Mausam, (1994), **45**, 3, 205-212

551.509.33 : 551.526.6 : 551.553.21

Variability of Indian summer monsoon : Relationship with global SST anomalies

R. K. VERMA

Indian Institute of Tropical Meteorology, Pune

(Received 12 November 1991, Modified 28 February 1994)

सार — इस शोध पत्र में ग्रीष्म कालीन मानसूनी वर्षा तथा समुद्र के सतहीय तापमान (एस एस टी) की विसंगतियों के भूमंडलीय सहसंबंध दर्शाने वाले मानचित्रों का अध्ययन प्रस्तुत किया गया है। अध्ययन की अवधि में महीनों के भिन्न-भिन्न समय के अंतरालों (मानसून वर्ष से पूर्व तथा साथ-साथ आने वाले वर्षों के महीने) पर कोएडस (सी ओ ए डी एस) (महासागर-वायुमंडल विस्तृत डाटा सेट) के आंकड़ों के उपयोग द्वारा विश्व के महासागरों के प्रत्येक $2° \times 2°$ अक्षांश-देशान्तर कोष्ठ पर तीस वर्षों (1950-1979) के मानसून सूचकांकों और समुद्र के सतहीय तापमान के बीच सहसम्बन्ध स्थापित किए गए हैं। समुद्री सतह के भूमंडलीय तापमान के साथ मानसूनी वर्षा के दूर संपर्कों का पता लगाने के लिए सहसंबंध दर्शाने वाले मानचित्र तैयार किए गए हैं और उनका विश्लेषण किया गया है।

मध्य और पूर्वी विषुवतीय प्रशान्त महासागर (नीनों क्षेत्र) के समुद्री सतह के तापमान के बीच पश्चता-सहसंबंधों से संकेत मिलता है कि मानसून दो प्रकार की परस्पर क्रिया से प्रभावित होता है। प्रथम परस्पर क्रिया मानसून से लगभग एक वर्ष पहले मध्य और पूर्वी प्रशान्त महासागर की समुद्री सतह के तापमान की विसंगतियों के साथ ग्रीष्मकालीन मानसूनी वर्षण की विसंगतियों का सकारात्मक सहसंबंध दर्शाती है। इससे यह पता चलता है कि एल-नीनो के दक्षिणी दोलन (एनसो) की उष्ण अवधि के लगभग एक वर्ष बाद आने वाला मानसून सामान्यत: आर्द्र होता है। इस स्थिति को देखते हुए यह कहा जा सकता है कि संभवत: यह परस्पर क्रिया उत्तरी गोलार्ध के शीतकालीन तापमान के प्रभाव का ही परिणाम है। मानसून के साथ विषुवतीय क्षेत्र के प्रशान्त महासागर की समुद्री सतह के तापमान की दूसरी प्रकार की परस्पर क्रिया ग्रीष्मकालीन मानसून से पहले शुरू होने वाले प्रबल नकारात्मक सहसंबंधों से प्रकट होती है। ये सहसंबंध अत्यधिक प्रबल परिमाण होते हैं। तथा इनका प्रभाव व्यापक क्षेत्र पर पड़ता है। इससे यह पता चलता है कि मानसून ऋतु से कुछ पहले और उसके दौरान पाई जाने वाली समुद्री सतह के तापमान की धनात्मक विसंगति मानसून को क्षीण बनाती है।

इस शोध पत्र में हिन्द महासागर तथा मानसून के बीच होने वाली वायु-समुद्र की परस्पर क्रिया पर भी विशेष बल दिया गया है। दो प्रमुख क्षेत्रों का पता लगाया गया है। प्रथम, परवर्ती शीत ऋतु और बसंत ऋतु के दौरान, भूमध्य रेखा के दक्षिण में मध्य हिन्द महासागर के क्षेत्र पर प्रबल सकारात्मक सहसंबंधों का पता चलता है। दूसरा प्रमुख क्षेत्र उत्तरी हिन्द महासागर में स्थित है। इसके सहसंबंध उल्लेखनीय रूप में नकारात्मक हैं। अटलांटिक महासागर की द्रोणी (बेसिन) के साथ कुछ दूर-संपर्कों का पता चला है, जिनकी व्याख्या करना कठिन है, परन्तु मानसून के मानीटरन और दीर्घ अवधि पूर्वानुमान में इनका अनुप्रयोगी उपयोग सिद्ध हो सकता है।

ABSTRACT. Global correlation maps of the summer monsoon precipitation anomalies and Sea Surface Temperature (SST) anomalies are presented. Thirty-year (1950-1979) time series of monsoon index is correlated with the SST time series at each $2° \times 2°$ latitude-longitude box of the world oceans using COADS (Comprehensive Ocean Atmosphere Data Set) data at various time lags of months *(i.e.,* months of years preceding and concurrent to the monsoon-year). Correlation-maps are prepared and analysed to identify teleconnections of monsoon precipitation with global SSTs.

