Intraseasonal oscillations over tropical Indian ocean in relation to monsoon onset and rainfall events over the peninsular India

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सार – भारतीय उपमहाद्वीप और उसके समीपवर्ती समुद्रों में दक्षिणी पश्चिमी मानसून के दौरान और उससे पहले पाँच वर्षों की अवधि (1995–1999) में उपग्रह से प्राप्त किए गए जलवाष्प के आँकड़ों का विस्तृत विश्लेषण किया गया है। इस विश्लेषण के लिए एन.ओ.ए.ए. ⁄ टी.ओ.वी.एस उपग्रह से प्राप्त तीन स्तरों (1000 है.पा. –700 है.पा., 700 है.पा.– 500 है.पा. और 500 है.पा. – 300 है.पा.) और सकल नमी संबंधी आँकड़ों का उपयोग किया गया है। इन आँकड़ों का उपयोग ग्रीष्मकालीन मानसून ऋतु के दौरान उष्णकटिबंधीय हिंद महासागर में उत्तराभिमुखी संचरित अंतः मौसमी दोलनों का अध्ययन करने के लिए किया गया है। इसके परिणामों से मध्य स्तर (700 है.पा – 500 है.पा.) और ऊपरी स्तर (500 है.पा. – 300 है.पा.) जल वाष्प में अंतः मौसमी दोलनों की उपस्थिति का पता चला। विशेष रूप से पूर्वी अरब सागर (ई.ए.एस.) में अंतः मौसमी दोलनों के लक्षणों और समय–विकास का अध्ययन करने के लिए वेवलेट विश्लेषण का प्रयोग किया गया है। पूर्वी अरब सागर में 8–15 दिन, 15–30 और 30–60 दिनों की अवधियों के अंतः मौसमी दोलन देखे गए। मध्य स्तर में नमी की उपलब्धता और क्षेत्रीय पवन गति के संबंध में मानसून के आगमन से पहले और उसके बाद प्रायद्वीपीय भारत के पश्चिमी तट में भारी वर्षा वाले दिनों का अध्ययन किया गया है। यह पाया गया है कि भारत के पश्चिमी तट में होने वाली वर्षा को पूर्वी अरब सागर के लिए जल वाष्प घटक और क्षेत्रीय पवन गति प्रभावित करते हैं।

ABSTRACT. Detailed analysis of the satellite derived water vapour for a five years period (1995-1999) prior to and during southwest monsoon is done over the Indian subcontinent and the adjoining seas. Three layer (1000 hPa – 700 hPa, 700 hPa –500 hPa and 500 hPa -300 hPa) and total moisture data available from NOAA/TOVS satellite are used for the analysis. These data are used to study the northward propagating intraseasonal oscillations in the tropical Indian Ocean during the summer monsoon season. Results indicate the presence of intraseasonal oscillations in the middle (700 hPa – 500 hPa) and the upper level (500 hPa – 300 hPa) water vapour. Wavelet analysis is applied to study the characteristics and time evolution of the intraseasonal oscillations especially over East Arabian Sea (EAS). Intraseasonal oscillations with periods ranging from 8-15 days, 15-30 and 30-60 days are seen over EAS. Heavy rainfall events over west coast of peninsular India are studied before and after the monsoon onset in terms of moisture availability in the middle level and zonal wind speed. The water vapour content and zonal wind speed over the Eastern Arabian Sea are found to influence rainfall over the west coast of India.

Key words – Indian summer monsoon, Monsoon onset, Intraseasonal oscillation, Heavy rainfall, Water vapour, Remote sensing.

1. Introduction

The southwest monsoon (June-September), accounts for more than 80% of the annual rainfall over India. The spatial and temporal distribution of summer monsoon rainfall over the country and its variability affects the agricultural output significantly. The delay in the onset of monsoon by a few weeks would affect the agricultural activity. Thus, the monitoring and forecasting of the summer monsoon's onset over Indian subcontinent is very much important for the economy of the country. The date of monsoon onset varied from 11 May in 1918 to 18 June in 1972. The normal date of onset over south Kerala is 30 May and over north Kerala is 1 June with standard deviations of about 8 days (Ananthakrishnan, 1988). In bringing the monsoonal rains over India, the cross equatorial flow of moisture and wind as well as the evaporation over the north Indian Ocean and adjoining seas are known to be important (Cadet and Reverdin, 1981; Joshi *et al*., 1990). By

studying the changes in mid-tropospheric water vapour from NOAA/TOVS for seven years over various regions of the Indian Ocean, Bay of Bengal and Arabian sea, Simon and Joshi (1994) found that the mid-tropospheric water vapour content (700-500 hPa) over western Arabian sea increases by 25% about 8-10 days before the monsoon onset.

