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Applications of satellite data in the study of monsoon variability

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Abstract. This paper discusses the use of satellite data for studying climate change, with particular emphasis on the inter-annual variability of the Indian southwest monsoon. Precipitation estimates made from INSAT-1B radiance data are shown to bring out the variations that occurred in the monsoon rainfall of 1987 and 1988. Outgoing Longwave Radiation derived from INSAT-1B shows good correspondence with precipitation patterns.

Keywords. INSAT data; monsoon variability; OLR; SST; satellite precipitation estimates.

1. Introduction

It may seem paradoxical that scientists studying global and climate change are making increasing use of an observational record that is relatively the shortest, viz., satellite data. Meteorological satellites are even being regarded as "sentinels" for the monitoring of climate and global change (Ohring *et al* 1991). The popularity of satellite data stems from the fact that the short-period availability, which is less than two decades in most cases, can be tolerated in view of the extensive spatial coverage provided by the meteorological satellites.

Satellites are the best and sometimes the only means of observation of many climatologically significant variables such as the earth-atmosphere radiation budget, extent of snow cover and sea ice, large-scale oceanic precipitation, ozone depletion, sea surface temperature, vegetation status and many more. The inter-annual variability associated with many climatic features is a result of the thermal and dynamic interaction between the earth's surface and the atmosphere through non-linear feedbacks. This is where satellites can be very important for monitoring anomalous changes in climatic behaviour.

The need to work out climatic teleconnections from satellite data has been recognised in the global observational and modelling programmes such as TOGA (Tropical Ocean Global Atmosphere) and WOCE (World Ocean Circulation Experiment). Satellite data can also fulfil to a large extent the requirements of climate models, particularly in the realistic parameterisation of clouds and surface albedo, both of which are vital components of the earth's radiation budget.

The present paper is confined to the inter-annual variability of the Indian southwest monsoon and contains a review of work done with various types of satellite data with particular reference to INSAT data. The Indian monsoon rainfall has not shown significant long-term decrease or increase in the past, but it does have a large variability on the inter-annual time scale. The actual causes of the inter-annual variability have not yet been fully understood. Correlations between Indian monsoon rainfall and the Eurasian snow cover of the preceding winter as also the northern hemispheric surface air temperature, have been found to be physically real, though small. Sensitivity experiments peformed with GCM models suggest that slowly varying boundary conditions of surface air temperature, sea surface temperature, snow cover and soil moisture can affect the inter-annual variability of monsoon circulation. However, the ENSO (El Nino – Southern Oscillation) phenomenon has been found to have a predominant influence on the inter-annual variations of the monsoon. There are strong associations between El Nino events and drought over India and between warm sea surface temperature anomaly over the equatorial Pacific Ocean and Indian monsoon rainfall deficit. The use of satellite data and satellite-derived parameters in the study of the inter-annual variability of the monsoon therefore holds out great promise. This is discussed in detail in the following sections.

2. Satellite cloud climatologies

It was in the late seventies that the prediction of cloudiness became one of the aims of climate models and this led to further work on cloud-radiation and cloud-climate interactions. It also brought out the need for an improved knowledge of the global cloud cover distribution and its variations on different time scales.

Some of the earliest attempts to derive a climatology of satellite-observed cloudiness over the tropics were those of Sadler and his co-workers (1969, 1976) and Miller and Feddes (1971). More recently, Garcia (1985) used NOAA satellite mosaics for the years 1971 to 1983 to identify areas of large-scale organised convection over the global tropics. The areas of convection appear in satellite imagery, both visible and infra-red, as what are called Highly Reflective Clouds (HRC). The identification of HRC was done manually, implying subjectivity, and there are other problems like inadequate temporal sampling over the diurnal cycle, different satellites having different observation times, etc. Garcia has compiled global maps of monthly mean HRC and its coefficient of variation and month-wise HRC means over the 13-year period. The maps show that over the monsoon regime, low values of year-to-year variability of HRC are associated with high values of HRC, as may perhaps be expected. This is particularly so over the eastern Arabian Sea in June, over the north Bay of Bengal in June-August and over the equatorial Indian Ocean in September. Garcia's atlas is a valuable data source for the Indian Ocean area for the pre-INSAT period.

