

Application of microwave remote sensing data for Indian summer monsoon studies

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सार – वायुमंडलीय और महासागरीय प्रक्रियाओं का अध्ययन करने के लिए पिछले कुछ दशकों से सूक्ष्मतरंग दूर संवेदन आँकड़ों का अधिक उपयोग किया जा रहा है। सूक्ष्मतरंग संवेदकों का लाभ यह है कि ये मेघों और कुछ हद तक वर्षा का पता लगा सकते हैं। सूक्ष्मतरंग दूर संवेदन प्रणाली से मानसून संबंधी अध्ययनों को महत्वपूर्ण दिशा मिली है क्योंकि ग्रीष्मकालीन मानसून ऋतु के दौरान एशिया के अधिकांश भाग मेघाच्छादित होते हैं और इस क्षेत्र में दृश्य और अवरक्त संवेदक ठीक से काम नहीं करते। सूक्ष्मतरंग संवेदन की सहायता से भारतीय ग्रीष्मकालीन मानसून को समझने और उसका पूर्वानुमान लगाने विशेष रूप से मानसून का आगमन, मानसून के अंत मौसमी दोलन, वर्षा की दैनिक परिवर्तनशीलता और परिसीमा स्तर अभिवाहों के संबंध में प्राप्त महत्वपूर्ण परिणामों का सार इस शोध-पत्र में प्रस्तुत किया गया है।

ABSTRACT. Microwave remote sensing is increasingly being used for studying the atmospheric and oceanic processes for the last few decades. Advantage of the microwave sensors is that they can see through the clouds and to some extent rain. Monsoon studies received considerable thrust from microwave remote sensing because clouds cover most parts of Asia during the summer monsoon season and the visible and infrared sensors poorly perform over this region. This paper summarizes the significant results obtained towards the understanding and forecasting of Indian summer monsoon especially monsoon onset, intraseasonal oscillation of monsoon, diurnal variability of rainfall and boundary layer fluxes with the help of microwave remote sensing.

Key words – Microwave remote sensing, Indian summer monsoon, Monsoon onset, Intraseasonal oscillation, diurnal variability and Remote sensing.

1. Introduction

Asian summer monsoon is caused by the differential heating of huge Asian landmass and the adjoining Indian Ocean during northern summer. Over India, summer monsoon normally arrives between 30 May and 2 June according to different estimates with a standard deviation of 8-9 days. In countries like India, whose economy is mainly depended on agriculture, an early or late arrival of monsoon would adversely affect the different sectors of the economy. During the summer monsoon season, rainfall has active and weak spells generally called as active and weak phases which are associated with the repeated northward propagation of the maximum cloudiness zone from Indian Ocean to the monsoon trough with a period of about 30-60 days (Sikka and Gadgil, 1980; Madden and Julian, 1994). Typical lower level (850 hPa) circulation prevails during active and weak phases are shown in Fig. 1.

Due to paucity of data, it is extremely difficult to monitor these atmospheric and oceanic processes and their interactions over the oceanic regions. Satellites are useful to monitor these processes in remote regions of the globe. In the initial phases of the satellite era, monsoon was monitored with the help of visual imageries provided by the polar orbiting satellites. Towards the end of the seventies the sounders in polar orbiting satellites; the shifting of the US GOES satellite to the Indian latitudes during MONEX experiment and the launch of Japanese GMS satellites provided new avenues. The beginning of eighties saw the INSAT series of the meteorological satellites. The new generation of meteorological satellites such as METSAT, Megha-Tropiques, etc will provide much more atmospheric information over the Asian monsoon regions.

Generally dense clouds are present in most parts of the Indian subcontinent during the monsoon season. As