Recently, using the atmospheric total water vapour content and sea surface wind speed data obtained from MSMR instrument onboard Oceansat-1, Simon *et al*., (2001) studied the progress of the onset of monsoon over Indian region. They noticed a significant increase of ~20% in total water vapour over western Indian Ocean about two weeks before the onset.

Occasionally onset like condition (called bogus onset) prevails in May for a short period prior to monsoon onset over Indian region. Increased wind speed at the lower troposphere and significant rainfall activity over south India are seen during these conditions (Flatau *et al*., 2001). Unlike the real onset, northward propagation of the cloudiness is generally limited to south Indian region during bogus onset. This situation possibly delays the real onset in June. Water vapour content of the atmosphere builds up temporarily during this short duration of bogus onset.

During summer monsoon season, active and break spells of rainfall are seen over India (Ramamurthy, 1969; Webster *et al*., 1998). Northward and eastward propagating intraseasonal oscillations appear to influence these spells (Maden and Julian, 1994; Sikka and Gadgil, 1980; Yasunari, 1980; Goswami and Ajaya Mohan 2001). Intraseasonal oscillations involve significant modulation of sea surface temperature (SST) and turbulent fluxes at the air-sea interface in the Bay of Bengal and equatorial West Pacific (Sengupta *et al*., 2001; Krishnamurti and Ardanuy, 1980). Widespread rainfall and stronger winds at lower levels are seen throughout Indian subcontinent during the active spells. In contrast, rainfall activity is confined to the foothills of Himalayas during break spells.

Strong cross equatorial low-level jet stream develops in response to the large meridional pressure gradient between Asian continent and Indian Ocean during monsoon season. This strong low-level wind, which flows nearly perpendicular to the western Ghat mountain ranges in the Indian Peninsula, can initiate deep convection upwind near the mountain range due to lifting of air by mountain blocking. Grossman and Durran (1984) studied the effect of western Ghat on the maintenance of deep convection off the west coast of India. Their study based on two dimensional mountain flow interaction model indicated that the amount of moisture in the layer from about the cloud base to 500 hPa plays a major role in the
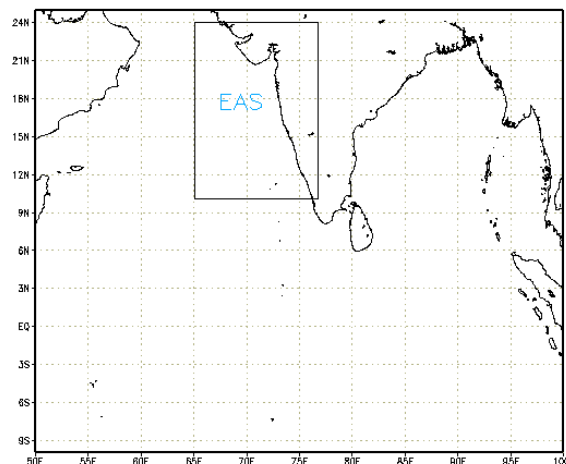

Fig. 1. Region of study

formation of deep convection offshore. Sarker (1967) found that the precipitation produced by stable upglide along the windward slopes of the mountains account for over 90% of the observed precipitation near the mountain crest. Thus, the rainfall over west coast of India is strongly influenced by both the moisture content of the atmosphere and the speed of the lower level wind flow.

Satellites have the capability to monitor wide parts of the globe with good temporal resolution. They provide valuable information about the state of the atmosphere and ocean over the data sparse oceanic regions. In the present paper satellite measured three level water vapour data are analysed to study the systematic changes in water vapour over the Indian region prior, during and after the monsoon onset. Effect of wind speed and moisture content on the west coast rainfall is also studied with this data set.