It is found that the lag-correlations with SST from central and eastern equatorial Pacific (Ñino-region) are suggestive of two types of interactions with the monsoon. The first one, which shows positive correlation of summer monsoon precipitation anomalies with the central and eastern equatorial Pacific SST anomalies about a year before the monsoon, suggests that the monsoon which follows about a year later of occurrence of warm episode of El-Nino-Southern Oscillation (ENSO) is generally wetter. It is also suggested that this interaction might be taking place through the influence of northern hemisphere winter temperatures. The second type of interaction of equatorial Pacific SST with monsoon is revealed through the strong negative correlations beginning before the summer monsoon and continuing with greater magnitude and over wider extent, suggesting that a warm SST anomaly just preceding and concurrent to monsoon season weakens the monsson.

Air-sea interactions between the Indian Ocean and monsoon are also emphasised in the analysis. Two key regions are identified. The central Indian Ocean south of the equator shows strong positive correlations during the late northern winter and spring. The other key region is in the north Indian Ocean. The correlations are significantly negative. Some teleconnections with the Atlantic basin are also revealed which are rather difficult to explain but may find useful applications in monitoring and long-range forecasting of the monsoon.

Key words — Indian summer monsoon, Global sea surface temperature, ENSO, Interannual variability, Teleconnections.

1. Introduction

Summer monsoon of southeast Asia is the most pronounced seasonal phenomenon of the global climate system. Its large spatial and temporal scales allow it to play an important role in the variability of the climate system. During recent decades, the global climate in general and the monsoons in particular

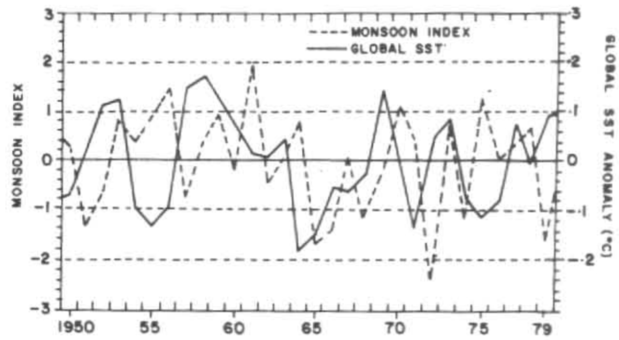

Fig. 1. Standardized rainfall departure values of Indian summer monsoon (MI) and the global SST anomalies (°C) from 1950 to 1979

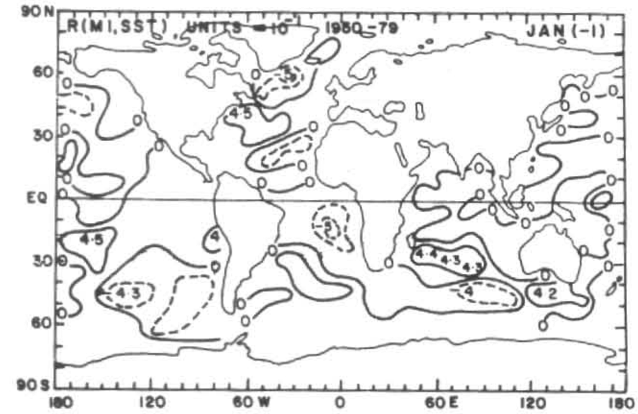

Fig. 2. Correlation coefficient (×10) of the Indian summer monsoon rainfall (MI) with monthly mean SST anomaly for January of the year preceding to monsoon-year, *i.e.*, for JAN (−1). Contour interval is 2.0 with negative values dashed. Significant correlations at more than 95% level are numbered. Data period : 1950-1979

have shown considerably large year-to-year variability (Verma 1990).

There is a growing body of modelling and observational evidence which suggests that the slowly varying boundary conditions of sea surface temperature (SST), soil moisture, sea ice and snow cover at the earth's surface can influence the interannual variability of atmospheric circulation. Based on numerical experiments with a global general circulation model (GCM), Charney and Shukla (1981) suggested that the Asiatic monsoon is a dynamically stable circulation system and its interannual variability is largely determined by the slowly varying surface boundary conditions. The physical mechanisms responsible for such influences are rather complex and depend upon the nature of the boundary forcing. However, the longer time scale atmospheric variability is dominated by the SST influence as its principle source of perturbations.

However, looking at the interannual variations of globally averaged SST anomalies and the monsoon rainfall in recent decades (Fig 1), it would be rather difficult to identify even an apparent relationship between the two : firstly, because information from various regions is suppressed in averaging the SST anomalies over the world oceans and secondly, the annual mean SSTs smooth out the monthly/seasonal variations which might be vital for a seasonal phenomenon like monsoon. Hence, spatial distribution of the relationship at monthly/seasonal time-lags ranging from few seasons prior to few seasons after the monsoon season is important to derive more comprehensive information of the relationship of monsoon with SSTs over the world oceans. The present study addresses to this aspect of the relationship.