A similar climatological exercise (IMD, 1990), based upon subjective measurement of satellite cloudiness through APT pictures of India and the neighbourhood, was made for the years 1982–1986. This gives the mean cloudiness, coefficient of variation and probability of occurrence of cloudiness < 2 octas and > 6 octas, on monthly, fortnightly and weekly basis during the monsoon months. The weekly maps are indicative of the advance, stabilisation and retreat of the south–west monsoon over the country.

The International Satellite Cloud Climatology Project (ISCCP) was conceived to take advantage of the global coverage provided by pooling together data from the geostationary and polar-orbiting meteorological satellites of different countries. The first aim of ISCCP was to build up a global satellite cloud climatology based upon 1983–1988 data, but the project has been extended beyond this period. It is recognised that the conversion of satellite-measured radiance information to cloud cover indices is not a straightforward process, and needs considerable refinement and standardisation. The development of cloud algorithms is, therefore, a major component of ISCCP besides collection and processing of satellite data and its archival.

ISCCP aims at providing a means to validate cloud fields generated by climate models. It will also aid in the design of parameterisation schemes for the representation of cloud-radiation feedback in simpler climate models. It will also provide the basic data for the diagnostic studies that must be carried out to complement those using climate models.

3. Satellite-based precipitation estimates

The earliest attempts at estimating precipitation from satellite imageries were those of Barrett (1970). Since then a large number of workers have been making efforts in this field. However, the only variation in their approach seems to be in the choice of the cloud characteristics and the value of the rain rate. The satellite-based precipitation estimates work out better with time-scales of a week or month and larger space scales such as $1° \times 1°$ or $2{\cdot}5° \times 2{\cdot}5°$ lat./long. grids. In general, Highly Reflective Clouds in the visible pictures, clouds with cloud top temperatures colder than 235°K, and regions with Outgoing Longwave Radiation (OLR) less than $240 W/m^2$ are characteristic indices of large-scale precipitation. The validation of the estimates with ground truth obtained from raingauge networks, ship observations and radars is a very important aspect on which enough efforts have not been put in.

A widely used method of estimating large-scale precipitation from infra-red radiance measurements made by satellites is that of Arkin (1979), developed further by Arkin and Meisner (1987). The method is well-suited for geostationary meteorological satellites whose data is available at least every 3 hours. Arkin defines the fractional clouding as

$$F_c = \frac{\text{Sum of pixels colder than a threshold temperature}}{\text{Total number of pixels}}$$

where the threshold temperature is typically 235°K and the area over which fractional clouding is computed is $2{\cdot}5 \times 2{\cdot}5°$lat./long. in extent. The precipitation is estimated as

$$P = K \times F_c \times N_o$$

where K is the rain rate, taken as 71·2 mm/day, and N_o is number of days over which the images are used.

Kelkar and Rao (1990) computed monthly averages of large-scale precipitation obtained from INSAT-1B for the area 40°–100°E and 35°N–25°S for the four monsoon months June, July, August and September over three years 1986, 1987 and 1988. These are reproduced in figure 1. Monthly maps have also been brought out for the period June 1986 to December 1988 by IMD (1989, 1990).

The 3-year mean pattern for June shows two maxima of rainfall, one in the north Bay of Bengal (> 700 mm) and the other in the eastern Arabian Sea (> 500 mm) with a minimum over Sri Lanka (< 100 mm). In July, the maximum rainfall area over Arabian Sea gets dissipated and the Bay maximum is less intense and moves south-eastwards. The 100 mm isopleth covers almost the whole of India. In August, the

