What have we learned about the Indian monsoon from satellite data?

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In the pre-satellite era, our understanding of the monsoon was based primarily on ground-based observations. The land–sea contrast in surface temperature was considered the primary mechanism that drives the monsoon. During the last 47 years a large amount of data has been obtained from satellites and this has altered our perception about the factors that influence monsoon rainfall. The satellite data has revealed that the clouds in the tropics move eastward along the equator and poleward from the equator to higher latitudes. The net radiant energy available to earth–atmosphere system was found to be a fundamental driving force for monsoon rainfall. The role played by water vapour in controlling vertical stability, latent heat of condensation and greenhouse effect was appreciated better after the advent of satellite data.

Keywords: Clouds, monsoon, satellite, vapour, water.

THE first satellite that was dedicated to the study of weather and climate was launched on 1 April 1960. During the last 47 years more than 300 satellites have been launched to monitor the weather and climate of the earth. Satellites have provided frequent, high resolution data over entire earth. Satellites have revolutionized the techniques of weather forecasting and climate prediction. They have enabled the meteorologists to see the birth and subsequent movement of storms over the oceans. Satellites have helped us understand the connections between climate extremes in different regions of the earth. They have played an important role in elucidating the relationship between warming of the ocean in the equatorial east Pacific Ocean and the anomalies of weather over India, America and Africa. In this review we examine the impact of satellite data on our understanding of the processes that influence the variability of the monsoon. On account of paucity of space, we do not discuss the large impact that satellite data has had on short-term forecasting of monsoon.

Monsoon theory in the pre-satellite era

In the 17th century, Edmund Halley proposed that the monsoon circulation was driven by contrast in surface temperature between the land and the ocean. In the pre-monsoon season, the surface temperature of the land is much larger than that of the ocean. The vertical motion that occurs on account of the difference in surface temperature between the land and the ocean does not penetrate more than a few kilometers. During the monsoon season there are deep clouds that can extend vertically up to the height of 10–15 km. The existence of these deep convective clouds cannot be explained through the theory of land–sea contrast in surface temperature. During the past 300 years the land–sea contrast theory has survived, although most meteorologists are aware of the serious limitations of the theory.

One of the fundamental limitations of this theory arises from the fact that after the monsoon onset there is hardly any difference between the surface temperatures of the land and the adjacent ocean. What sustains the monsoon for four months although the land–sea contrast in surface temperature disappears after the monsoon onset? Webster and Fasullo[1] have stated that after the onset of the monsoon, the importance of the surface temperature gradient decreases and the overall driving of the monsoon is taken over by the heating of the troposphere over the continents through the release of latent heat. They have argued that monsoon may be thought of as a great solar collector. The latent heat of condensation that is released over the heated continents, and which drives the established monsoon, is the summation of the evaporation occurring at the surface of the ocean between the winter hemisphere and the heated continents.

In the pre-satellite era, there were very few observations over the oceans and hence the role played by oceanic regions adjacent to the land as well as those well away from the land was not well understood. In the early 20th century, Gilbert Walker proposed a bold hypothesis that oscillations of surface pressure in the equatorial Pacific Ocean (called Southern oscillation) influence the Indian monsoon. This influence cannot be explained through the simple theory of land–sea contrast. Hence Walker's hypothesis was not accepted during his lifetime. A better understanding of the influence of the warming of the eastern equatorial Pacific Ocean (called El Nino) came when the satellite data showed clearly the higher cloudiness in the equatorial Pacific during El Nino. In the subsequent sections, we will show how the analysis of

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*For correspondence. (e-mail: jayes@caos.iisc.ernet.in) satellite data has fundamentally altered our understanding of the roles played by the oceans, water vapour, and radiation budget on the strength of the monsoon.

Clouds during the monsoon

Clouds can be sensed from satellites because they reflect more solar radiation than ice-free ocean or snow-free land. Sensors used to identify clouds are called imagers and have provided valuable information about the movement and structure of monsoon cloud systems. In 1980, Sikka and Gadgil[2] used the visible cloud imagery from National Oceanic and Atmospheric Administration (NOAA) satellite data to demonstrate that the maximum cloudy zone (MCZ) had two preferred regions during the Indian summer monsoon. The primary location of MCZ was around 20°N around the monsoon trough while the secondary location was in the equatorial region (see Figures 1 and 2). They showed that these cloud bands moved from the equatorial region to the monsoon trough at the rate of around 1° latitude per day (see Figure 3). During some occasions clouds emanating from the equatorial region move northward and southward simultaneously[3] (see Figure 4). This work was extended to different regions in the tropics by Gadgil and Srinivasan[4] using both infrared and visible data from satellites. They showed that poleward migration of clouds occurs in many tropical regions. The analysis of satellite data showed that the concept of withdrawal of 'southwest monsoon' and subsequent onset of 'northeast monsoon' was unnecessary. During the southwest monsoon the MCZ migrated from south of the equator to 30°N while during the 'northeast monsoon' the clouds migrated from south of the equator to 15°N. The term 'northeast monsoon' is misleading because the winds from the north-east hardly play a role in the northward migration of cloud bands during the winter monsoon.