Studies, based on observations, by Bjerknes (1966, 1969), were the first among early research works, to hypothesise that equatorial Pacific SST anomalies produce large changes in the mean tropical Hadley circulation. Keshavamurty (1982) and Lau (1985) experimented with the idealised SST anomaly and with the 15-year interannual variations of SST respectively, in the equatorial Pacific and showed qualitative impact on monsoon precipitation, in agreement with the observed precipitation. Empirical evidence of the suppressed summer rainfall over the Indian region during El-Nino years have also been indicated. There have been some studies which emphasised the role of Arabian Sea/north Indian Ocean SST on the summer monsoon precipitation (Shukla 1975, Shukla and Mishra 1977, Saha and Bavadekar 1973, Pisharoty 1981, Joseph and Pillai 1984 and 1986, Kusuma Rao and Goswami 1988). These studies have not explored the relationship of monsoon with the SST of the Indian Ocean south of the equator the region known to play a key role in the genesis of southwest Asian summer monsoon, mainly due to lack of data. The present study overcomes this constraint by using the SST from COADS. This study includes the Atlantic basin also, as some teleconnection between monsoon and the SST anomalies in Atlantic basin cannot be ruled out altogether, in view of the studies by Lamb (1978), Hastenrath (1984), Folland *et al.* (1986), Lough (1986) and Wright (1987). A comprehensive and up to date research survey of ENSO in the context of the interannual variability of the global climate system is provided in the book by Philander (1990) published recently.

The analysis time frame is partitioned to look into the relationship of monsoon with the SST anomalies for the seasons preceding, concurring and succeeding to the Indian summer monsoon season. This is done with a view to understand the possible feedback mechanisms between the global SST and the monsoon which may ultimately lead to better prediction of monsoon/ENSO.

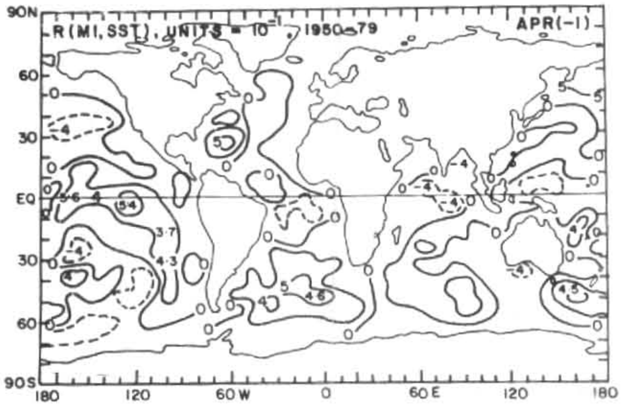

Fig. 3. Same as Fig. 2 but for SST anomaly for APR (−1)

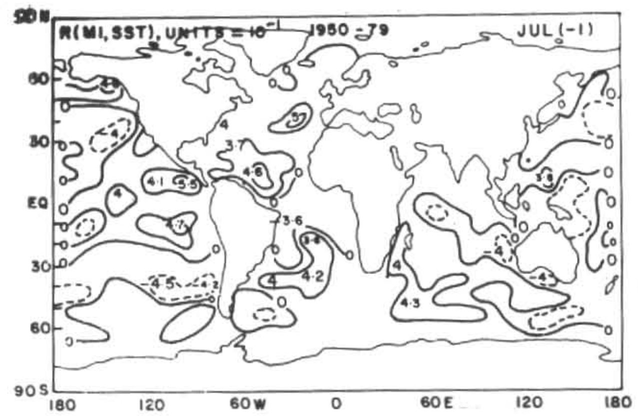

Fig. 4. Same as Fig. 2 but for SST anomaly for JUL (−1)

2. Data and analysis procedure

The thirty-year period from 1950 to 1979 is considered for the present study. Indian summer monsoon precipitation data is taken from Mooley and Parthasarathy (1984). They constructed the long-term time series by area-weighting rainfall during June through September over the contiguous region of India excluding hilly areas. This homogeneous series of rainfall is considered to be a satisfactory representative of the large scale performance of Indian summer monsoon and its variability on the short-term climatic scale. The rainfall departure value is standardized by the long-term standard deviation and denoted as MI (Monsoon Index). This series is shown in Fig. 1. Sea surface temperatures are taken from COADS. Release 1 (1985) which provides values at resolution of monthly summaries of the individual reports in 2° latitude × 2° longitude boxes. Correlations are computed between the series of monsoon index and the series of monthly mean SST anomaly at each box of the world oceans beginning in January of the year preceding to monsoon-year or JAN (—1) through December of the monsoon-year or DEC (0). Isolines of correlation coefficients × 10 are drawn on the world base map. Thus, altogether twenty-four correlation maps were first drawn. However, it was considered sufficient and reasonable to present and discuss only the maps of representative (central) months of each three-month season except monsoon season. These maps are shown in Figs. 2-12. Negative (positive) correlation values are depicted by dashed (continuous) lines. Regions of significant correlations at more than 95% level (*i.e.*, 0.35 for a sample of 30 values) are numbered.