2.   Data and methodology

Daily TOVS derived water vapour sounding data are available from NOAA-NESDIS, USA in a 2.5° Lat. × Long. grids.   Daily water vapour data during May to September for the five years (1995-1999) are used in the present study. Data gaps are present during 5-11 June, 1995; 5-7 July 1996 and 24 June 1998. The TOVS sensor onboard NOAA polar orbiting satellite has three infrared channels (8.3, 7.3 and 6.7 μm) and has the capability to provide three layer (1000 hPa −700 hPa, 700 hPa −500 hPa and 500 hPa - 300 hPa) moisture data. The TOVS observed water vapour estimates are within 15% of the *in situ* values. Since the water vapour over the Eastern Arabian Sea (EAS-10°N, 24° N; 65°E, 77° E) undergoes substantial variations prior to and during the monsoon season, this region is considered for detailed analysis (Fig. 1). In addition to
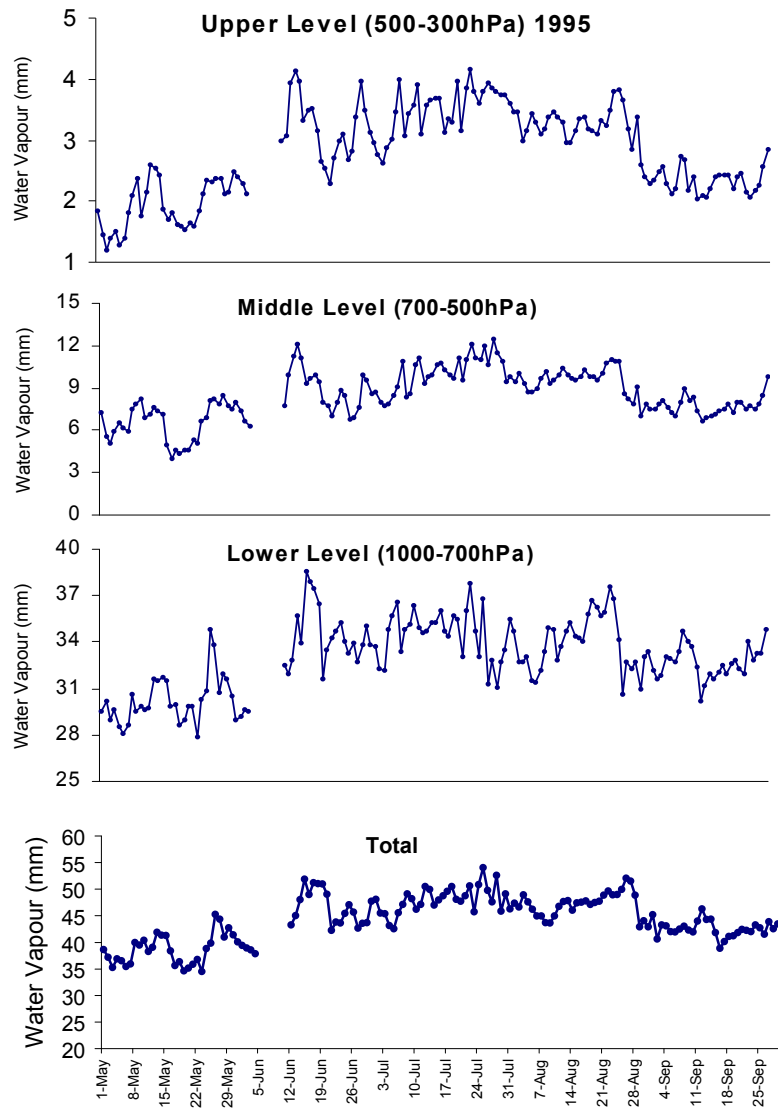
Fig. 2. Variation of water vapour in three levels and total

that, the infrared sounder is able to provide valuable information in more number of grids over Eastern Arabian Sea when compared to the Bay of Bengal because of the relatively less cloud contamination over this region. Daily zonal wind data at 700 hPa level with the horizontal resolution of 2.5° Lat. × Long. grids available from NCEP reanalysis data set are also used for the analysis.

In general, mathematical transformations are applied to meteorological and oceanographic signals to obtain most distinguished further information from that signal that is not readily available in the raw signal. To analyze the intraseasonal oscillations over the Indian region,

Morlet wavelet transform is used. Wavelet transform is capable of providing the time and frequency information simultaneously, hence giving a time-frequency representation of the signal.