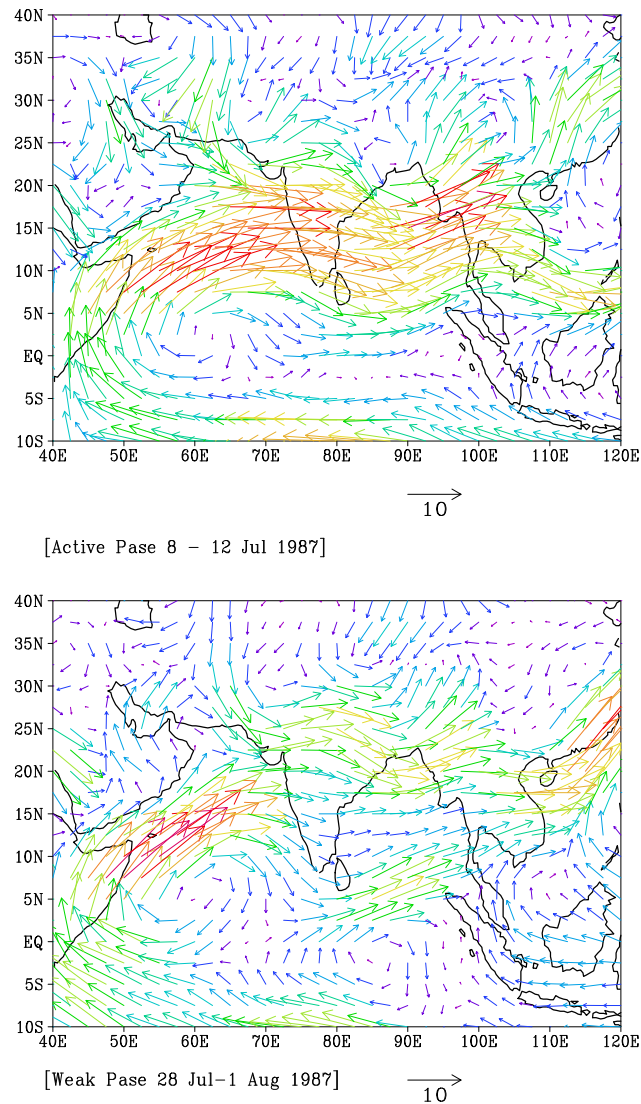


Fig. 1. Average 850 hPa winds from NCEP/NCAR reanalysis during (top) active [8-12 July 1987] and (bottom) weak [28 July-1 August 1987] phases of the Indian summer monsoon

the visible and infrared sensors can only see the cloud tops, it is difficult to monitor the meteorological and oceanic processes completely with the help of these sensors. In the last four decades, microwaves have been increasingly used for remote sensing. They have the capability to penetrate cloudiness, and to some extent rain. This paper summarizes the significant results obtained with the help of microwave remote sensing towards the understanding of Indian summer monsoon.

2. Microwave remote sensing

Microwave spectrum extends from 0.03 cm to 30 cm wavelength (frequency between 0.3 GHz and 300 GHz)

portion of the electromagnetic spectrum. Most important reason for using microwaves for remote sensing is their ability to penetrate clouds (to some extent rain) and some penetration into soil surface. However heavy rainfall attenuates the microwaves to some extent.

Microwave sensors can be used any time of the day or night because they are independent of sun as the source of illumination. Microwave sensors are generally divided into two categories according to their modes of operation. They are active and passive sensors. Active sensors use their own source of illumination and therefore have a transmitter and a receiver. Passive sensors (called as radiometers) simply measure the microwave radiation

emanating from the scene under observation. Passive sensors are used for monitoring sea surface wind speed, surface temperature, integrated water vapour, cloud liquid water, rain, etc. Active sensors are generally used for oceanic wind vector, sea surface heights and rainfall retrievals.

Use of microwave spectrum for the observation of planet Earth was first explored by the Soviet satellite Cosmos-243 launched on 23 September 1968. Since then, microwave radiometers have been carried onboard several spacecrafts including Cosmos 384, Nimbus 5, 6 and 7; Skylab; TIROS; SEASAT; Bhaskara, etc. Over the past three decades, microwave observations are being widely used for a number of meteorological applications worldwide. The Special Sensor Microwave Imager (SSM/I) flown onboard the Defence Meteorological Satellite Programme (DMSP) series of satellites since 1987, has proved to be extremely useful for meteorological analysis and forecasting applications. Space borne scatterometer for measuring ocean surface wind vector was first tried onboard Skylab in 1973. Subsequently SEASAT, ERS 1 & 2, ADEOS, Quikscat carried scatterometers. Altimeter measures ocean surface topography, significant wave height, and surface wind speed. Altimeter was first flown on Skylab and followed by GEOS, SEASAT, ERS-1, and TOPEX. Rain radars are meant for measuring rainfall in the tropical region. TRMM carried the first rain mapping radar.