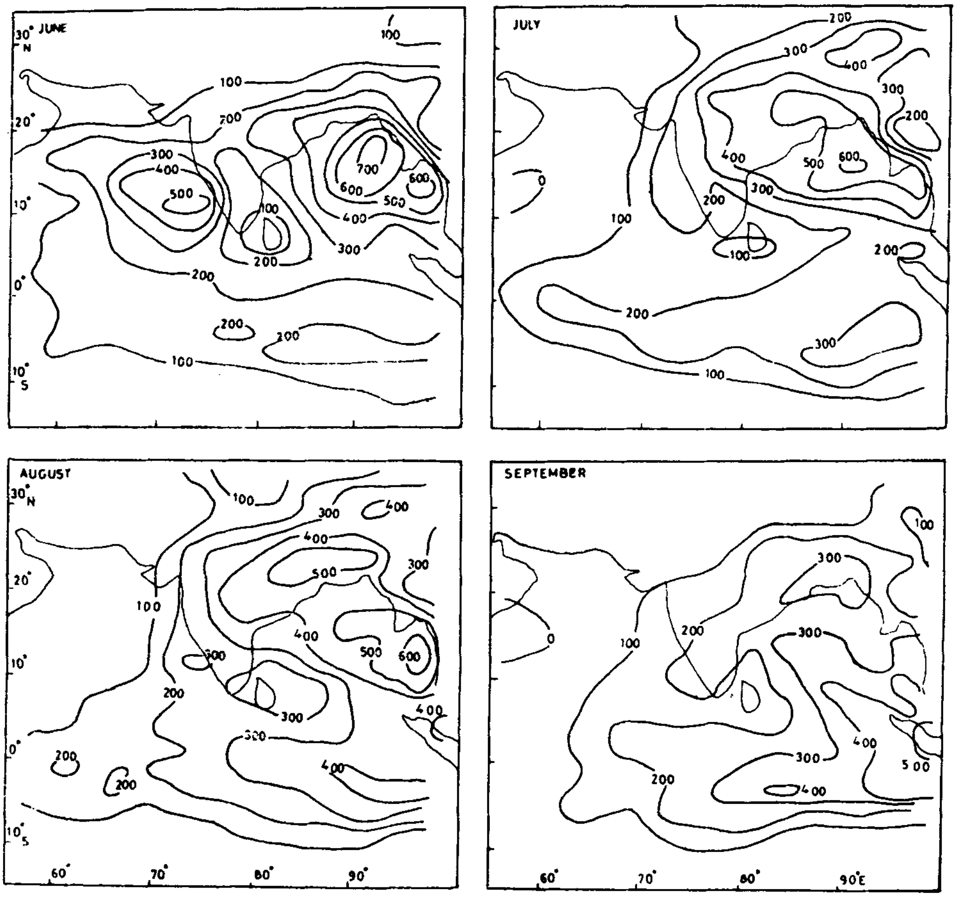

Figure 1. Monthly precipitation estimates (in mm.) from INSAT-1B for June, July, August and September, averaged over 1986–1988.

July pattern persists to a large extent, but in the southern hemisphere, the belt of heavy rainfall is seen to intensify particularly off Sumatra (> 400 mm). The September pattern resembles the monsoon withdrawal pattern very well.

The monsoon season of 1987 was characterised by a large deficiency of rainfall over most parts of India, while the 1988 monsoon was one which gave abundant rain all over. The monsoon of 1986 was an in-between situation. Thus the satellite-based precipitation averages of figure 1, although based on only 3 years data, cover two opposite extreme situations and therefore could be considered meaningful.

Figures 2 and 3 show the anomalies in satellite-based precipitation for 1987 and 1988 from the 1986–88 monthly averages. In 1987, although the onset of monsoon was quite normal, its northward movement was retarded. This is seen in the predominantly negative anomalies during June and July. In August, positive anomalies are seen over northwest India and Bay of Bengal. In September again, negative anomalies are commonly noticeable. In 1988, a clear contrast prevails in comparison with 1987, with positive anomalies over most of the area in all the months except over parts of the Bay in June and August.