Wavelet transform uses generalized wave functions called wavelets that can be stretched and translated both in time and frequency. The continuous wavelet transform is defined as follows (Weng and Lau, 1994)

$$W(b,a) = (1/\sqrt{a})\int\Psi^*(t\text{-}b/a)s(t)\ dt$$

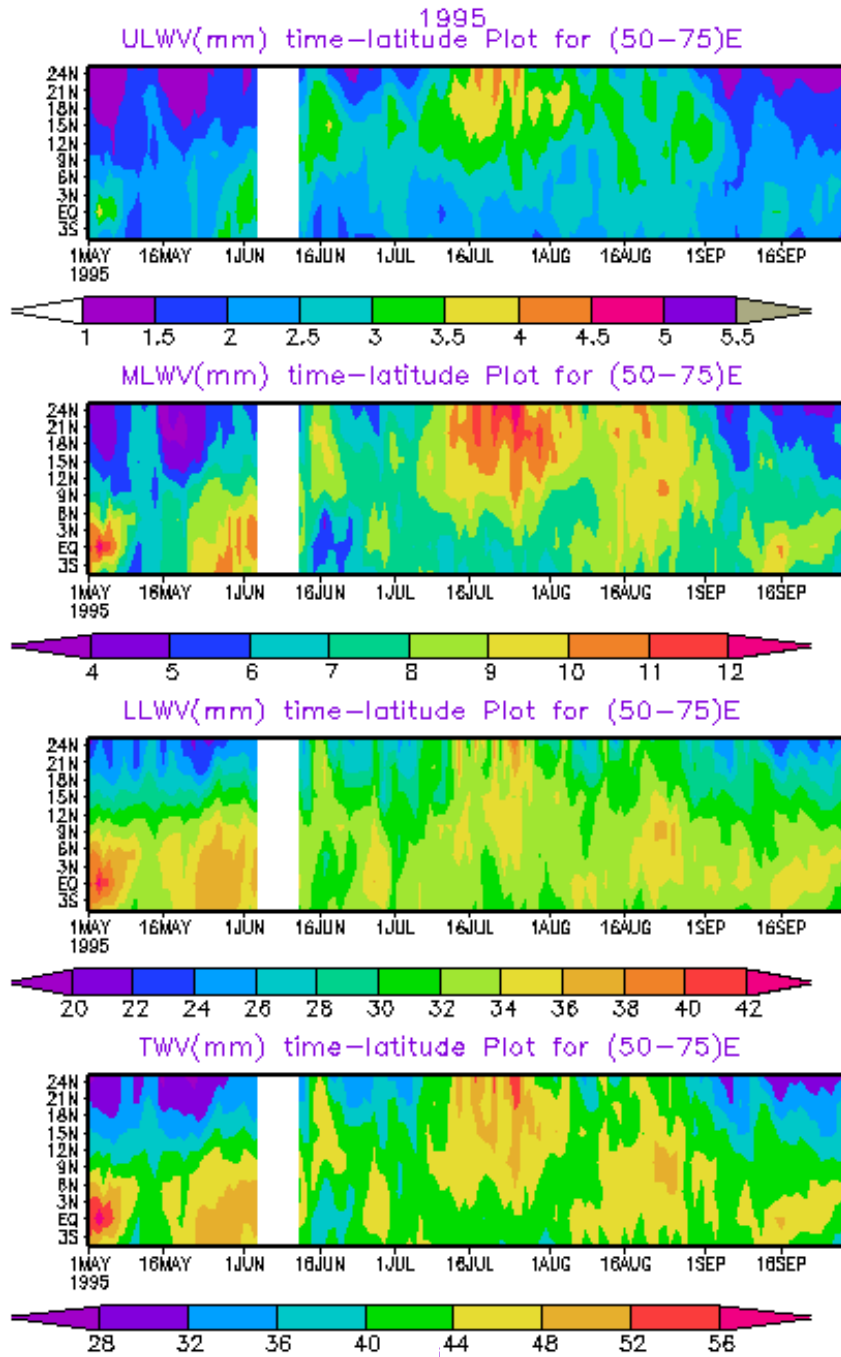where Ψ^* is the complex conjugate of Ψ

Fig. 3. Time latitude plot of water vapour May – September over Arabian Sea

b is the position (translation) parameter

a (>) is scale (dilation) parameter

The   analyzing   wavelet $\Psi(t)$ for   Morlet wavelet   transform   is $\Psi(t)$ = $e^{ik\Psi t}e^{-|t.t|/2}$,which is