India launched nearly identical two low orbiting satellites namely Bhaskara-I and Bhaskara-II in 1979 and 1981 respectively at an altitude of about 520 km. These two satellites carried microwave payloads called Satellite Microwave Radiometer (SAMIR). This is a passive multi-frequency microwave radiometer making observations of the earth's radiation in the 22 GHz water vapour channel. With the launch of Multi-frequency Scanning Microwave Radiometer (MSMR) onboard Oceansat-1, India also entered the important field of passive microwave remote sensing in a full-fledged manner. Some future microwave missions with active microwave sensors are planned in India and a few (*e.g.* Oceansat-2) are in advanced stages of completion.

2.1. *Basic principles of passive microwave remote sensing*

An object at absolute temperature T_o with surface emissivity ϵ greater than zero emits thermal radiation at all wavelengths. The brightness temperature can be $T_A = \epsilon T_o$. The surface emissivity has a value from zero to unity and is a function of surface roughness, polarization, incidence angle, complex dielectric constant, frequency and physical temperature. Thermal radiation power per unit bandwidth

is very weak at microwave wavelengths for most objects. In general, all objects both emits and reflects thermal radiation. If the intervening atmosphere between radiometer and object is lossy, the radiation emanating from the object will be attenuated, and the atmosphere itself will emit thermal radiation. A radiometer will thus yield a brightness temperature T_B given by the radiative transfer equation :

$$T_B = t (\epsilon T_o + R T_R) + (1-t) T_S$$

Where

t = atmospheric transmissivity

ϵ = emissivity of object

T_o = absolute temperature of object

R = power reflectivity of surface

T_R = equivalent absolute radiation temperature incident on object

T_S = absolute temperature of lossy atmosphere between object and radiometer

Changes in the observed brightness temperature could be due to one or more factors such as changes in emissivity, physical temperature of the surface or due to changes in atmospheric constituents. Measurement of brightness temperature at the resonance absorption frequencies of the atmospheric constituents (*e.g.* water vapour absorption frequencies are 22.235 GHz & 183 GHz) as well as in the window regions allow us to determine several atmospheric as well as surface geophysical parameters. It is to be remembered that the atmospheric parameters can be measured only over the Oceans. This is due to the fact that against the cool radiative background of ocean ($\epsilon = 0.4$), the warm radiative temperature of atmospheric water provides good contrast, whereas against the warm radiative background of land surfaces ($\epsilon = 0.9$) the atmospheric water does not give such a contrast.

From the brightness temperature, geophysical parameters are estimated employing several procedures. The theoretically simplest but in practice very expensive and difficult method of estimation is the empirical regression method. In this method, simultaneous data of brightness temperature and parameters are collected in large number and under varying weather conditions. Then a multiple regression of each parameter with the brightness temperature is made. Once the coefficients of these regression are known from a sizeable data set,