3. Correlations of monsoon precipitation index with global SST anomalies

3.1. *Correlations with SSTs preceding to monsoon*

Figs. (2-7) depict the relationship of summer monsoon precipitation during June to September with world SST anomalies during months representing seasons of previous year and seasons preceding monsoon under consideration. These maps show how the large scale monsoon activity correlates with the SSTs in different ocean basins during the period about a year and a half prior to the onset of monsoon. Such maps help identify the key regions in world oceans having teleconnections with the Asiatic summer monsoon wherever correlations remain above significant level persistently for a considerable period of at least a season over a relatively large area. These teleconnections will not only help in predicting and monitoring the monsoon but also in understanding the mechanisms of interaction between monsoon and SST.

Most remarkable relationships are seen in the Pacific basin, particularly in the Nino regions of central and east equatorial Pacific. The regions are characterised by reversal in correlation sign from significantly positive to significantly negative, as the seasons progress from DJF (—1) represented by JAN(—1) through MAM (0) represented by APR (0)— a season just preceding the monsoon. The transition is equally significant, since it evolves at the eastern equatorial Pacific off the Peru coast. This, therefore, suggests that the large SST anomalies in the central and east equatorial Pacific influence the monsoon either favourably or unfavourably depending upon the lag. The positive correlations from JAN (−1) to about OCT (−1) would suggest that warmer SSTs in the equatorial Pacific

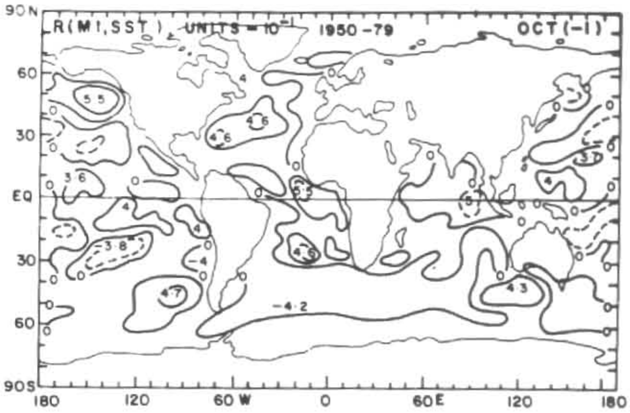

Fig. 5. Same as Fig. 2 but for SST anomaly for OCT (−1)

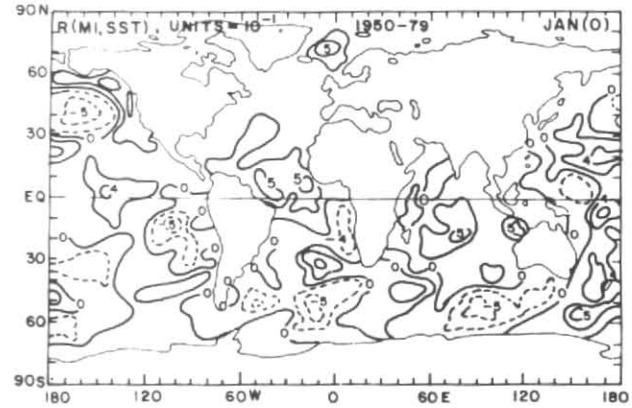

Fig. 7. Same as Fig. 2 but for SST anomaly for APR (0)

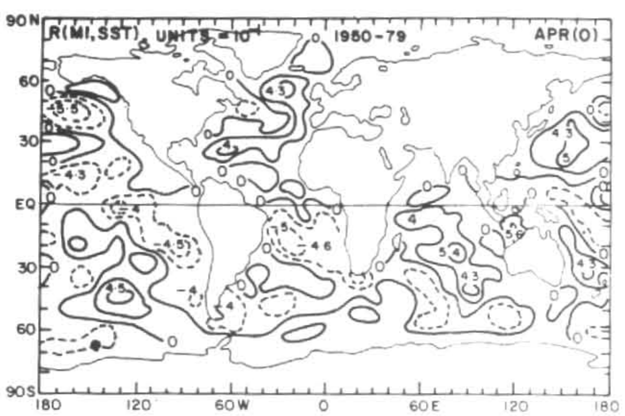

Fig. 6. Same as Fig. 2 but for SST anomaly for JAN (0)

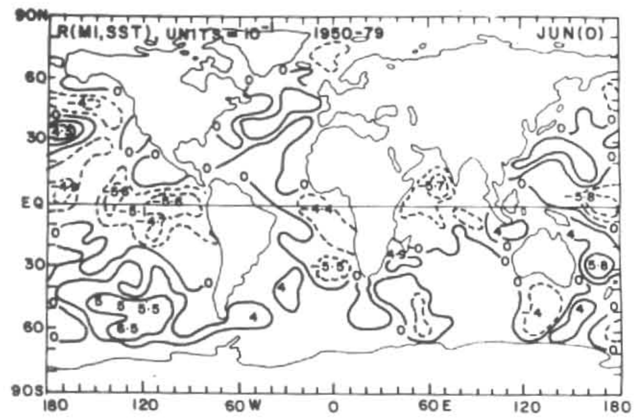

Fig. 8. Same as Fig. 2 but for SST anomaly for JUN (0)

