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Fluctuations in satellite-derived moisture fields over the Indian ocean and their possible linkage with the onset of the monsoon over India

N Gautam
Department of Earth and Planetary Sciences, 1397 CIVL Bldg, Purdue University,
West Lafayette, ~~IN~~ 47907-1397, USA
~~and~~
P C Pandey
Meteorology and Oceanography Group, Space Applications Centre (ISRO), Ahmedabad 380 053

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The TIROS operational vertical sounder (TOVS) and special sensor microwave imager (SSM/I) data for the period from April to September over four different years (1980, 1981, 1984 and 1988) onboard NOAA series and DMSP (Defence Meteorological Satellite Programme) satellites have been used to study the coherence of moisture fields in the box areas near the equator, the Arabian sea and the Bay of Bengal regions and the possibility of using the observed characteristics to relate with the onset of the Indian summer monsoon. A clear-cut trend reversal in moisture values has been observed over the box areas near the equator and at higher latitudes after the arrival of the monsoon. The temporal analysis of cross-over point between the boxes near the equator and the boxes at higher latitudes demonstrates the potential of observing the onset of the monsoon over India about a week earlier than the normal time, using weekly averaged moisture fluctuations in the box near the Somali coast and the box over the Arabian sea. The comparison of moisture values among different boxes has also been made. The present analysis indicates the eastward increment in moisture values.

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1 Introduction

The south-west monsoonal wind carries a large amount of moisture to the Indian subcontinent. The origin of this moisture, which produces intense rainfall over India, is considered to be a cross-equatorial flux from southern Indian ocean and evaporation from the Arabian sea. Due to the lack of wind and humidity data over the ocean, there is an uncertainty about the contribution of these sources of moisture for monsoonal rainfall. Pisharoty[1] computed moisture fluxes across the equator and water vapour budget over the Arabian sea and found that Indian south-west monsoon picked up most of its moisture from the Arabian sea. Findlater[2] studied the interhemispheric transport of air in the lower troposphere over the western Indian ocean and brought out the significant contributions of jet to mass transport of air between the southern and northern hemispheres through mean flow patterns for January and July. Later Saha[3] and Saha and Bavedekar[4] found that the cross-equatorial flux to be 60-80% of the moisture transported across the west coast of India. This result contradicts Pisharoty's findings. Ghosh *et al.*[5] also computed moisture fluxes across the equator using data of 1973 Monsoon Experiment and found results favouring Pishorty's findings[1]. Later Cadet and Raverdin[6,7] showed the importance of cross-equatorial flux, compared to evaporation, in the water vapour buget over the Arabian sea using ship reports made during the 1975 summer monsoon. On the basis of all this work, it is clear that relative contributions of the cross-equatorial flux and evaporation over the Arabian sea to the flux over the west coast of India are still important and to be debated. Howland and Sikdar[8] performed a very detailed study of moisture transport during a few days of 1979 monsoon and observed dramatic changes in the kinematics and moisture fields at the time of onset.

Space-borne observing platforms provide the moisture data with a good coverage over the oceanic region and high frequency of observations. One of the objectives of NOAA/TIROS-N series of satellites is to infer operationally the water vapour profiles from the measurements of outgoing radiation reaching its high resolution infrared sounders (HIRS). Cadet[9] has extensively used NOAA data to study the fluctuations in atmospheric water vapour fields for the 1979 summer monsoon in relation to active/break phases of monsoon. Kishtwal *et al.*[10] have studied the nature and modes of intraseasonal fluctuations of lower layer moisture fields in different zones of monsoon regions using NOAA/HIRS data.