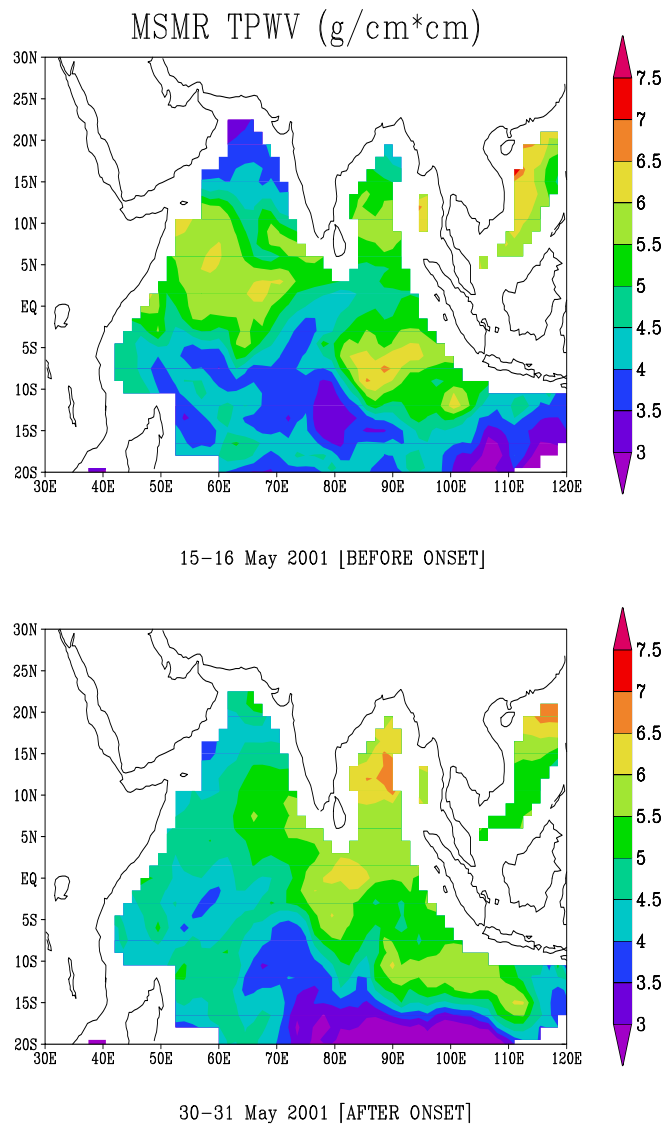


Fig. 2. MSMR measured total precipitable water vapour over Indian monsoon region few days prior to and after the monsoon onset in 2001. Onset occurred in 2001 on 23 May (one week earlier than normal date)

hopefully they will be applicable at other times and places so that the meteorological or oceanic parameters could be estimated from brightness temperature observations even without the need of *in situ* observations.

2.2. Active microwave sensors

Active microwave sensors (radars), operated from satellites are scatterometers, altimeters and Synthetic Aperture Radars (SAR). Scatterometers can measure backscattered power from the surface at different azimuth

angles. These measurements can be related to the roughness spectrum of the ocean surface and the wind vectors (which cause these roughness). Altimeters are nadir looking short pulse radars meant primarily for measurement of sea level. But altimeters also measure the strength of the backscattered power. Sea surface wind speed is deduced from it with the help of an algorithm connecting surface wind speed with backscattering coefficient. SAR is radar, which makes use of a technique known as aperture synthesis to achieve high spatial resolution. Detailed discussion about the theory of active