starting from about a year and a half earlier to monsoon and persisting for about three seasons are generally favourable for a good monsoon precipitation and *vice-versa.* During the next two seasons the correlations in this key region tend to weaken, transitioning towards the reversal sign from positive correlations to negative correlations commencing from the eastern most equatorial Pacific region and spreading to almost entire Pacific equatorial belt by APR (0), *i.e.,* by the season just preceding the summer monsoon. This suggests that the SST anomaly in the east equatorial Pacific has a tendency to change sign during the northern spring. It is consistent with the findings of Cane and Zabiak (1985) and others who argue that the atmosphere and ocean become decoupled during spring time due to climatological factors.

The north Pacific basin reveals two more regions of teleconnection with the monsoon. The latitudinal belt between 40°N and 50°N and to the east of date-line shows significant negative correlations during about 6 months prior to monsoon [Figs. (6-8)]. This was amply demonstrated after the recent ENSO event of 1986-87 The region of north Pacific was much cooler (~ 1°C) than normal during December 1987 to May 1988. This anomalous feature was followed by a good monsoon (MI = 1.6) in 1988. Also, it has been revealed that the monsoon which is phase-locked with the reversal of ENSO is generally good (Verma 1990).

A region of significant positive correlation around 30°N in the western and central-north Pacific is also revealed. This appears consistent with the mode of first empirical orthogonal function of the variability in the SST over the Pacific revealed by Weare *et al.* (1976), which is characteristic of ENSO, showing that the temperatures in the north-central Pacific vary out of phase with temperature anomalies in the eastern equatorial Pacific.

The correlations in the Indian Ocean basin at longer time-lags, say from JAN (−1) to OCT (−1), are generally very weak. This, therefore, would suggest that SST anomalies in the Indian Ocean, much before the onset of monsoon, are not relevant for the large-scale activity of the monsoon. About two seasons before the

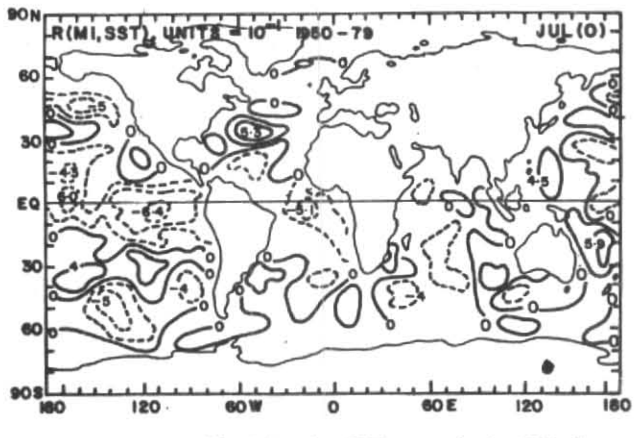

Fig. 9. Same as Fig. 2 but for SST anomaly for JUL (0)

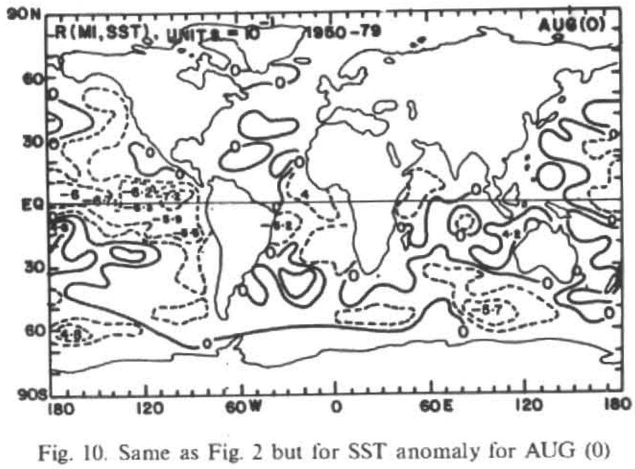

Fig. 10. Same as Fig. 2 but for SST anomaly for AUG (0)

summer monsoon onset over south Asia, *i.e.*, from JAN (0), the correlations start becoming significant. The region is generally located south of the equator and southeast of Madagaskar extending up to the southwest coast of Australia. The correlations are positive implying that warmer SSTs in this region are favourable for a good monsoon and *vice-versa*. There is progressive increase in the magnitude of the correlation as well as in the extent of the region from JAN (0), reaching maximum (cc about 0.6) during APR (0).

The statistically significant positive correlations in the southern Indian Ocean sub-tropical belt, antecedent to the summer monsoon, are of considerable importance. This relationship of monsoon with the SST in the Indian Ocean south of the equator, spread over about two seasons in advance of the monsoon, may be useful guidance tool for the long range forecast of monsoon and for monitoring its year-to-year variability.

Correlations, antecedent to monsoon, in the Atlantic basin, are generally weak and variable except being positive during OCT (—1) through JAN (0) in the equatorial belt. It would be rather difficult to seek any simple explanation for this.