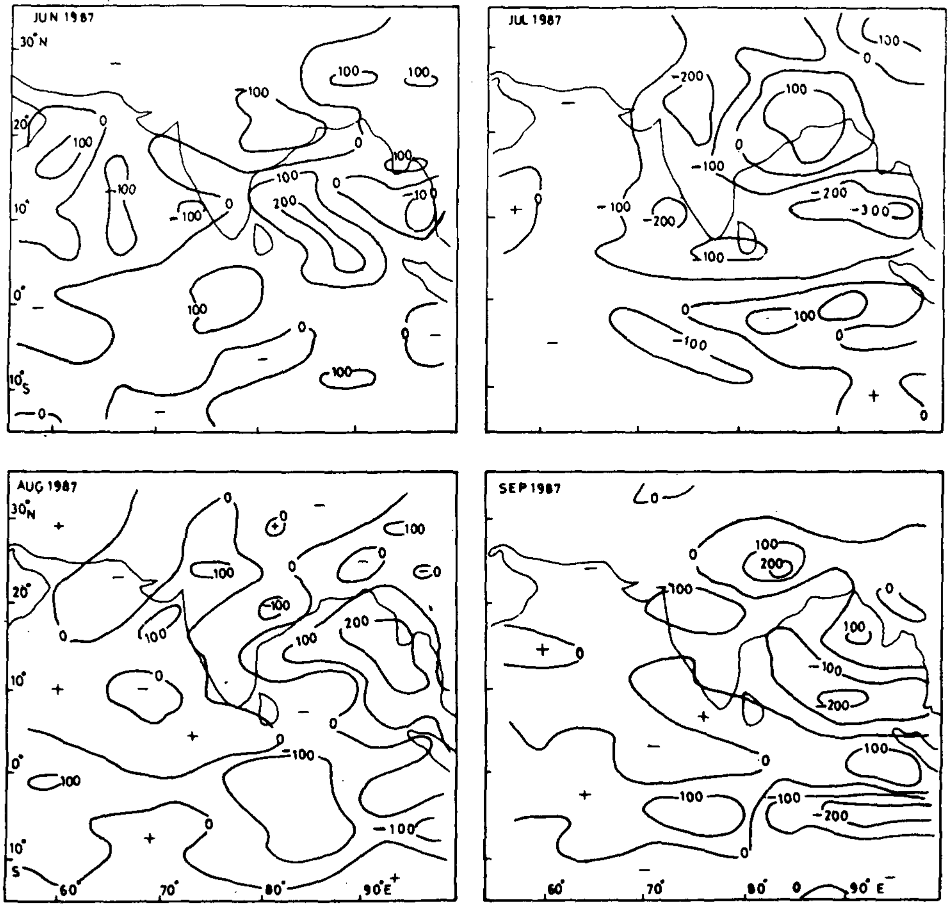

Figure 2. Anomalies of monthly precipitation estimates (in mm.) from INSAT-1B for June, July, August and September 1987 compared to monthly average for 1986–1988.

4. Outgoing Longwave Radiation (OLR)

Scanning radiometers on-board the meteorological satellites measure the radiance in narrow windows within the visible and infra-red spectra. For example, in the case of the INSAT VHRR these windows are 0·55–0·75 and 10·5–12·5μ respectively. The broad-band outgoing longwave radiation and the planetary albedo are derived indirectly from such window measurements by applying physical and/or statistical algorithms. Further, the OLR data sets of different satellites are not strictly comparable because of differences in the filter response curves, radiometer calibration, instantaneous field of view of the sensor, observation times during the diurnal cycle, etc. A 10-year climatology of OLR derived from NOAA polar orbiting satellite data over the years 1974 to 1983, with corrections applied for changes in satellites and procedures, was compiled by Janowiak *et al* (1985). However, a finer analysis has shown that the possibility of the existence of a bias in the NOAA OLR data for 1982 onwards cannot be ruled out (Gadgil *et al* 1990).