Earlier Pandey *et al.*[11] and Pathak and Gautam[12] have also studied atmospheric moisture over the Arabian sea (hereafter AS) and the Bay of Bengal (hereafter BB) using Bhaskara-II SAMIR data and found higher moisture over BB than those over AS. Gautam *et al.*[13] studied monthly mean moisture fields derived from NOAA/HIRS data for three years during south-west monsoon and found higher moisture over BB than those over AS. The plausible explanation for the above observational fact was attributed by them[13] to be positive net moisture flux divergence over AS and negative net moisture flux divergence over BB. Recently Kishtwal *et al.*[14] studied the surface level transport for three years using NOAA/HIRS data and examined the relative contribution of cross-equatorial flux and evaporation over AS. Their results show that relative contribution is variable but most of the time cross-equatorial flux is significantly larger than evaporation over AS. They[14] also pointed out that it is highly dependent upon the boundary chosen in the computations. Ananthakrishnan *et al.*[15] also studied the seasonal variation of water vapour in the atmosphere over India.

However, in this study an attempt has been made to observe and analyse temporal fluctuations in satellite derived moisture values near the equatorial Indian ocean, and over AS and BB and the possible linkage between the moisture and the onset and advancement of the monsoon using NOAA/TOVS and SSM/I data.

2 Data and analysis

The TIROS-N/NOAA 'finished product' precipitable water vapour data for the period April-September over three different years (1980, 1981 and 1984), and special sensor microwave imager (SSM/I) derived water vapour data for the year 1988 over the same period have been used. The TIROS-N/NOAA series of operational meteorological satellites carry a high resolution infrared sounder (HIRS) and microwave instruments which provide complete global coverage of temperature and moisture profile data. A description of TIROS-N operational vertical sounder (TOVS) has been given by Smith *et al.*[16]. The TOVS instrumentation includes three channels directed to the retrieval of precipitable water. They are positioned spectrally at 8.3, 7.3 and 6.7 μm and roughly sense the troposphere from surface to 300 mbar level in three broad layers (surface to 700, 700-500 and 500-300 mbar level). The water vapour amounts of these three layers are combined to obtain the total water vapour in the atmosphere. Water vapour above 300 mbar is negligible. The NOAA satellite provides water vapour data on a global scale and these data are affected by the presence of clouds in the instrumental field of view (IFOV). The TOVS sounding product is derived from HIRS, one of the TOVS instruments. The HIRS measures the intensity of upwelling radiation in the various spectral intervals that occur at the maxima over the broad layers and depths of the atmosphere. These radiance measurements are processed into earth-located calibrated radiances values. The estimates of the water vapour in three broad layers are done using clear radiances (radiances corrected for cloud effects and angle of view). Accuracy of precipitable water was found to be ~20%.

The passive microwave data from special sensor microwave imager (SSM/I) onboard 'Defence Meteorological Satellite Programme F08' satellite for the year 1988 has also been used. The SSM/I consists of 7 separate total power radiometers centered at 19.35, 22.235, 37 and 85 vertical and horizontal frequency (GHz) (except 22.235 GHz which is only at vertical) each simultaneously measuring the microwave emission coming from the earth and intervening atmosphere. The SSM/I provides ocean surface wind speed, water vapour content, liquid water content and rain rate over ocean surface. Each SSM/I data over open ocean is only considered. A SSM/I cell is considered over open ocean only if it is a minimum of 100 km away from the coastline. Wentz[17] has described the SSM/I in detail.

Four different box areas near the equator over Indian ocean, one box area over AS near the west coast of India and one box area over BB near east coast of India have been considered to study the fluctuations in weekly averaged moisture values. Figure 1 shows the location of these boxes over the equatorial Indian ocean, AS and BB, respectively. Land portion of the boxes 5 and 6 are not considered for analysis. The boxes 1-3 represent the cross-equatorial sections of the Arabian sea and box 4 for the Bay of Bengal. Box 5 represents the part of the Arabian sea from where the moisture flux directly enters the west coast of India. Kishtwal *et al.*[14] has shown that during the period of monsoon activity, the moisture flux crossing the west coast of India far exceeds the cross-equatorial flux into the Arabian sea; so there is a net flux divergence over the box 5. On the other hand, over the Bay of Bengal region (box 6),