3.2. *Correlations with SST anomalies concurrent to monsoon*

From the discussion that follows in this section it may be clear that correlation maps of individual months during this period are more appropriate instead of the representative month's map only. These are depicted in Figs. 8-11. The tropical belt, more prominently the belt between 10°S & 10°N in the central and eastern Pacific shows negative correlations, implying that warmer SSTs concomitant to monsoon, in the equatorial belt, are associated with the drier monsoon and *vice-versa*.

This is obviously due to El-Nino during which the dominant tropical centres of convective activity and rising motion shift eastward resulting in an altered configuration of east-west overturning circulation cells (Walker cells) and causing anomalous subsidence over south Asia.

Among all the oceanic basins, the most remarkable correlations, as high as —0.72, are revealed in the equatorial belt of Pacific. These correlations, actually, are in continuation from the months preceding to monsoon (section 3.1). The magnitudes of the correlations have increased. This could imply that the association of warmer (colder) SSTs with the drier (wetter) monsoon is much stronger during the concurrent months compared to the SST anomalies during the preceding months though the sign of the correlation remains same.

In the Indian Ocean, during this season of the northern summer, more relevant regions are the equatorial belt and the Indian seas, namely, the Arabian Sea and the Bay of Bengal. The correlations are negative but weak except in June (onset phase of monsoon) and in September (withdrawal phase of monsoon) when the Indian seas reveal stronger negative correlations. This suggests the association of warmer SSTs in these regions with weaker monsoon. The relationship is physically plausible. The weaker monsoon (often linked with ENSO) implies shallow convection, less cloud cover and weaker lower tropospheric southwesterlies. These anomalies would tend to increase the radiational heating of the sea surface and reduce the upwelled cooling respectively—both the processes tending to increase the SST—hence the concurrent negative correlation between the north Indian Ocean SST anomalies and the monsoon precipitation.

It is interesting to note that the negative correlations in the Indian seas are weakest during July and August

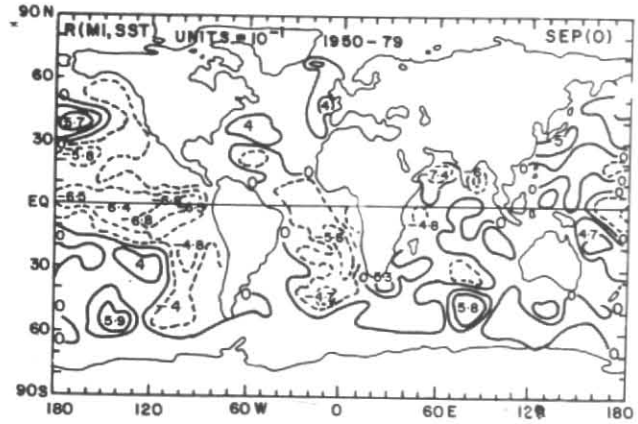

Fig. 11. Same Fig. 2 but for SST anomaly for SEP (0)

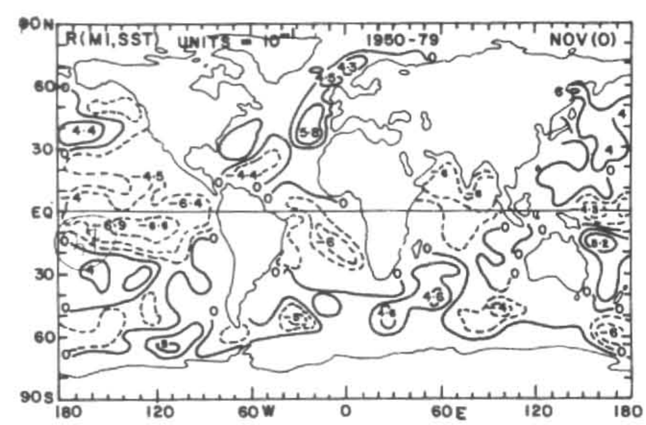

Fig. 12. Same as Fig. 2 but for SST anomaly for NOV (0)

(months of the peak monsoon activity). The lower tropospheric winds over the Indian seas are strongest during this peak monsoon period and play dominant role in determining the SST anomalies, which, because of thorough mixing of the thermocline by strong winds, are generally smaller in magnitudes. This leads to small interannual variations in the SST anomalies and hence its correlations with the Indian monsoon rainfall are weak and non-significant during July-August.

Prominent negative correlations with the SST anomalies in the equatorial Atlantic basin appear to be due to the same factors as in the north Indian Ocean since ENSO related anomalies are of global nature.

3.3. *Correlations with SST anomalies succeeding to monsoon*

Relationship of monsoon index with the SST anomalies during the season following the monsoon is depicted in Fig. 12 for the representative month—November. Qualitatively, the relationship reflected during this period, remains essentially the same as during the months concurrent to monsoon (as described in section 3.2). Negative correlations with the SST anomalies in the equatorial belts of all the three oceans persist.