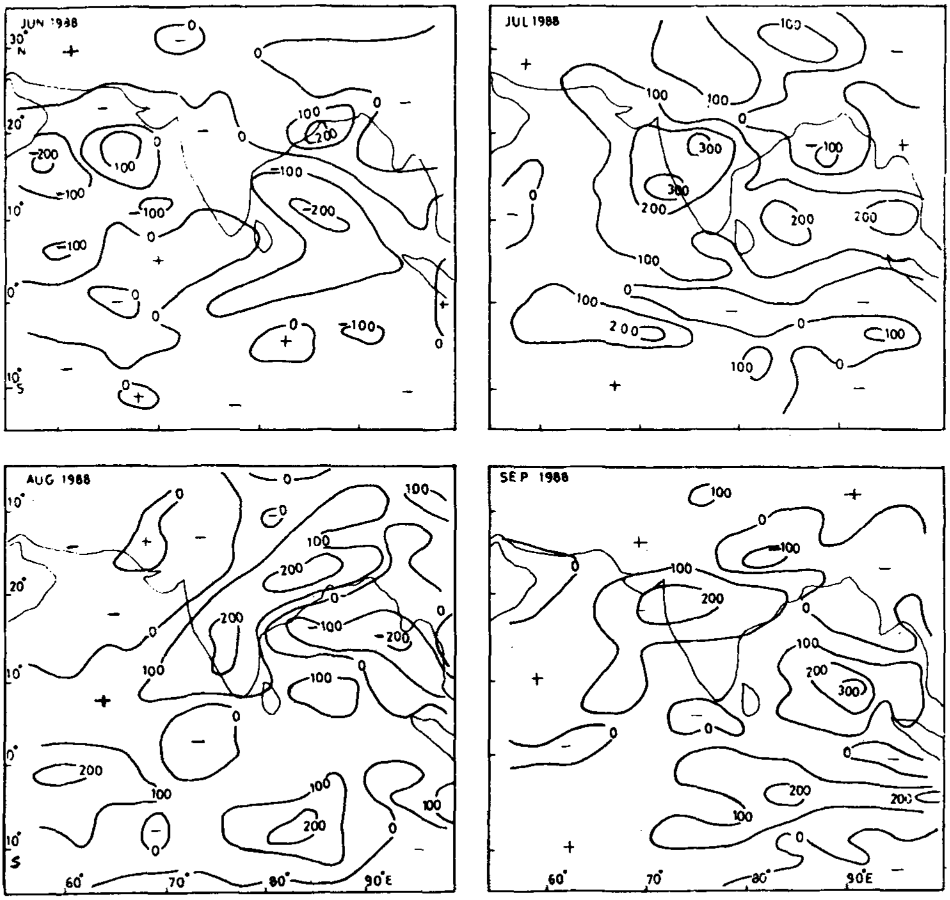

Figure 3. Anomalies of monthly precipitation estimates (in mm.) from INSAT-1B for June, July, August and Sept. 1988 compared to monthly average for 1986–1988.

The Earth Radiation Budget (ERB) sensors of the NIMBUS-6 and -7 satellites have provided another data base over the 10-year period 1975–85 (Bess *et al*, 1989). The ERB data was obtained with Wide Field of View (WFOV) radiometers which recorded broad-band short and longwave radiances.

The OLR is primarily modulated by the temperature of the earth's surface and/or that of the overlying cloud top. As such, OLR decreases poleward from 30° latitudes in both hemispheres, with decreasing temperature. However, in the tropical zone, with its suppressed variations in temperature, the OLR becomes more dependent on the cloudiness. Thus the lowest values of OLR over the tropics tend to be associated with the areas of strongest convection and precipitation.

Over the Indian region and its neighbouring Indian Ocean area, INSAT-1B OLR monthly mean patterns are very similar to those of precipitation estimates during the southwest monsoon months (Arkin *et al* 1989) as may be seen from figure 4(a). The relationship between the two is, of course, inverse. Rao *et al* (1989) have also