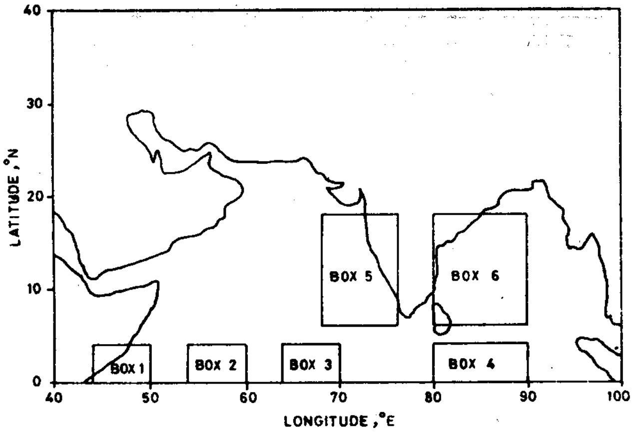

Fig. 1—Geographical representation of boxes over Indian ocean

there is a large inflow of moisture from its western and southern boundaries, while a small outflow takes place through northern and eastern boundaries. This leads to a net flux convergence over this region. Thus, these areas emphasized the importance of inflow of moist air northward across the equator during monsoon and evaporation over AS and BB. Moisture values over these boxes (1-6) were averaged over a week. In the case of data gaps in any box, the value has been interpolated using pre- and post-weeks data. The fluctuations in moisture have been studied using time series of satellite derived moisture over above defined domain (Fig.1).

3 Results

3.1 Fluctuations in moisture fields

The analysis of weekly averaged moisture (hereafter WAM) values in different boxes in the four years from April to September indicates interesting phenomenon that occurs in these years. Time series begins from 1 which represents the first week starting from 1st April for all the years and it terminates at 26th week (29th September) for 1980 and 1981, and 31st week (4th November) for 1984 and 27th week (6th October) for 1988. The interesting features observed from moisture variations are:

(i) A clear-cut trend reversal in moisture values is seen in boxes 1-3 when compared to that in box 5 in the Arabian sea and similarly in box 4 compared to that in box 6 in the Bay of Bengal (Figs 2-5). The approximate times of cross-over points in the respective boxes are given in Table 1. The temporal movement of the cross-over points from box 1 to box 4 shows that the cross-over points between box 1 and box 5 occur about a week earlier than those between box 2 and box 5, and box 4 and box 6. An attempt has been made to examine these cross-over points in