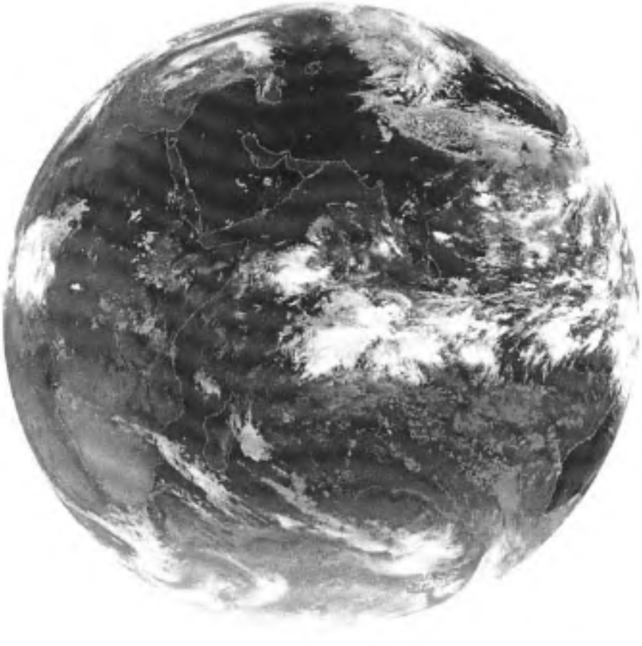


Figure 1. Brightness temperature in the infrared channel from METEOSAT on 15 June 2006 showing the Inter-Tropical Convergence Zone just below the equator (courtesy: http://www. sat.dundee.ac.uk).

The radiation emitted to space by the earth–atmosphere system is called the Outgoing Longwave Radiation (OLR). This has been measured by satellites for the past 47 years. A low value of OLR (below 200 W/m^2) indicates the presence of deep clouds. The data from the Advanced Very High Resolution Radiometer (AVHRR) provided by the NOAA of USA has been widely distributed among the meteorological community. This data has been used extensively to understand cloud organization and propagation in the tropics. Wang and Rui[5] used pentad-mean OLR from satellites to examine both latitudinal and zonal migration of cloud bands. They identified the existence of both northward and eastward moving cloud bands. They showed that during the Indian summer monsoon the northward moving cloud bands were independent of the eastward moving cloud bands. The analysis of OLR data from satellites has enabled meteorologists to interpret the complex cloud movements in terms of equatorially trapped waves. The equatorial trapping of the waves occurs on account of the variation of the vertical component of the earth's rotation with latitude. Some of the waves that have been identified are the Madden Julian Oscillation (MJO), Kelvin waves and mixed Rossby-gravity waves. The dominant signal of cloud movement in the equatorial region is associated with MJO. The MJO is identified through deep cloud systems and precipitation that moves slowly eastward along the equator at a speed of about 5 m/s (Figure 5). The spatial scale of MJO is in the range 10,000–20,000 km and hence MJO has an influence on climate in the entire tropical region. The deep clouds in the MJO exist in the Indian and West Pacific oceans only. In the East Pacific and Atlantic oceans MJO is identified by the changes in winds and surface pressure and its speed of eastward propagation is much higher (30–35 m/s). During the active phase of MJO the deep clouds have a nocturnal peak but exhibit an afternoon peak during the weak phase. In the region between 10°N and 15°N westward migrating cloud bands are observed. Most climate models have been unable to simulate accurately the slow eastward migration of MJO.

Gambheer and Bhat[6] used the INSAT-1B brightness temperature data to examine the deep cloud systems in the Indian region. They showed that most deep clouds decay within a few hundred kilometers from the place of their genesis. The mean speed of propagation of these systems was 7–9 m/s. Roca and Ramanathan[7] used the INSAT-1B data to study the cloud organization during summer and winter monsoon. They showed that cloud systems smaller than 100 km × 100 km never reach the tropopause. The deepest clouds occur in systems organ-