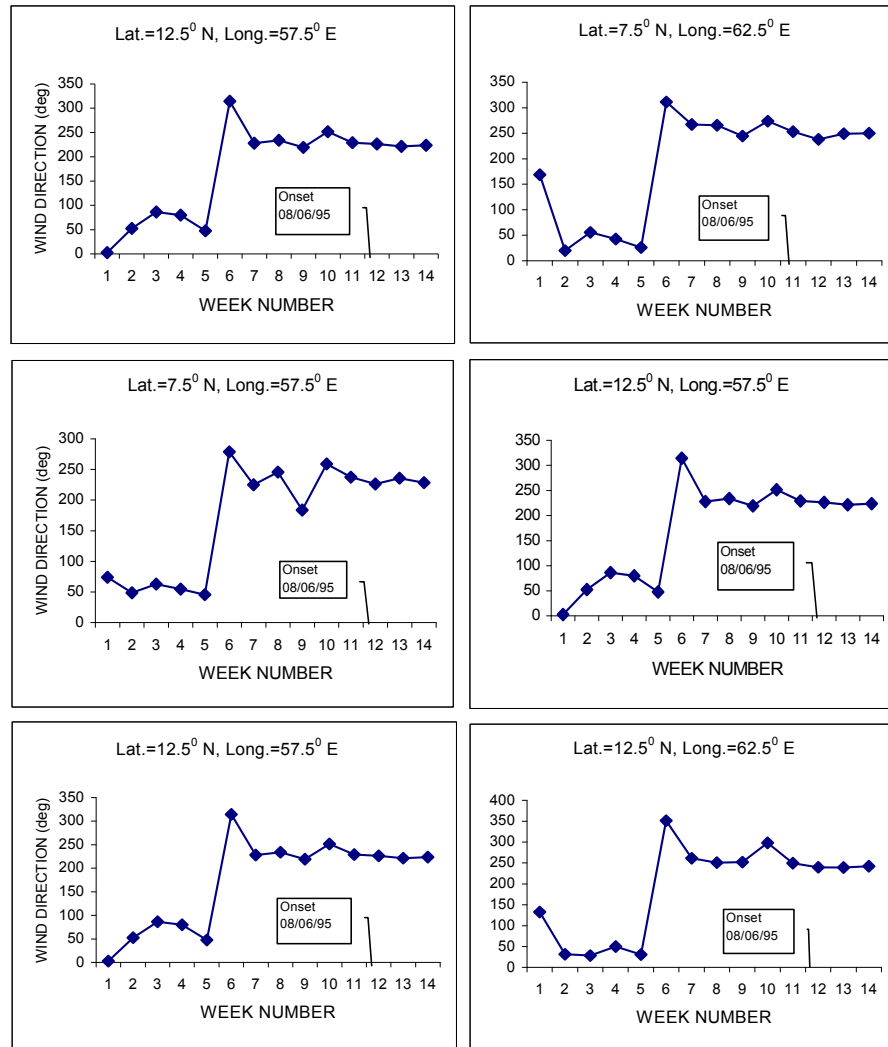


Fig. 3. Change in ERS scatterometer derived wind direction during monsoon onset 1995. Note the onset date in x-axis. Week number 1 correspond to 27 March to 2 April and 14 correspond to 26 June to 2 July 1995

microwave remote sensing and retrieval of geophysical parameters are beyond the scope of this paper and can be found elsewhere (Ulaby *et al.*, 1986).

3. Applications of microwave remote sensing for monsoon studies

3.1. Summer monsoon onset

Onset of monsoon or arrival of rainy season over India is normally declared on the basis of rainfall, wind, temperature, moisture, cloud, state of the sea, etc. over the Indian monsoon region. There are practical difficulties in forecasting the date of onset because all these parameters are highly variable in space and time. Adequate data of

these parameters in a wide region surrounding Indian subcontinent are required on real-time for the accurate forecasting of monsoon onset.

In Fig. 2 MSMR derived precipitable water vapour few days prior to and after the onset are presented. Large scale changes occur in atmosphere during onset is evident from this figure. One important feature is the substantial moisture build up over the Arabian Sea. Before onset thermal inversion is present in the lower atmosphere over the western and northwestern Arabian Sea and the atmosphere is unfavourable for deep convective activity (Narayanan and Rao, 1981). The increase in moisture content immediately after the onset shows the breaking of the inversion and increase in convective activity. After

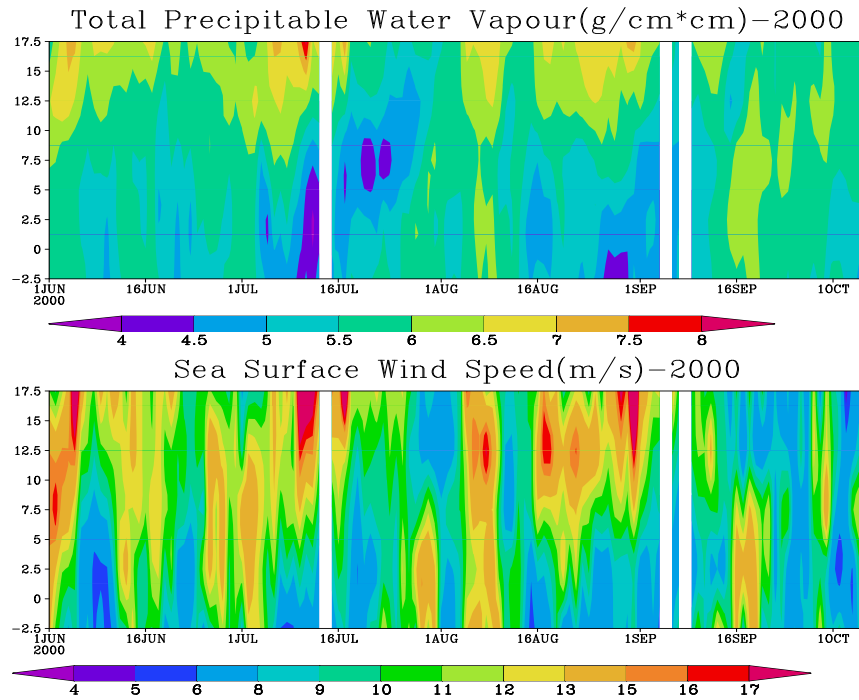


Fig. 4. The time series of the daily area averaged total precipitable water vapour and sea surface wind averaged in 5° lat \times 10° long. boxes over Bay of Bengal starting from 5°S - 0° , 85°E - 95°E box to 15°N - 20°N , 85°E - 95°E box. The discontinuities in the plots are due to the data gaps

onset especially when the monsoon is active, region of peak precipitable water (about 6 g cm^{-2} and above) is found over the North Bay of Bengal.