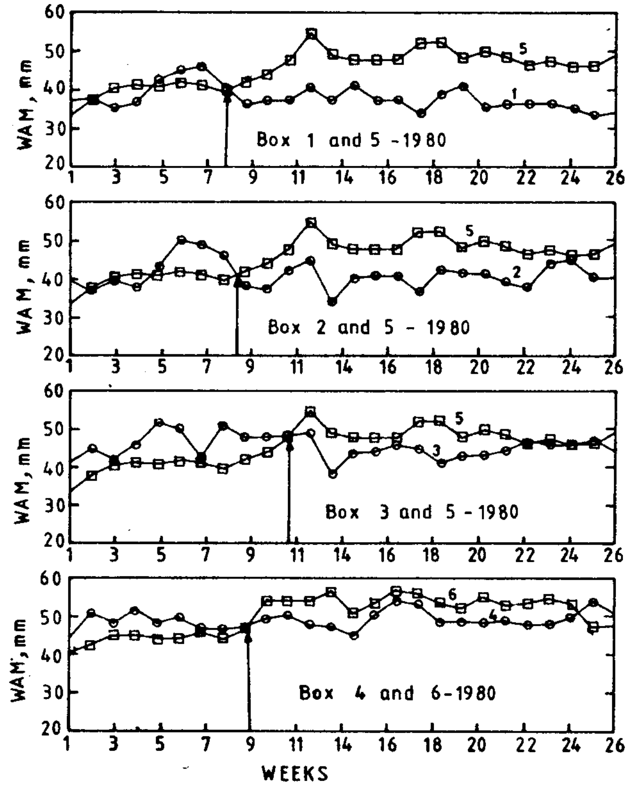

Fig. 2—Time series of WAM values for the year 1980

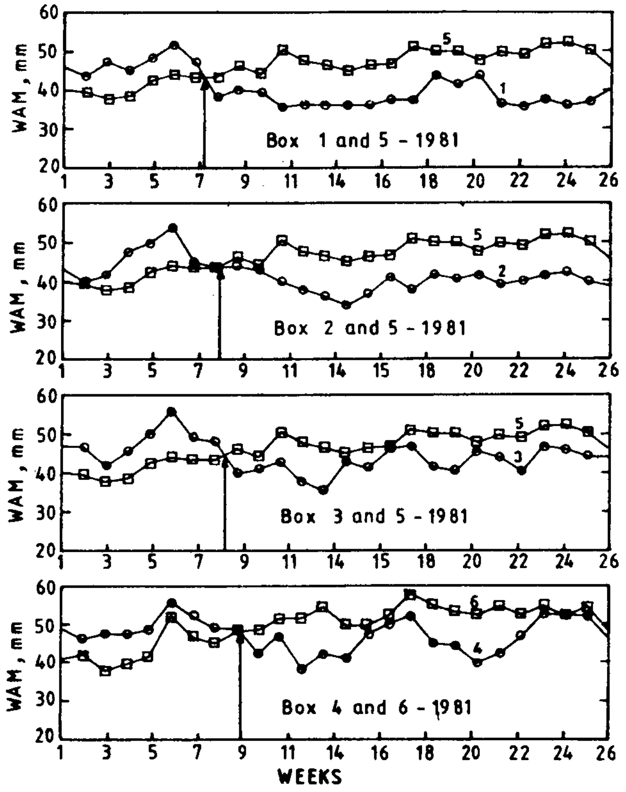

Fig. 3—Time series of WAM values for the year 1981

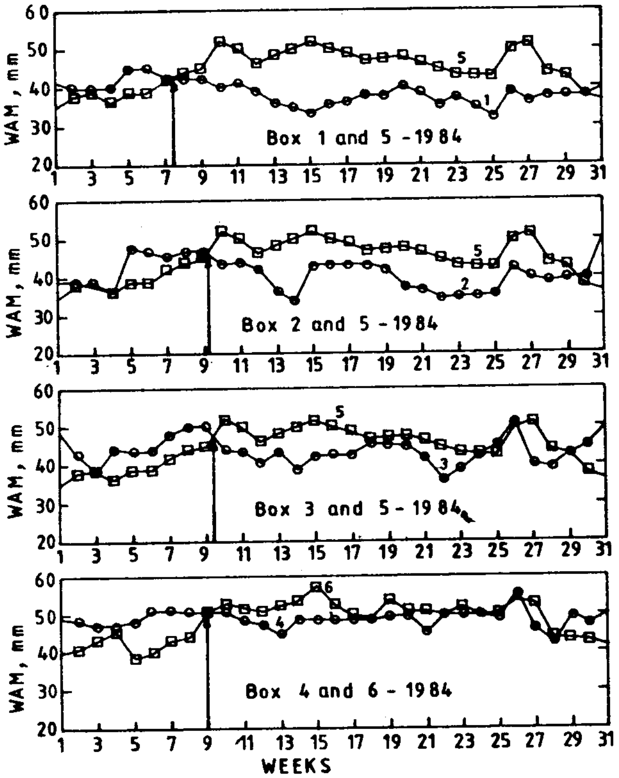

Fig. 4—Time series of WAM values for the year 1984

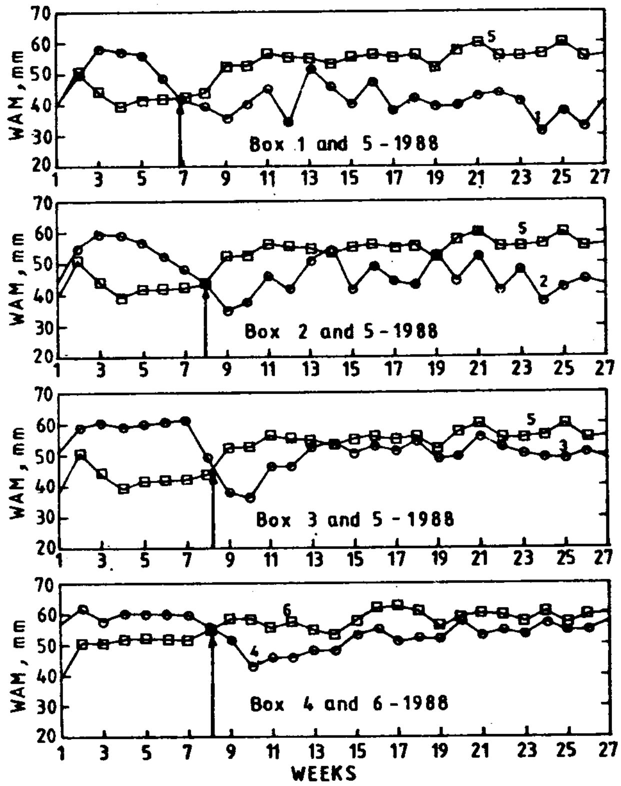

Fig. 5—Time series of WAM values for the year 1988

Table 1—Cross-over points (CP) for different boxes

Years	CP- 1 & 5	CP- 2 & 5	CP- 3 & 5	CP- 4 & 5
1980	~ Before 8 weeks	Between 8 & 9 weeks	Between 10 & 11 weeks	~ 9 weeks
1981	~ After 7 weeks	~ 8 weeks	~ 8 weeks	~ 9 weeks
1984	~ After 7 weeks	~ 9 weeks	~ 9 weeks	~ 9 weeks
1988	~ Before 7 weeks	~ 8 weeks	~ 8 weeks	~ 8 weeks

Table 2—Monsoon onset date over Kerala

Years	Monsoon onset date over Kerala
1980	1 June
1981	30 May
1984	31 May
1988	26 May

relation to the onset of the monsoon over Kerala in the four years. The dates of the onset of the monsoon over Kerala in all these years are given in Table 2. These onset dates were provided by India Meteorological Department and refers to the coast of Kerala. The onset of the monsoon shows that the cross-over points for box 1 and box 5 in all the years occur atleast a week earlier. As we move to other boxes the cross-over points show systematic shifts. For box 3 and box 4 the cross-over is almost simultaneous except for the year 1980 (Figs 2-5). So, it can be concluded that the WAM values in box 1 and box 5 are having some predictive value than those in other boxes for the onset of the monsoon over Kerala.

(ii) The WAM values in box 1 and box 2 are found to decrease sharply in 3-4 weeks around the onset time by about 15-20 mm (30-40%). After the cross-over, the averages of the WAM values for all the years are found to be less than those before the cross-over point. However, the WAM values in boxes 3 and 4 are characterized by sharp decrease in 1981 and 1988, while they decrease slowly in the year 1980 and 1984.

(iii) The WAM values in box 5 and box 6 are found to be characterized by a sharp increase (25-35%) within 3-4 weeks around the onset time in all the years. It is found to increase by ~ 15 mm during this period. After the cross-over point the average values of WAM for all years are found to be higher than those before the cross-over period.

Earlier Cadet[9] and Kishtwal *et al.*[14] also observed the decrease in moisture values near the Somali coast and the increasing trend over AS before the onset of the monsoon. However, in the present work, their observations are confirmed from satellite derived precipitable water values. The phenomena of cross-over may be attributed to the gradual build up of atmospheric moisture storage over the Arabian sea, which starts a few weeks before the onset of monsoon. In fact, the role of this moisture storage over the Arabian sea is very critical in triggering the convective instability over the Arabian sea which results in a sudden release of kinetic energy. However, the physical mechanism behind this phenomena is still not well understood.

