Potential

(b) 200 hPa Velocity Potential 1997

Figs. 6 (a&b). Velocity potential anomalies at 200 hPa for 1997 for (a) observed and (b) model data

substantially to a maximum of >2 K by February, 1998 (not shown). Even though the phasing of the cooling in the east and the warming in the west was different, together they generated a large anomalous reversed SST gradient from east to west. The anomalous heating and cooling of the upper ocean was so strong that the actual SST gradient reversed between November 1997 and March 1998. Along with the establishment of the reversed anomalous temperature gradient, the usually weak westerly winds were replaced by very strong surface easterly winds beginning generally in June, 1997, and reaching a maximum over the central equatorial Indian Ocean in December when anomalies exceeded –6 m/s (not shown).

The warmth in the Indian Ocean continued through the summer of 1998, even with a cold phase ENSO event becoming fully established in the equatorial Pacific Ocean. This is contrary to the correlation in SST anomalies for ENSO Pacific and Indian Ocean. Nearly the entire Indian Ocean basin is positive anomalies, typically greater than 0.5 K averaged over the season. Furthermore, the western Pacific warm anomalies were greater than 1K, extending out into the entire western Pacific Ocean.

4. Results

Figure 1 shows the seasonal summer mean anomalies in SST. During 1987, 1991 and 1997, the classical El

Niño pattern is found with warmer than normal SSTs in the equatorial central and east Pacific and cooler than normal SSTs in the west Pacific. The magnitude and the spatial extent of the SST anomalies for 1997 in the central and east Pacific are much greater than previous El Niño events, comparable to the event of 1983. The anomaly patterns are also different over the Eastern Hemisphere in terms of warm anomalies in the Indian Ocean, which develop during the mature/decaying phase of El Niño. The tongue of cooler than normal water is also extending from the maritime continent into the southern hemisphere supporting a features of mature/decaying El Niño events (Rasmusson and Carpenter 1982). Similar, but opposite features exist for the La Niña years (1989 and 1998) as discussed in section 3. The SST anomaly pattern during these years may show differences in the precipitation and circulation pattern over the west Pacific and Indian Oceans that could have an impact on the Indian summer monsoon.

TABLE 2

Monsoon indices for zonal wind, observed CMAP rain rates , and model rain rate (from left to right) for the summer season (JJAS). The lower row indicates the standard deviation for the respective column

Year	Zonal Wind Monsoon Index	% of Normal Rain Observed (CMAP)	% of Normal Rain Model
85	-4.0	-3	8
86	-0.5	-8	-10
87	-2.8	-13	12
88	-0.7	37	-1
89	-3.7	14	-10
90	-0.6	-11	-13
91	0.4	6	0
92	0.8	22	27
93	-1.2	2	-7
94	0.4	6	-19
95	1.8	7	-5
96	-1.6	29	-23
97	7.1	14	153
98	4.6	30	41
σ	2.9	18	17

The impact of the El Niño was less for the Asian monsoon domain. The spatial distribution of precipitation over India was highly variable in 1997 (IMD 1997), although on the all-India scale the monsoon was quite normal. Figs. 2 & 3 shows rainfall anomaly during the recent El Niño and La Niña years in the monsoon domain for the NOAA NCEP Climate Prediction Center Merged Analysis of Precipitation (CMAP) data (Xie and Arkin 1997) and model output respectively. The CMAP precipitation over India suggests anomalies generally less than 5 mm/day, with slightly larger anomalies over the ocean, especially near the equator. The Indian precipitation during the El Niño year of 1987 was below average, following the typical El Niño response (Rasmusson and Carpenter, 1983). The weak 1991 El Niño generated a sign opposite to the typical response according to the CMAP data. The precipitation anomalies for the La Niña years of 1989 and 1998 are positive over India, while the strong El Niño year of 1997 had an above normal monsoon season. During 1997, rainfall across Western Indonesia was significantly below normal that is clearly shown in the CMAP based observation (Fig. 2e) and model simulation (Fig. 3e). The model is able to simulate rainfall deficit correctly over Indonesian region for the 1997 season with some bias in location. The magnitude of rainfall anomaly over this region is more or less simulated by the model, with an order of magnitude of 7 mm/day. A drought resulted in well-below normal rainfall, contributing to vast, uncontrolled wildfires in Sumatra and Borneo. In most of the years shown in the figures the model is able to simulate rainfall correctly over the ocean, especially 10° latitude to either side of the equator. Over land, the model has trouble representing the proper anomalous signal in the observed rainfall. In most of the El Niño year the model is able to simulate the northward migration of the convection maximum in the monsoon region but during the La Niña years the northward movement of convection is very weak. Much of the problems with the rainfall over land may be attributed to the low order land-surface scheme, as well as the low-resolution vertical structure. Furthermore, the use of various convection schemes show drastic results in signal over the globe, suggesting that either the use of multiple convection schemes are needed in a super ensemble sense (Krishnamurti *et al.* 1999) or a best scheme for the regions of interest may need to be selected.