Several workers analysed the satellite measured meteorological and oceanic parameters to identify the precursors that indicate the arrival of onset well in advance (Simon *et al.*, 2001; Rao *et al.*, 1998; Bhatia *et al.*, 2001). Two such promising precursors that indicate the arrival of onset over India by few weeks in advance are identified in these studies based on microwave sensor data. They are

- (i) Significant increase in water vapour over west Arabian Sea and
- (ii) Wind reversal over Arabian Sea and western Indian ocean.

Atmospheric water vapour increases sharply by about 20% over west Arabian Sea nearly 2-3 weeks prior to monsoon onset over India (Simon *et al.*, 2001). Microwave sensors such as MSMR, SSM/I and TMI captured this increase during the years of their operation. But this increase is poorly captured by the standard data sets such as NECP/NCAR reanalysis may be due to coarse resolution and data scarcity. Sea surface wind vectors observed by ERS-1 and ERS-2 scatterometers show the

large-scale wind reversal occur over Arabian Sea and western Indian Ocean (Rao *et al.*, 1998) about 3 weeks prior to onset over India (Fig. 3). This reversal is generally followed by large increase in wind speed suggesting the strengthening of low-level monsoonal flow over Arabian Sea.

These two parameters are very much important in the sense that they can be used for long-range forecasting of onset. Comparison of the predicted onset dates using these precursors and actual onset dates in various years showed very good agreement between the two. Since the microwave data are available only for few years (one decade or so), reliability of the onset prediction using these precursors should be validated for a more number of years before making them operational.

3.2. Intraseasonal oscillation of Indian summer monsoon

Within the summer monsoon season rainfall exhibits pulsating nature with active and weak periods. These periods (or phases) are associated with the repeated northward propagating maximum cloudiness zone with a period of about 30-60 days (Sikka and Gadgil, 1980; Madden and Julian, 1994). This oscillation is popularly known as intraseasonal oscillation of the summer monsoon. Period of this oscillation is highly variable.

Intraseasonal oscillation is seen in atmospheric as well as oceanic parameters. It appears that significant phase differences exist between the intraseasonal oscillations in various parameters. Characteristics of this oscillation are studied intensively with the aim of predicting the seasonal mean rainfall and active/weak phases in rainfall activity in advance.

Most significant contribution of the microwave sensors towards the understanding of intraseasonal oscillation is that they provide continuous atmospheric and oceanic data in the densely clouded Indian monsoon region. Combined with other conventional and satellite data, microwave data (SST, water vapour content, etc.) from MSMR, SSM/I and TMI are studied to understand the combined evolution and northward propagation of large-scale intraseasonal oscillation (Sengupta *et al.* 2001; Sathiyamoorthy *et al.*, 2002). In Fig. 4, repeated northward propagation of the intraseasonal oscillation over Indian region is evident in the MSMR derived precipitable water and sea surface wind speed during a monsoon season. One of the striking features captured by the MSMR is the lead-lag relationship of intraseasonal oscillations in precipitable water vapour and sea surface wind speed. Intraseasonal oscillation in water vapour always leads the surface wind speed by about 4-5 days over Indian region. On the other hand high frequency oscillations generated by depressions, easterly waves, etc. do not exhibit such a phase lag. Thus it becomes obvious that the physical processes associated with the large-scale intraseasonal oscillation and the transient high frequency systems embedded in it are rather different.

3.3. Diurnal variability of Indian summer monsoon

Several attempts were made in the past to identify the possible presence of diurnal variability in the Indian region especially during summer monsoon season. Riehl (1979) noted that land-sea breeze is greatly reduced when the onshore wind exceeds 7 ms^{-1} , a condition often encountered on the Indian west coast during the monsoon. Gray and Jacobsen (1977) showed that oceanic deep convection often has an early morning maximum and an evening minimum. Bergman and Salby (1997) showed that the error in the monthly mean deep cloud fraction over tropical continents could be as high as 100% if the diurnal variability is not considered.