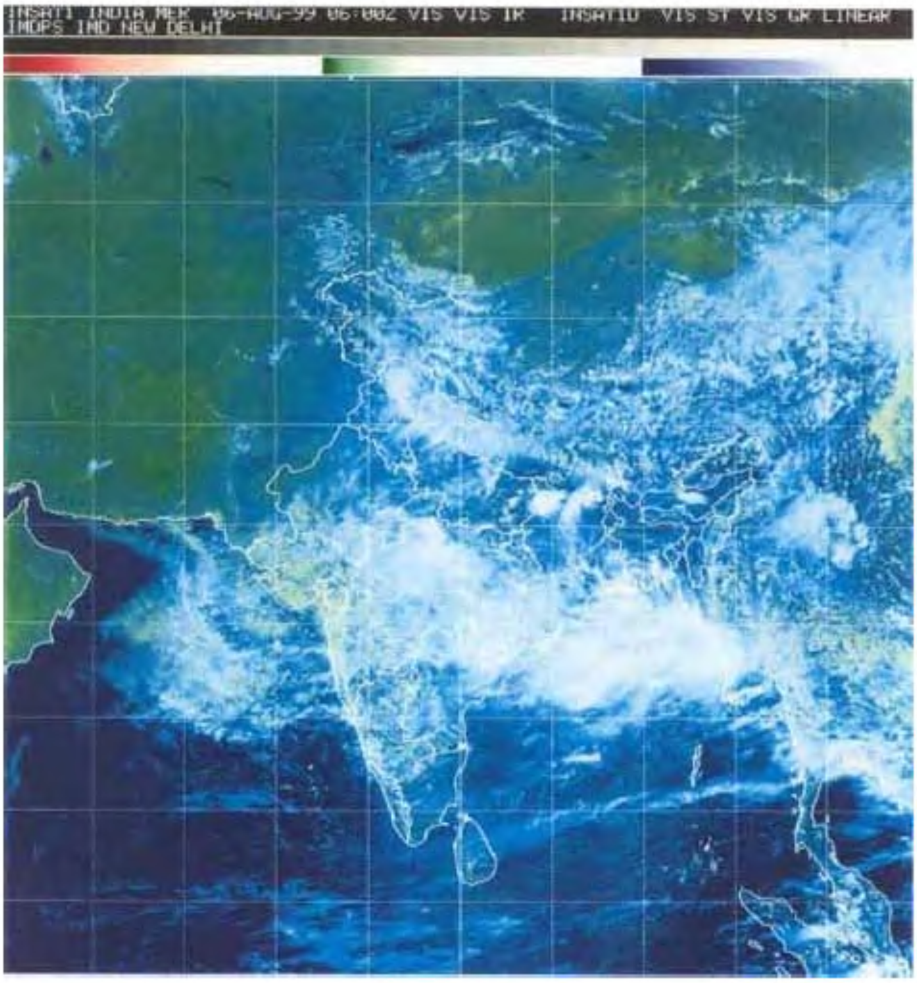


Figure 2. Infrared brightness temperature from INSAT 1D on 6 August 1999 showing the Inter-Tropical Convergence Zone in the northern Bay of Bengal.

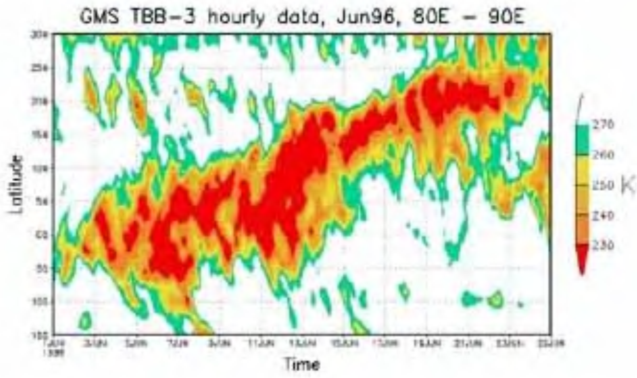


Figure 3. Variation of brightness temperature during July showing northward migration of cloud bands during the monsoon season.

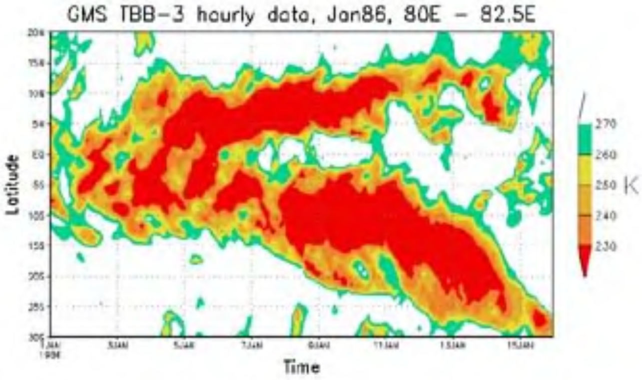


Figure 4. Variation of brightness temperature during January showing simultaneous northward and southward migration of cloud bands.

ized over the scale of 1000 km × 1000 km. They showed that these features are similar in winter and summer. This is a remarkable result since it indicates that the organization of cloud systems is not very different during the summer and winter monsoon. This goes against the traditional view that land–sea contrast plays an important role in the evolution of the monsoon clouds. In addition to deep clouds and shallow clouds, satellite data has revealed the existence of mid-level clouds (around 5 km) where melting of ice occurs. The mid-level clouds play an important role in the moistening of the upper troposphere. The Tropical Rainfall Measurement Mission (TRMM), launched on 27 November 1997, was a joint US–Japan mission to estimate tropical rainfall and understand tropical climate variability. The satellite used for TRMM carried a precipitation radar (active sensor) and several passive sensors in the visible, infrared and microwave spectrum. To obtain higher temporal sampling in the tropics, this satellite was launched in an orbit that was inclined 35° to the equatorial plane[8]. This mission has provided new data about the spatial and temporal variability of precipitation in the tropics and the impact of this variation on tropical climate. TRMM provided the first accurate estimate of the convective and stratiform precipitation in the tropics from a satellite. Hirose and Nakamura[9] have shown that TRMM precipitation radar provided the first estimate of vertical profile of rainfall over the tropical regions.