The large-scale circulation anomalies over the Indian monsoon region are presented in Figs. 4 & 5 for the 850hPa and 200hPa levels. The model tends to weaken the low-level westerlies for the 1987 and 1991 warm seasons, but also in 1989. The 1989 reversal may be a result of the local effects of colder than normal Indian Ocean SSTs. The winds for 1988 season (not shown), which was the mature season for the strong cold event, were slightly stronger westerly, but not enough to generate a strong rainfall anomaly signature as observed in the CMAP data. The model does generate significantly stronger westerly low-level winds in 1997 and 1998 (Figs. 4e & 4f), which support the significantly larger rainfall the model generated for those years (Figs. 2e & 2f and Table 2, column 3). The CMAP data similarly suggests that larger than normal rainfall occurred both those years (Table 2, column 2). At upper levels (Fig. 5), the 1987 and 1989 (Figs. 5a & 5b) seasons clearly have weaker easterly winds along the equator and weaker westerly winds north of 20°N. This is supportive of a weaker monsoon season. A clear structure in the upper wind anomalies is not as evident in the 1991 and 1992 (Figs. 5c & 5d) seasons, which might be expected from the weaker tropical SST anomalies during those seasons. Again, as in the low-level winds, the upper level winds suggest a strengthened monsoon in 1998, but in 1997, the upper level wind is not as typically expected in an El Niño monsoon season. There are stronger westerly winds north of 20°N and stronger easterly winds near the equator.

Table 2, column 1, shows results from a zonal wind monsoon index defined for the model. The index is defined similar to that of Webster and Yang (1992) who showed that ENSO might have impact on the low-level westerly and upper level easterly winds over the monsoon region. They develop a Dynamical Monsoon Index (DMI) of interannual variability based on the anomalous vertical shear of the zonal wind. We define our model index as

$$M = \overline{\overline{\left[\left(u_8 - \overline{u}_8\right) - \left(u_2 - \overline{u}_2\right)\right]}}^{x,y,t} \tag{1}$$

where u is the zonal wind, the over bar indicates a seasonal average and the double over bar indicates a seasonal and spatial average. The spatial average is over the domain between 5°N and 20°N, 55°E and 85°E. For the most part, the index sign corresponds to the anomalous rainfall of column 3, for the model.

The response of the large-scale circulation to the 1997 was substantial. The velocity potential anomalies at 200 hPa in 1997 were greater than in all the previous El Niño year (figure not shown). This indicates a major perturbation to the Walker circulation, with strong anomalous ascent over the central east Pacific and descent over Indonesia and the eastern Indian Ocean. Figs. 6(a&b) shows observed and model simulated velocity potential anomalies at 200 hPa for 1997. It shows a strong meridional gradient in the velocity potential over the longitudes of Indonesia and the eastern Indian Ocean. This figure suggests the important changes in the local Hadley circulation with its rising branch north of the equator and subsidence to the south between equator and 20°S. This local Hadley circulation is different from the mean reverse Hadley circulation that has its descending branch near 30°S associated with the Mascarene High. So the local Hadley circulation was an important factor in the synoptic, seasonal behaviour of the Indian summer monsoon. The model's shift of velocity potential anomaly from observed by about 20° to the east may help explain the model's over-excessive rainfall in 1997 compared to the CMAP analysis.

5. Conclusions

On large scales the strength of the monsoon is influenced by a modulation of the Walker circulation. The subsidence over the West Pacific and South East Asia is generally supported by the El Niño response. The anomalous Walker circulation is a response to the eastward shift of the convection in response to the extension of the warm pool into the central Pacific. The 1997 El Niño was no exception, but the local environment around India may have contributed to the above average monsoon season as the Indian Ocean SST anomalies were large.

The results show the modulation of the local Hadley circulation may play an important role during the El Niño year. During El Niño year suppression of convection over the maritime continent and the equatorial Indian Ocean was marked. The Tropical Convergence Zone (TCZ) is more active during El Niño years particularly in 1997 as the convergence zone was shifted substantially to the north. This shift in convergence due to the heating of the Indian Ocean generated a north south Hadley anomaly which is strong enough to counteract the remote influences of the Pacific SST anomalies.

The model forced by observed SST does a reasonable job over the oceanic regions of the Indian domain, but does fairly poor during most seasons over land. The exceptions to this are during 1990, 1992, 1997, and 1998. These results need to be tested within an ensemble framework, using varying initial conditions, as well as with varying physics. Furthermore, an implementation of a better land-surface scheme may vastly improve the results over land.

Results of this study suggest that the monsoon predictability not only requires a better understanding of the monsoon-El Niño relationship, but also regional coupled processes and their modulation by long-term climate change. More analysis is needed with more years, perhaps using synthetic SSTs (Verzone *et al.* 2000).

Acknowledgements

This work was supported by the following grants to Florida State University: NASA Grant NAG8-1199, NASA NAG5-4729, NOAA Grant NA86GP0031, NOAA Grant NA77WA0571, NSF Grant ATM-9612894 and NSF Grant ATM-9710336.

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