In the Pacific equatorial belt correlations are significantly negative. However, in the eastern sector the magnitudes are higher and latitudinal extent wider. Poleward to this region of negative correlation, in the sub-tropics of either hemisphere, are regions of positive correlations. This pattern persists in all the three months of post-monsoon period and the relationship in the eastern equatorial belt shows tendency to strengthen slightly from October through December (not shown).

In the equatorial region and the Indian seas of the Indian Ocean the area of significant negative correlation increases and the magnitude decreases slightly as compared to September. It seems that the SST anomalies, more or less, persist for few months even after the monsoon withdrawal in September in the northern parts of the Indian Ocean.

In the Atlantic basin, the correlations are generally negative in the tropical belt and significantly large to south of the equator and off the African west coast. This might be linked with the large scale dry conditions associated with ENSO and modulated by the seasonal cycle.

4. Discussion and conclusions

Global maps of correlations between summer monsoon precipitation and sea surface temperatures are presented. The analysis has identified many centres of action in the world oceans which play significant role in the interannual variability of the global climate system. The most dominant one is in the equatorial Pacific, particularly in the central and eastern Pacific. Obviously, this is linked with ENSO. The present analysis has brought out clearly the phase relationship between Pacific SST anomalies and monsoon precipitation. The positive correlation of summer monsoon precipitation with the central and eastern equatorial Pacific SST anomalies about a year before the monsoon suggests that, in the statistical sense, the monsoon which follows after about a year of occurrence of a warm episode of ENSO, is generally wetter or good. Such a long time lag-relationship can not take place directly between the SST anomaly and monsoon precipitation. Then what could be the cause of such a relationship ? The answer, probably, lies in the results of the following studies : Jones and Kelly (1988) demonstrated that the temperature integrated over the entire Northern Hemisphere (NH) atmosphere was highly correlated with the east equatorial Pacific SST. They showed that the maximum positive correlation occurred when the NH temperatures lagged by six months. Verma *et al.* (1985) revealed a strong positive correlation between NH winter (January-February) temperature and the subsequent summer monsoon precipitation (*i.e.*, with about 6 months' lag). Northern Hemispheric temperature anomalies and snowcover anomalies being contemporary, one could as well link the correlation through snowcover over NH. The negative correlation between the Eurasian snowcover and the monsoon precipitation has been revealed in many studies (some recent ones are by Verma 1990 and Barnett *et al.* 1989). Thus, the one-year lag-relationship between equatorial Pacific SST and monsoon is well corroborated. It suggests that warmer equatorial central and eastern Pacific in summer months, followed by warmer winter in NH, are likely to lead to a wetter summer monsoon. This points out to one of the possible mechanisms in the interannual variability of the global climate system linking equatorial Pacific SST, NH atmospheric temperature and the Asiatic monsoon. The relationship also identified a parameter for monitoring and long-range forecasting of the monsoon.

In the Pacific, one more key region of teleconnection with the monsoon is revealed. SST anomalies in the belt between 40°N and 50°N close to the dateline show significant negative correlations during about six months prior to monsoon.

The correlations of monsoon with equatorial Pacific SST from about two seasons preceding through about two seasons following the monsoon offer to suggest a feedback mechanism between ENSO and monsoon. The correlation coefficients are negative throughout, but the magnitude and the extent increase during this period, spreading in the equatorial Pacific from east to west. This suggests a positive feedback between ENSO and monsoon in which the warm SST anomaly creates weak monsoon (or negative precipitation anomaly) over south Asian region, which in turn enhances the warm SST anomaly. This feedback mechanism can not continue further, probably beyond one cycle, as by that time the summer monsoon perturbation has withdrawn from southeast Asia with the advance of season in the annual cycle. On the other hand, the energy available might strengthen the Walker circulation which tends to restore the normal conditions over the tropical Pacific, conducive for reversal of ENSO.

The analysis has identified two key regions in the Indian Ocean, whose SST anomalies show strong relationship with the monsoon. The central Indian Ocean basin south of the equator shows strong positive correlaions with SST anomalies occurring during late northern winter and spring. The relationship of summer monsoon rainfall over India with the preceding season's SST anomalies in the central Indian Ocean is of significance as they may provide a useful guidance tool for the long-range forecast of monsoon well in advance. Another key region in the Indian Ocean lies well within the monsoon circulation consisting of the Arabian Sea and the Bay of Bengal. The relationship here is negative occurring during the period of monsoon and during the post-monsoon season.

Monsoon teleconnections with the SST anomalies in the Atlantic basin are generally weak and variable except during the season preceding to monsoon, in the equatorial belt.

Acknowledgements

The author gratefully acknowledges his thanks to Dr. A.H. Oort of Geophysical Fluid Dynamics Laboratory, Princeton University, U.S.A. for making available the COADS sea surface temperature data for the study and offering valuable suggestions. The author also thanks the Director, Indian Institute of Tropical Meteorology, Pune for his encouragement.