The results obtained from TRMM show that most climate models are not able to simulate correctly the relative amount of convective and stratiform clouds in the tropics. TRMM data showed that the cloud systems in tropical Africa are deeper and more intense than those in the Amazon. The data from TRMM precipitation radar showed that mesoscale convective systems were more common in the Bay of Bengal than in the Indian land region. TRMM carried a lightning detector and this showed that the lightning flashes were ten times more frequent over land than over oceans.

Radiation budget and the monsoon

Before the advent of satellites, scientists had only a vague idea about the impact of radiation on the monsoon. The amount of solar radiation reflected to space had to be guessed from ground-based observations. Satellites enabled scientists to measure the radiation budget of the earth directly from space. The radiation budget sensors used during 1960s and 1970s were not sophisticated enough to provide an accurate estimate of the radiation budget. The sensors used in satellite during this period measured the radiation from earth in certain regions of the solar spectrum. This data was then extrapolated to the entire solar spectrum (i.e. 0.2 micron to 4 micron). The errors in the extrapolation from narrow-band data to the broad-band were large. In addition, the angular variation of solar reflectivity was not accurately estimated. To tackle these problems, the National Aeronautics and Space Administration (NASA) launched the Earth Radiation Budget Experiment (ERBE) in 1980s. Three satellites launched during this period carried broad-band sensors that provided an accurate estimate of the total solar radiation reflected and infrared radiation emitted by the earth–atmosphere system. The angular variation of solar reflectivity (also called albedo) was accounted for through new bi-directional reflectivity models and better temporal sampling. The data obtained from ERBE indicated that the climate models did not simulate the cloud radiative properties accurately. There has been, however, a remarkable improvement in the ability of the climate models to simulate the radiation budget of the tropics after the ERBE data became available. The net radiation at the top of the atmosphere (i.e. the difference between absorbed solar radiation and the emitted long-wave radiation) is an important quantity since it indicates the energy available for driving the monsoon circulation. The ERBE data was useful to understand the impact of clouds on the radiation budget. The ERBE data showed that in most of the tropics the impact of the clouds on the short-wave radiation and long-wave radiation was equal in magnitude and opposite in sign. Hence the effect of clouds on the net radiation at the top of the atmosphere was small[10]. Rajeevan and Srinivasan[11] showed, however, that the Bay of Bengal region was unique. They showed that clouds caused a net radiative cooling in the Bay of Bengal during the summer monsoon. They demonstrated that this was on account of the presence of deep and highly reflective clouds in the Bay of Bengal.

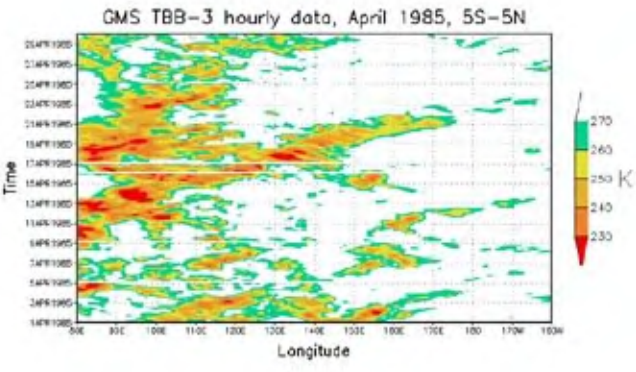


Figure 5. Zonal migration of cloud bands along the equator during April 1985.

The radiation data from ERBE showed that the net radiation at the top of the atmosphere over parts of Sahara was *negative* in summer. This result was surprising since the amount of solar radiation incident in Sahara in summer is very high. Most regions in the world have positive net radiation at the top of the atmosphere during summer. The net radiation over parts of Sahara was negative in summer because of two factors. The high reflectivity of desert sand caused a substantial fraction of incident solar radiation to be reflected to space. In addition, the low-humidity of the desert allowed a large fraction of the emitted radiation to escape to space. Srinivasan and Smith[12] used the hypothesis of Neelin and Held[13] to demonstrate that one of the reasons for the absence of monsoon in Sahara was the low or negative net radiation in this region. The satellite data thus provided a new insight regarding the factors that control monsoon rainfall. Srinivasan[14] has shown that the seasonal variation of monsoon rainfall is a function of the variation of net radiation at the top of the atmosphere and the total integrated water vapour in the atmosphere. This simple model of the seasonal variation of rainfall during the monsoon does not invoke the concept of land–sea contrast. In this view it is the energy and moisture budget that play a fundamental role in modulating the seasonal variation of monsoon rainfall. The simple model of the monsoon proposed by Srinivasan[14] can be written as