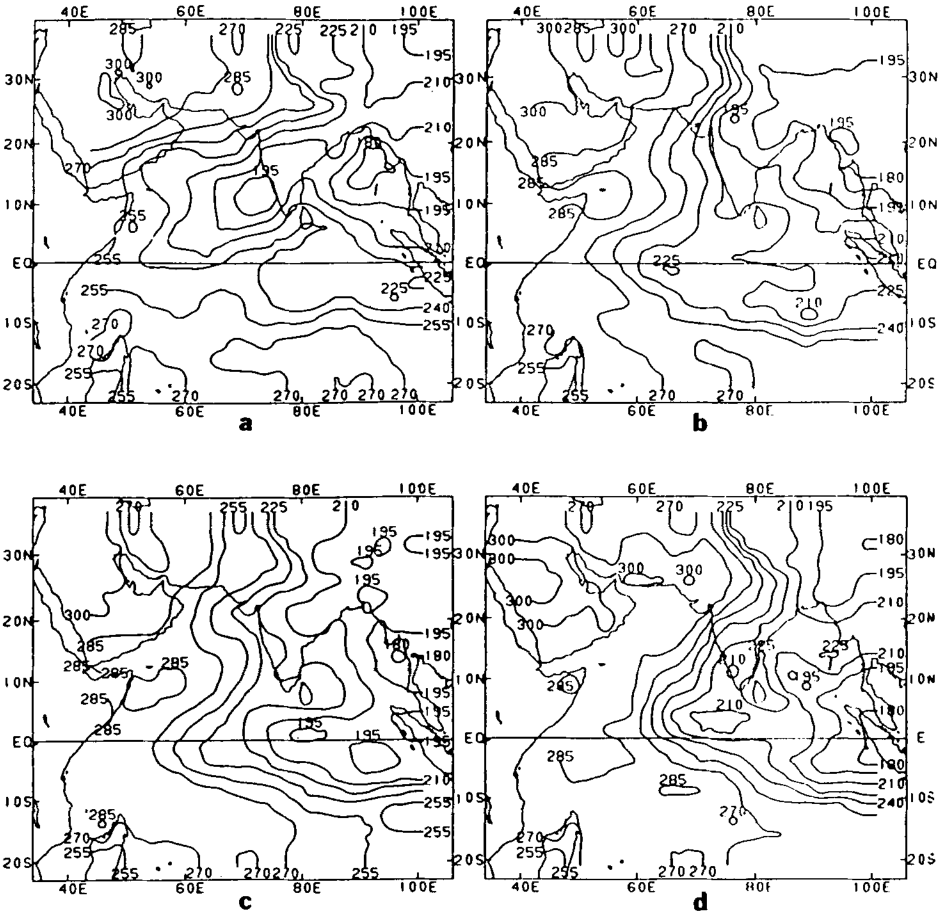

Figure 4(a). Monthly mean OLR (in watts/m^2) from INSAT-IB for (a) June, (b) July, (c) August and (d) September 1986.

shown that for this region, the INSAT-1B OLR has a threshold value of 250 W/m^2 which demarcates raining from non-raining areas. However, the correspondence between OLR and precipitation is not of a one-to-one nature, implying that while OLR is a good index of convection activity, all precipitation does not arise from convective clouds.

Satellite OLR has come into wide use as a proxy for large-scale rainfall in studies of inter-annual variability. The analysis of NOAA OLR data set by Nitta and Yamada (1989) suggests that the level of activity of tropical convection was generally higher in the eighties than in the seventies. Ardanuy and Krishnamurti (1987) used the NIMBUS OLR fields to examine inter-annual variability with particular reference to the 1982–83 ENSO event.

It is certainly to be expected that as a larger and reliable OLR data set gets built up over the coming years, the OLR anomalies will find an important place in the study of inter-annual variations of the monsoon.