References

Barnet, T.P., Dumenil, L., Schlese, U., Roeckner, E. and Latif, M., 1989, "The effect of Eurasian snow-cover on regional and global climate variations", *J. Atmos. Sci.*, **46**, 661-685.

Bjerknes, J., 1966, "A possible response of the atmospheric Hadley circulation to equatorial anomalies of ocean temperature" *Tellus*, **18**, 820-829.

Bjerknes, J., 1969, "Atmospheric teleconnections from the equatorial Pacific", *Mon. Weath. Rev.*, **97**, 163-172.

Cane, M.A., Zebiak, S.E., 1985, "A theory for El-Nino and the Southern Oscillation", *Science*, **228**, 1085-1086.

Charney, J.G. and Shukla, J., 1981, Predictability of monsoons, *Monsoon Dynamics*, Eds Sir James Lighthill and R.P. Pearce, Cambridge Univ. Press, 99-110.

Folland, C.K., Palmer, T.N. and Parker, D.E., 1986, "Sahel rainfall and worldwide sea temperatures, 1901-85", *Nature*, **320**, 602-607.

Hastenrath, S., 1984, "Interannual variability and annual cycle : mechanisms of circulation and climate in the tropical Atlantic sector, *Mon. Weath. Rev.*, **112**, 1097-1107.

Jones, P.D. and Kelly, P.M., 1988, Causes of interannual global temperature variations over the period since 1861. 'Long and short term variability of climate—lecture notes in earth sciences 16', Eds H. Wanner and U. Siegenthaler, Springer-Verlag, 18-34.

Joseph, P.V. and Pillai, P.V., 1984, "Air-sea interaction on a seasonal scale over north Indian Ocean—Part I : Interannual variations of sea surface temperature and Indian summer monsoon rainfall", *Mausam*, **35**, 323-330.

Joseph, P.V. and Pillai, P.V., 1986, "Air-sea interaction on a seasonal scale over north Indian Ocean—Part II : Monthly mean atmospheric and oceanic parameters during 1972 and 1973", *Mausam*, **37**, 159-168.

Keshavamurty, R.N., 1982, "Response of the atmosphere to sea surface temperature anomalies over the equatorial Pacific and the teleconnections of the southern oscillation", *J. Atmos. Sci.*, **39**, 1241-1259.

Lamb, P.J., 1978, "Large-scale tropical Atlantic surface circulation patterns associated with subsaharan weather anomalies", *Tellus*, **30**, 240-251.

Lau, N.C., 1985, "Modelling the seasonal dependence of the atmosphere response to observed El-Ninos in 1962-76", *Mon. Weath. Rev.*, **113**, 1970-1996.

Lough, J.M., 1986, "Tropical Atlantic sea surface temperature and rainfall variations in subsaharan Africa", *Mon. Weath. Rev.*, **114**, 561-570.

Parthasarathy, B., Sontakke, N.A., Munot, A. and Kothawale, D.R., 1990, "Vagaries of Indian monsoon rainfall and its relationship with regional/global circulation", *Mausam*, **41**, 301-308.

Philander, S.G.H., 1990, El-Nino, La-Nina and the Southern Oscillation, International Geophysics Series, **46**, Academic Press, Inc., 9-56.

Pisharoty, P.R., 1981, Sea surface temperature and the monsoon, *Monsoon Dynamics*, Eds. Sir James Lighthill and R.P. Pearce, Cambridge Univ. Press, 237-251.

Rao, K.G. and Goswami, B.N., 1988, "Interannual variations of sea surface temperature over the Arabian Sea and the Indian monsoon : A new perspective", *Mon. Weath. Rev.*, **116**, 558-568.

Saha, K.R. and Bavadekar, S.N., 1973, "Water vapour budget and precipitation over the Arabian Sea during the northern summer", *Quart. J.R. Met. Soc.*, **99**, 273-278.

Shukla, J., 1975, "Effects of Arabian Sea surface temperature anomaly on Indian summer monsoon : A numerical experiment with the GFDL model", *J. Atmos. Sci.*, **32**, 503-511.

Shukla, J. and Mishra, B.M., 1977, "Relationship between sea surface temperature and wind speed over central Arabian Sea and monsoon rainfall over India", *Mon. Weath. Rev.*, **105**, 998-1002.

Verma, R.K., Subramaniam, K. and Dugam, S.S., 1985, "Inter-annual and long-term variability of the summer monsoon and its possible link with northern hemispheric surface air temperature", *Proc. Indian Acad. Sci. (Earth Planet. Sci.)*, **94**, 187-198.

Verma, R.K., 1990, "Recent monsoon variability in the global climate perspective", *Mausam*, **41**, 315-320.

Weare, B.C., Navato, A. R. and Newell, R. E., 1976, "Empirical orthogonal analysis of Pacific sea surface temperatures", *J. Phys. Ocean*, **6**, 671-678.

Wright, P.B., 1987, "Variations in tropical Atlantic sea surface temperatures and their global relationship", Report 12, Max-Planck-Institut fur Meteorologie, Hamburg, 52 pp.