$$P = E + Q_{\mathrm{net}}/\{[C/p_{\mathrm{w}}] - 1\},$$

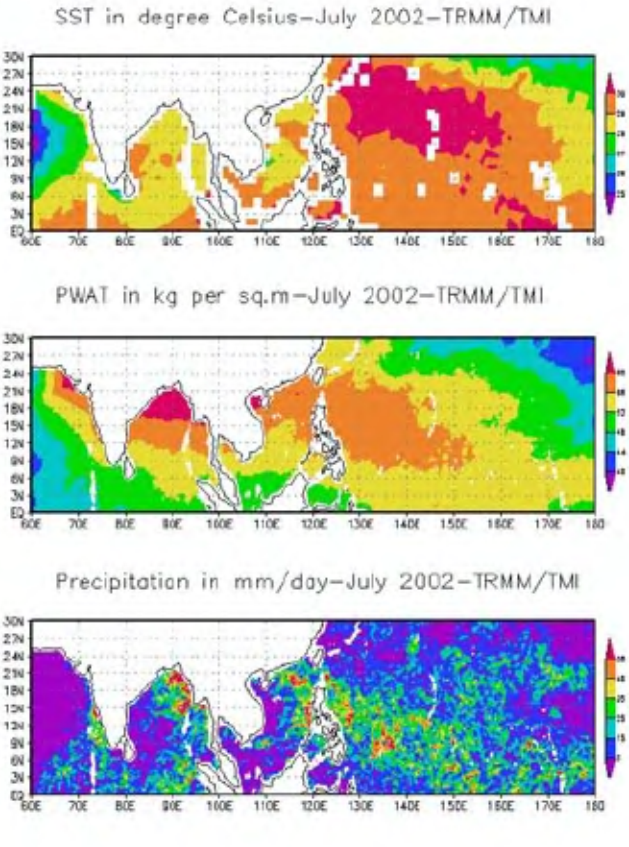
where P is rainfall, E is the evaporation, Q_{net} is the net radiation at the top of the atmosphere, P_{w} is the vertically integrated water vapour in the atmosphere, and C is related to the vertical stability. Most of the parameters in this equation can be derived from satellite data.

Sea surface temperature, water vapour and the monsoon

Before the advent of satellites, the data on sea surface temperature (SST) was obtained from ships and hence this data did not have global coverage. Satellites have provided global data on SST for the past 30 years. SST data have been obtained primarily from the measurement of the emission of the infrared radiation from the surface of the ocean when the sky is clear. During the monsoon season, SST has to be retrieved from the microwave emission from the ocean surface. The TRMM and OCEANSAT satellites used the 10 GHz channel to obtain SST during the monsoon. The spatial pattern of SST and its temporal evolution have a large impact on climate variability in the tropics. Gadgil *et al.*[15] used satellite data to show that deep clouds appear in the tropics when the SST exceeds 28°C. Hence warm pools in the tropical ocean have a profound impact on climate variability in the tropics. The satellite data has been useful to understand the relationship between rainfall and SST in different tropical oceans. They have enabled us to understand how the east–west oriented cloud systems called the Inter-Tropical Convergence Zones (ITCZ) respond to changes in the magnitude of the SST and the latitudinal gradient of SST. The data from TRMM has shown that sub-seasonal variation of SST has an impact on the active-break cycle of the monsoon[16].

The variations in SST have a profound influence on the amount of water vapour in the atmosphere. Water vapour influences the earth's weather and climate in three different ways. Water vapour absorbs the infrared radiation emitted by the earth's surface and hence warms the earth (greenhouse effect). Since the molecular weight of water vapour is less than that of air, the presence of water vapour makes the atmosphere lighter and hence more buoyant. The heat released when water vapour condenses in the atmosphere drives the atmospheric circulation and hence has a profound influence on the weather and climate.

The water vapour in the atmosphere has been measured from satellites using infrared or microwave sensors. The water vapour in the upper atmosphere has been inferred from infrared absorption band of water vapour at 6.3 micron. The total water vapour in an atmospheric column under cloudy conditions can be inferred from water vapour absorption band in the microwave part of the spectrum. When the 6.3 micron infrared absorption band of water vapour is used, one can estimate the water vapour above the clouds while the microwave sensors provide information on water vapour both below as well as above clouds. The ISRO satellite BHASKARA launched in 1979 carried a microwave radiometer (SAMIR) at 19 and 22 GHz. The data from the radiometer was used to estimate the total water vapour and liquid water in a vertical column of the atmosphere. The data from BHASKARA showed for the first time the pattern of variation of total water vapour over the oceans[17]. The data from the microwave sensor in the TRMM satellite has shown that the Bay of Bengal is unique because it has the highest water vapour content in the world during the summer monsoon season (see Figures 6 and 7). The mechanisms that lead to such a high value of water vapour in the atmosphere over the Bay of Bengal have not been fully understood so far. The presence of Himalayas close to a warm ocean surface


SST in degree Celsius–July 2002–TRMM/TMI

PWAT in kg per sq.m–July 2002–TRMM/TMI

Precipitation in mm/day–July 2002–TRMM/TMI

Figure 6. Integrated water vapour, rainfall and SST from Tropical Rainfall Measurement Mission showing the high water vapour content in the Bay of Bengal.

can assist in the transport of water vapour to the upper troposphere and hence lead to high water vapour content. Water vapour in the upper troposphere plays an important role in controlling deep convection and hence also the transition from active to break phase of the Indian monsoon[18].