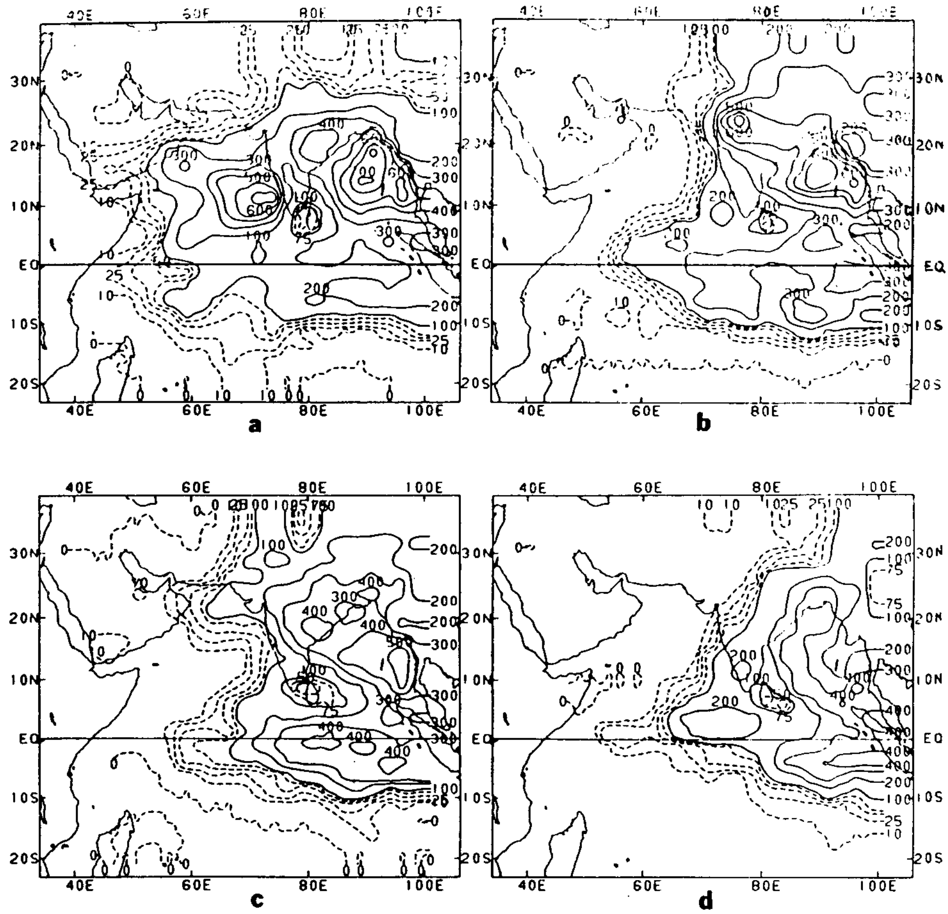

Figure 4(b). Monthly precipitation estimates (in mm.) from INSAT-1B for (a) June, (b) July, (c) August and (d) September 1986.

5. SST-Precipitation relationships

The El Nino Southern Oscillation (ENSO) phenomenon is now known to be strongly associated with the inter-annual variability of rainfall in the tropics in general and the Indian monsoon in particular. A knowledge of this association can have great value in the prediction of monsoon behaviour if the occurrence of ENSO is monitored or if it can be predicted.

During warm episodes of El Nino, negative precipitation anomalies over the Indian Sub-continent are known to be associated with the positive SST (Sea Surface Temperature) anomalies over the eastern and central equatorial Pacific Ocean. The first appearance of positive SST anomalies near the South American coast usually precedes the monsoon by many months (Rasmusson and Carpenter 1983).

In the mean patterns, the location and seasonal migration of the oceanic convective zones and regions of high SST largely coincide (Rasmusson and Arkin 1985). Specially, the tropical oceanic regions of OLR less than 240 W/m^2 are found to be confined