Rainfall data with high temporal resolution is necessary for the diurnal variability studies. With the available rainguage network, it will be extremely difficult to study the nature of this variability, its horizontal extent and ultimately end up in inconclusive results. With the availability of geostationary satellites in the last few decades, it became possible to study the diurnal variability to some extent. The polar orbiting satellites equipped with

rain/cloud sensitive visible and microwave sensors (*e.g.* SSM/I) are generally placed in a sun synchronous orbit and provide data over a region only twice a day. Due to their fixed equatorial crossing time, these sensors could not capture the diurnal variability. Some of these studies led to indecisive and contradicting conclusions about the diurnal variability due to inadequate temporal resolution.

TRMM is the first satellite equipped with active microwave sensor for rainfall estimation from space with good temporal and spatial sampling in the tropical region. However prior to TRMM, with the help of TOPEX radar altimeter, which is in a non-sun synchronous orbit, attempts were made to study the rainfall over Indian Ocean. Though the TOPEX and TRMM rain radars are in non sun-synchronous orbits, the latter has better temporal coverage than the former. In addition, altimeter can provide rainfall data only over ocean where as rain radar in TRMM can provide both over oceans and land. As a result TRMM data is expected to depict the diurnal variability in monsoonal rainfall and its horizontal extent in a better way.

Differential attenuation of radar signal due to rain at two widely separated frequencies of TOPEX altimeter *viz.*, 5.3 GHz and 13.6 GHz were proposed for rainfall estimation studies. Consistent diurnal variability is not seen in the TOPEX derived rainfall over Arabian Sea and Bay of Bengal from year-to-year (Bhandari and Varma 1996; Varma *et al.*, 2001). But the analysis of the TRMM data showed the presence of pronounced continental scale diurnal mode in the Asian summer monsoon (Krishnamurti and Kishtawal, 2000). It appears that during summer monsoon season, precipitation is confined to the Bay of Bengal and the west coast of India in the morning hours. During evening hours, the location of high precipitation shifts over land areas.

3.4. Boundary layer fluxes

Air-sea interaction processes play an important role in the organization of various tropical systems. Exchange of heat from ocean to atmosphere is by evaporation and also to some extent, by sensible heat. The latent heat is the crucial driving force for tropical atmospheric circulation and is an important input to various global circulation models. In bringing the monsoonal rain over India, the cross equatorial flow of moisture as well as evaporation over north Indian ocean and adjoining sea, which act as the main reservoir of heat and moisture is equally important. Hence it becomes important to study the air-sea interaction processes over the seas flanking Indian subcontinent and variability of the oceanic heat fluxes in relation to summer monsoon activity (Simon and Desai, 1986; Holt and Raman; 1987).

The important parameters required for estimating the heat exchange (latent and sensible) are the specific humidity at the surface and the near surface air temperature, which are not directly measured by the satellites. Few techniques were developed to extrapolate these parameters from satellite data so that latent and sensible heat fluxes can be estimated at the air-sea interface over moderate space and time scale. Surface-level humidity over Arabian Sea and Bay of Bengal has been estimated using the SSM/I derived precipitable water vapour and the global relation between monthly mean precipitable water and surface-level humidity (Nair *et al.*, 1995). Multi-linear regression method using brightness temperature data from MSMR to estimate surface latent heat flux over global oceans were done (Singh, 2001).

The values of latent heat flux over Arabian Sea are higher than that over the Bay of Bengal during pre-monsoon and monsoon months and almost same or less during other months. The latent heat flux values over the Indian Ocean vary from 100 Wm^{-2} in August near the Somali coast to 400 Wm^{-2} in June.

4. Summary

This paper summarized the works done towards the understanding the monsoon and its variability mainly using microwave data from several satellites. All weather capability is the prime attraction of this newly emerging field. Some of the recent results about the monsoon onset, intraseasonal variability, diurnal variability and boundary layer fluxes obtained from the microwave sensors were elucidated in this paper. It will be possible from the future microwave sensors with good temporal and spatial resolution like sensors onboard Megha-Tropiques, Envisat, etc. which will yield better understanding about the monsoon process.

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