The vertical profile of water vapour has a profound impact on the vertical stability of the atmosphere. The vertical profile of water vapour over the oceans can be determined by using many narrow band sensors in the absorption band of water vapour in the infrared or microwave region of the spectrum. These are called sounders. The analysis of the water vapour profile data has shown that the water vapour near the ocean surface leads precipitation by one pentad over the Indian Ocean and Western Pacific oceans. This shows that the moistening of the lower troposphere is a pre-requisite for convective precipitation. On the other hand, the upper level water vapour lags the peak in precipitation by 1–2 pentads, as the upper troposphere is moistened following intense convection. Monitoring of the atmospheric parameters from satellites has helped in the prediction of monsoon onset over Kerala[19–21]. A significant moisture buildup occurs over western Arabian Sea in the pre-monsoon season. The data from Oceansat-1 (MSMR) and TRMM/TMI showed that integrated water vapour increases by 20–25% over Western Arabian Sea, two and a half weeks before the onset of monsoon over Kerala (see Figure 8). This increase is a necessary condition for the onset of monsoon over Kerala. The evolution of wind vector from scatterometer (Quikscat) during the onset phase of the monsoon has shown that the reversal of wind direction in the western Arabian Sea takes place about three weeks before the onset of monsoon over Kerala. The water vapour absorption band has been useful for deriving winds in the mid-troposphere. This channel has also been used to track the trajectory of parcels leaving clouds[22].

Rainfall from satellite data

Before the advent of satellites it was not possible to estimate the amount of rainfall over the oceans. Satellites can be used to estimate rainfall because deep clouds produce more rain than shallow clouds. Cloud height can be estimated from infrared emission from the top of the clouds and hence one can obtain an estimate of rainfall from infrared sensors in satellites. Arkin *et al.*[23] showed that the brightness temperature data from INSAT-1B can be used to estimate the rainfall over India. The estimate of rainfall based on infrared radiation is not accurate because this technique is indirect. The direct method of estimating rainfall is based on identifying large raindrops or ice particles in the atmosphere. Large raindrops can be detected by using sensors in the microwave region of the spectrum. The wavelength of this radiation is around 1–10 mm and the frequency is in the range of 10–200 GHz. New methods have been developed to combine the rainfall derived from infrared data from geostationary satellites with that derived from microwave data from polar-orbiting satellites to obtain a more accurate estimate of rainfall[24]. The temporal sampling is higher in geostationary satellites but the microwave data from polar-orbiting satellites provide a more direct method to infer rainfall. Hence combining the two methods becomes necessary. During the past decade we have obtained, for the first time, a reasonable estimate of the total rainfall over the tropical oceans. The interannual variation of tropical rainfall has shown clearly the interaction between rainfall over the oceans and continents in the tropics. The connection between shift in rainfall pattern in the equatorial tropics and the Indian monsoon is well known. The availability of satellite data over the Indian Ocean enabled Gadgil *et al.*[25] to demonstrate a tele-connection between the equatorial Indian Ocean and the Indian summer monsoon. We know now that all El-Nino events do not always lead to the failure of Indian monsoon because of the impact of convection in the equatorial Indian Ocean on the Indian summer monsoon.

The estimate of rainfall over oceans from satellite data has altered fundamentally our understanding of the factors that control the tropical weather and climate. We know that the latent heat released during the condensation of water vapour plays an important role in influencing the

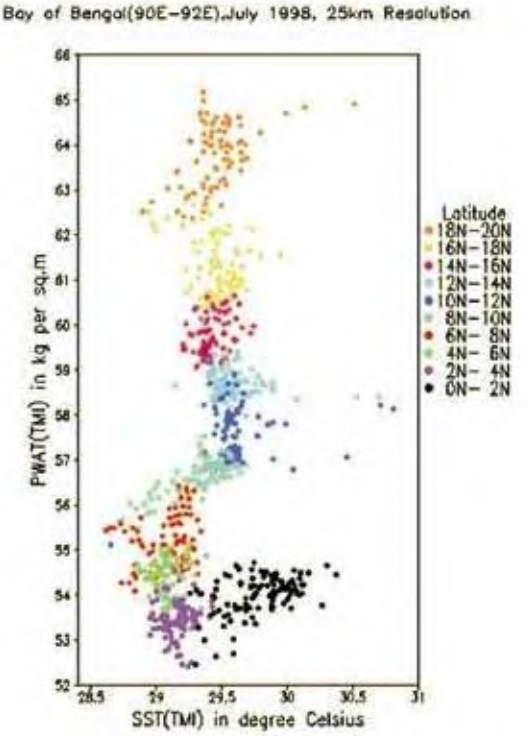


Figure 7. Relationship between integrated water vapour and sea surface temperature in the Bay of Bengal from Tropical Rainfall Measurement Mission.