4 Comparison of WAM values

Figure 6 [(a), (b), (c) and (d)] shows the scatter plots of WAM values of box 1 vs box 2, box 2 vs box 3. box 3 vs box 4 and box 5 vs box 6 for the year 1980. It has been found that the 85% WAM values for the box 2 are greater than those of box 1; ~80% of box 3 WAM values are greater than those of box 2; ~85% of box 4 WAM values are higher than those of box 3; and more than 95% of WAM values of box 6 are found to be higher than those of box 5. Scatter plots for the years 1981, 1984 and 1988 show similar results. It has been found that most of the time box 6 shows higher WAM values than those of box 5 for all the years. Earlier Pandey *et al.*[11], Pathak and Gautam[12], and Gautam *et al.*[13] have shown that BB is characterized by higher moisture values than those over AS on a monthly scale. It is interesting to note the eastward increasing trend in moisture values near the equatorial Indian ocean. Earlier Gautam *et al.*[13] also observed same eastward increasing trend in monthly mean moisture fields from 40° to 100° E in the northern and equatorial Indian ocean. The plausible explanation for eastward increasing trend in moisture field could be attributed to decrease in net moisture flux divergence in the boxes from west to east. However, this observational facts are not readily physicallly explainable and needs further analysis. A physical explanation could be attempted with the help of circulation and sea surface temperature data over this region.

5 Conclusions

This study demonstrates the potential for prediction of the onset of monsoon a week earlier than the normal time from the time series of satellite derived moisture fields over the Indian ocean. The eastward increasing trend in moisture over the Indian ocean during southwest monsoon is confirmed. This

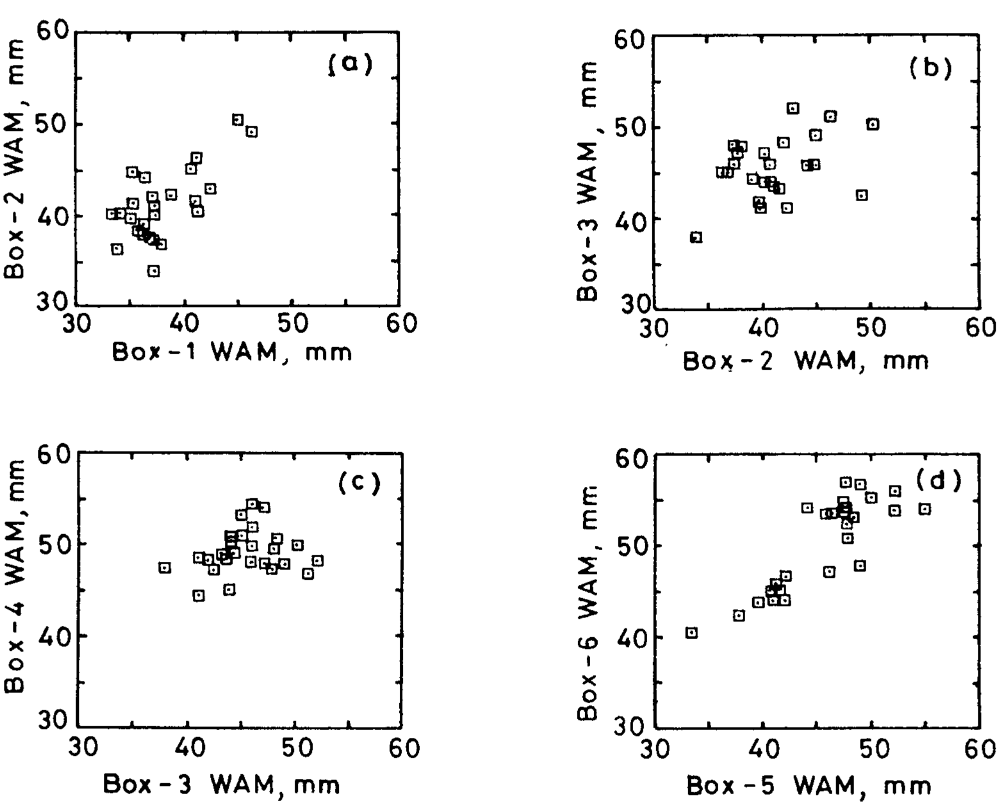

Fig. 6—Scatter plot between WAM values of different boxes for the year 1980 (a) box 1 vs box 5; (b) box 2 vs box 5; (c) box 3 vs box 5; and (d) box 4 vs box 6

observational fact should be further studied in conjunction with sea surface temperature and ocean surface wind data. The large number of future operational satellites and innovative applications of their data will enable us to study the fluctuations in atmospheric and oceanic parameters on daily basis and would give an overall idea of monsoon onset.

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