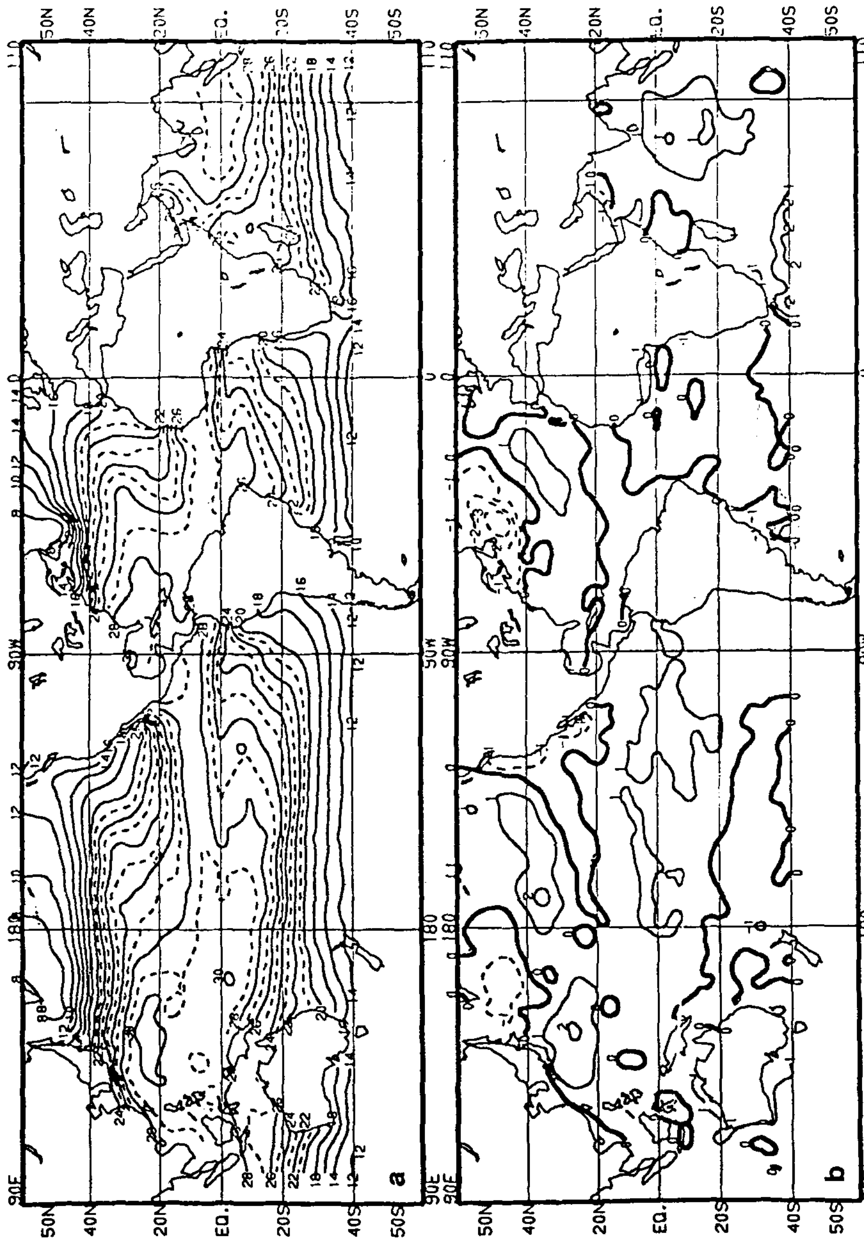

Figure 5. Monthly mean SST (°C) and its anomaly for July 1991, as a typical example of the maps published in Climate Diagnostics Bulletin.

to the warm areas which are bounded by the 27 or 28°C isotherms of SST. This association is important to the understanding of the ENSO phenomenon. The major sea-air forcing takes place in the equatorial Pacific. Here a relatively small SST anomaly in a climatologically warm region produces a much more pronounced atmospheric response than would occur with a much larger SST anomaly in a dynamically unfavourable cold region.

The close monitoring of the SST anomalies over the global ocean has now become possible through the SST retrievals routinely made from meteorological satellites, primarily the polar-orbiting satellites. The accuracy of satellite SST retrievals has been improving over the years and monthly SST anomaly fields for the tropical oceans are now routinely published in the Climate Diagnostic Bulletins of the Climate Analysis Centre, Washington D.C., U.S.A. (figure 5). The anomalies are derived with reference to the global SST (COADS) climatology of Reynolds (1988). Although SST's are also being extracted from INSAT data (Kelkar *et al* 1989) for the Indian Ocean region, the extensive clouding over the area during the monsoon season makes SST retrieval very difficult. It is, therefore, of limited use in establishing local SST-precipitation relationships over the Indian Ocean area.

The negative correlation between SST anomalies over the equatorial eastern and central Pacific and the Indian monsoon rainfall has been found to be significant (Angell 1981; Rasmusson and Carpenter 1983). The correlation is weak with respect to SST of April and May but improves with the progress of the monsoon season. However, regional SST anomalies over the Indian Ocean have small inter-annual variations and their correlations with monsoon rainfall have not been conclusively established. Studies with ship SST measurements over the Arabian Sea, however, indicate that in heavy rainfall years, the sea surface is relatively warmer during the months of April-June and colder during August-October (Rao and Goswami 1988).

6. Concluding remarks

The monsoon visits India every year and it is a very regular phenomenon in the broad climatological sense. In the context of global and climate change, its year-to-year variations from the mean are, however, very important. While the intra-seasonal variations of the monsoon are relatively well-observed and well-understood, the inter-annual variations are not. Satellite observations and derived parameters, though available for the recent twenty years or less, have already made a significant contribution to studies of inter-annual variability of tropical climate. As more data become available over the coming years, on regional and global scales, satellite data would certainly be expected to provide further insights into hitherto unknown facets of the problem.

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