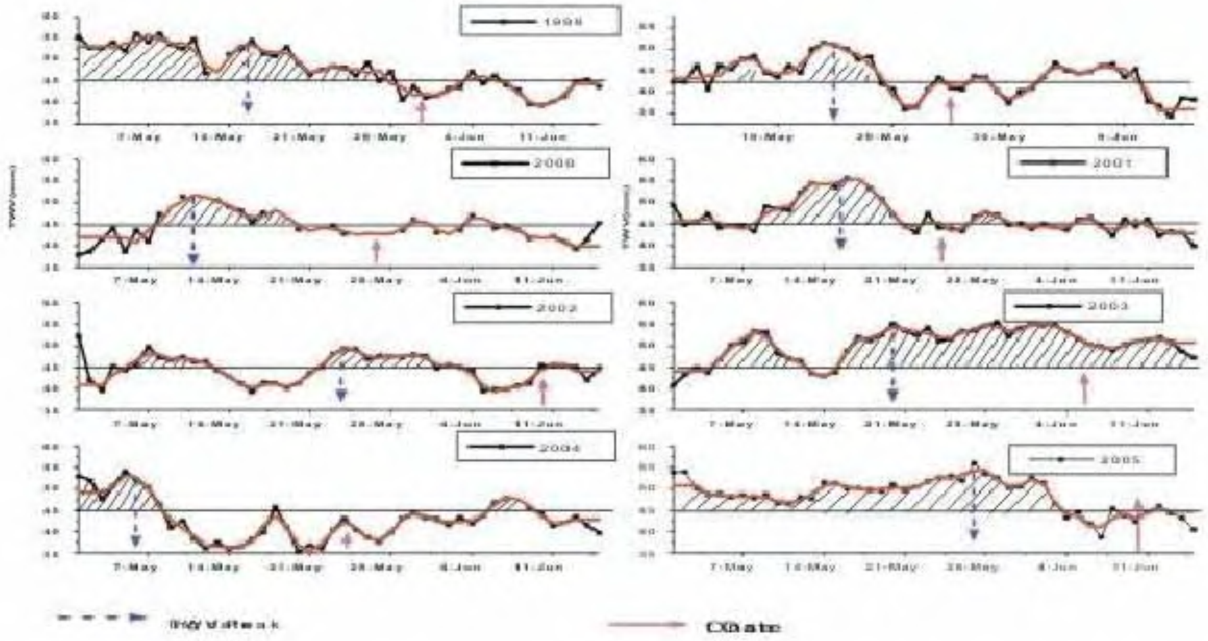


Figure 8. Relationship between date of monsoon onset and the date when the total integrated column water vapour reached a peak.

winds in the tropics. Srinivasan and Nanjundiah[26] showed that the winds in the western Arabian Sea (near Somalia) accelerate two days after the enhancement of convection in the Bay of Bengal. This shows clearly that it is the convection and rainfall in the Asian monsoon region that modulates the westerly winds in the Arabian Sea. The winds in the Arabian Sea bring moisture to the Indian land mass. The condensation of this moisture releases latent heat in the atmosphere over India that leads to further increase of the winds in the Arabian Sea.

TRMM rainfall data showed that the maximum rainfall over land occurred in the afternoon or evening while the maximum rainfall over ocean occurred in the early morning. Krishnamurti and Kishtwal[27] used the data from TRMM and METEOSAT-5 to demonstrate that there was a continental scale diurnal fluctuation of clouds and rainfall in the Indian monsoon region. The estimate of rainfall from satellites has revealed for the first time that the convective rain constitutes, in the mean, 24% of the rain area while accounting for 67% of the rain volume. In view of the interaction among clouds, radiation and rainfall during monsoon season, it is necessary to examine the evolution of these parameters simultaneously[28]. This is possible now because there are constellation of satellites with meteorological payloads. The measurements of SST by TRMM microwave imager, together with simultaneous measurements of surface winds by the Quick Scatterometer (QuikSCAT), have revealed that the coupling between the ocean and the atmospheric boundary layer on scales smaller than a few thousand kilometers in regions of strong SST fronts is much stronger than had been inferred previously from sparse *in-situ* observations.

Conclusion

The data obtained from satellites during the past 47 years has revealed a complex pattern of meridional and zonal variation of clouds in the tropics with periods ranging from a few days to 90 days. The satellite data have shown that the traditional hypothesis that land–sea contrast was the primary driving force of the monsoon is inadequate. Satellite data has revealed the important role played by the net radiative heating of the earth–atmosphere system as well as the vertical stability of the atmosphere. The vertical stability of the atmosphere is strongly influenced by how humidity and temperature varies with height. There has been a remarkable progress in our understanding of monsoon processes during the past 50 years but it has not been adequate to develop climate models that predict the inter-annual variation of the monsoons. The major weakness in climate models has been the manner in which clouds are parameterized. A dramatic improvement in the accuracy of prediction by climate models will occur if and only if more satellite data is obtained about the temporal evolution of cloud systems in the tropics. In April 2006, NASA launched a satellite called CLOUDSAT. This satellite has provided, for the first time, new information about the vertical profile of clouds through a radar. We need more information about the ice and liquid water content in clouds. This can be achieved if satellites carry sensors that cover the wavelengths from the visible to the microwave region and they sample the birth, growth and demise of cloud systems. This demands that the satellite should not be in a polar orbit but in a low inclination orbit that provides higher temporal sampling in the tropics.

An Indo-French satellite mission called Megh-Tropiques has been proposed with the launch date scheduled to be in 2009. This satellite will not be put in a polar orbit but in an orbit that is inclined 20° to the equatorial plane and hence ensure higher temporal sampling in the tropics. This satellite will have a radiation budget sensor, microwave radiometer, microwave humidity profiler and radio occultation-based temperature and humidity profiler. The data from this satellite will provide more insight into the evolution of cloud systems in the tropics and hence increasing our understanding of monsoon cloud processes. The availability of large amount of data from new satellites in the coming decades will lead to a better understanding of the complex processes associated with the monsoon. This is bound to increase our ability to make a more accurate prediction of the monsoon rainfall.

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Intraseasonal oscillation of tropical convergence zones: Theory and prediction

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The intraseasonal oscillation of Tropical Convergence Zones (TCZ) over the Indo-Pacific region has been studied. Both meridional and zonal propagating modes with timescales of about 40 days are prominent over the Indian and West Pacific regions. The mechanisms governing both these modes are reviewed. It is found that ocean–atmospheric interaction plays an important role in modulating these modes. The role of oceans is further highlighted in a series of seasonal forecasts using a coupled ocean–atmosphere model. It is found that forecasts of intraseasonal oscillations show significant improvement upon assimilation of sub-surface ocean data from the ARGO (a global programme to observe sub-surface profiles in the oceans) array of floats.

Keywords: Intraseasonal variation, prediction, Tropical convergence zones.

THE MJO/ISO (Madden–Julian Oscillation/Intraseasonal Oscillation) simulations and forecasts have been an area of great scientific interest in recent years. At present, diversity of opinion exists on the modelling of this phenomenon. One needs to understand the central issues that govern the structure, motion and maintenance of this phenomenon. Some authors emphasize the pivotal role of cumulus convection for the maintenance of the MJO/ISO[1–4]. Randall *et al.*[2] emphasize the need for a cloud resolving nonhydrostatic microphysical model for its simulation. Nakazawa[5] observed that an envelope moving east on the time scale of 20 to 60 days, carries within it cloud lines that propagate eastward at a phase speed of roughly 5 to 7 degrees longitude per day. These two scales seem to move in unison and closely coupled. There are other studies that seem to provide simulations of the MJO without recourse to the explicit cloud modelling. Zhang and Mu[3] showed that refinement of cumulus parameterization is central for the modelling of this phenomenon. They found that a refinement of the Zhang-McFarlane[6] cumulus parameterization scheme was necessary for the simulation. He utilized an NCAR coupled model: the CCM3. Two separate studies[7,8] emphasized the need for uncoupled and coupled models for the modelling of the MJO. Wave–CISK (conditional instability of the second kind) was proposed[4] following the work of Lindzen[9] as a source of excitation for the globally traversing MJO waves. This called for a modulation of equatorial Kelvin waves from the effects of wave-induced convection as contrasted from ordinary CISK that calls for Ekman convergence for the drive of convection.

Poleward propagation of rainbands starting from near the equator and culminating in the northern trough zone is a unique feature of Intertropical Convergence Zones (ITCZ) over the Indo-Pacific region[10].

In this article we look at mechanisms governing MJO/ISO (both zonally and meridionally migrating systems). We propose that the oceans have a major role on these timescales of several months. We feel that coupled assimilation with a good coverage of global data in the atmosphere and in the ocean is important. Towards this end we have exploited the ECMWF database, the best estimates of precipitation for the atmospheric part of the data assimilation and the Reynolds SSTs (sea surface temperatures) and the global ARGO database for the oceans.

Mechanisms governing ISO

We first discuss mechanisms governing zonally moving ISO over the equatorial region and this is followed by a discussion of mechanisms governing the poleward moving ISO which are prominent during the northern summer (June–September) season over the Indo-Pacific region.

Zonally propagating ISO

Various theories have been proposed to explain the eastward movement of ISO. Majority of the mechanisms invoke the interaction of heating and movement of waves. The theories can be broadly classified as follows: i) Wave–CISK mechanism, ii) WISHE mechanism, iii) Charge–discharge theory, iv) Wave–wave interaction in spectral space.

Many excellent reviews[11,12] have discussed these mechanisms (i–iii). We therefore discuss them briefly here. The mechanisms (i–iii) suffer from the shortcoming that many assumptions have to be made to select the right scale (i.e. the planetary scale). The wave–wave interaction mechanism has the advantage that the combination

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