plane   wave   modulated   by   a   Gaussian. The   Morlet wavelet   transform   is   applied   to   the   area   averaged daily   water   vapour   field   over   the   selected   regions for   the   pre-monsoon   and   monsoon   seasons   for   1995-1996.   The   length   of   the   data   sets   is   kept   as   128   days (1   May   to   5   September).   Few   data   gaps   in   the
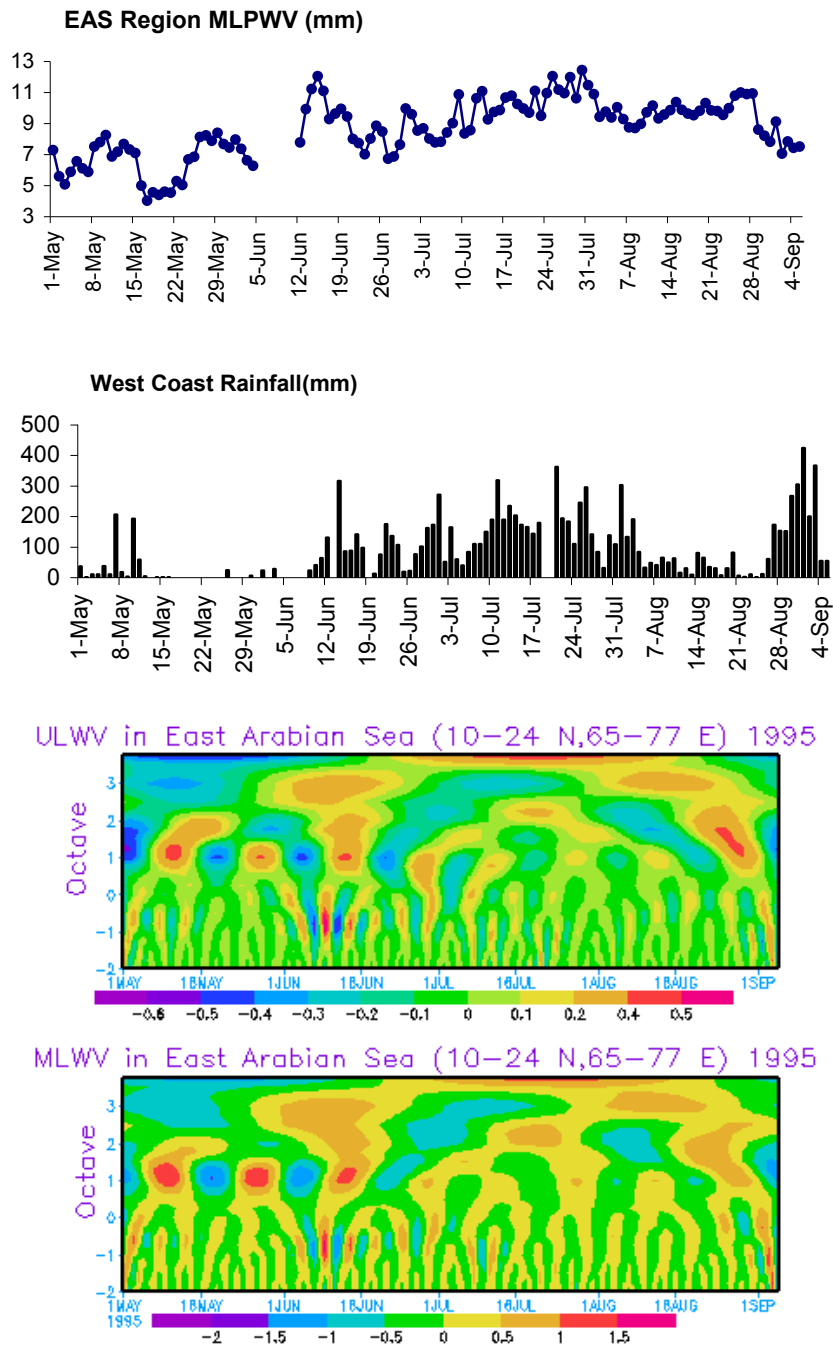
EAS Region MLPWV (mm)

West Coast Rainfall(mm)

ULWV in East Arabian Sea (10–24 N,65–77 E) 1995

MLWV in East Arabian Sea (10–24 N,65–77 E) 1995

Fig. 4. Wavelet analysis of middle and upper level along with West Coast rainfall and daily averaged middle level water vapour

time series are filled by linear interpolation and the number of voices per octave is kept 4. The abscissa is time (days) and the ordinate is in Octave (log 2). The Octaves - 2, -1, 0, 1, 2, 3 are corresponding to 2, 4, 8, 16, 32 and 64 day periods respectively.

3. Results and discussion

To show the evolution of atmospheric water vapour prior to and during onset and the following monsoon season, the time series of water vapour in the three levels
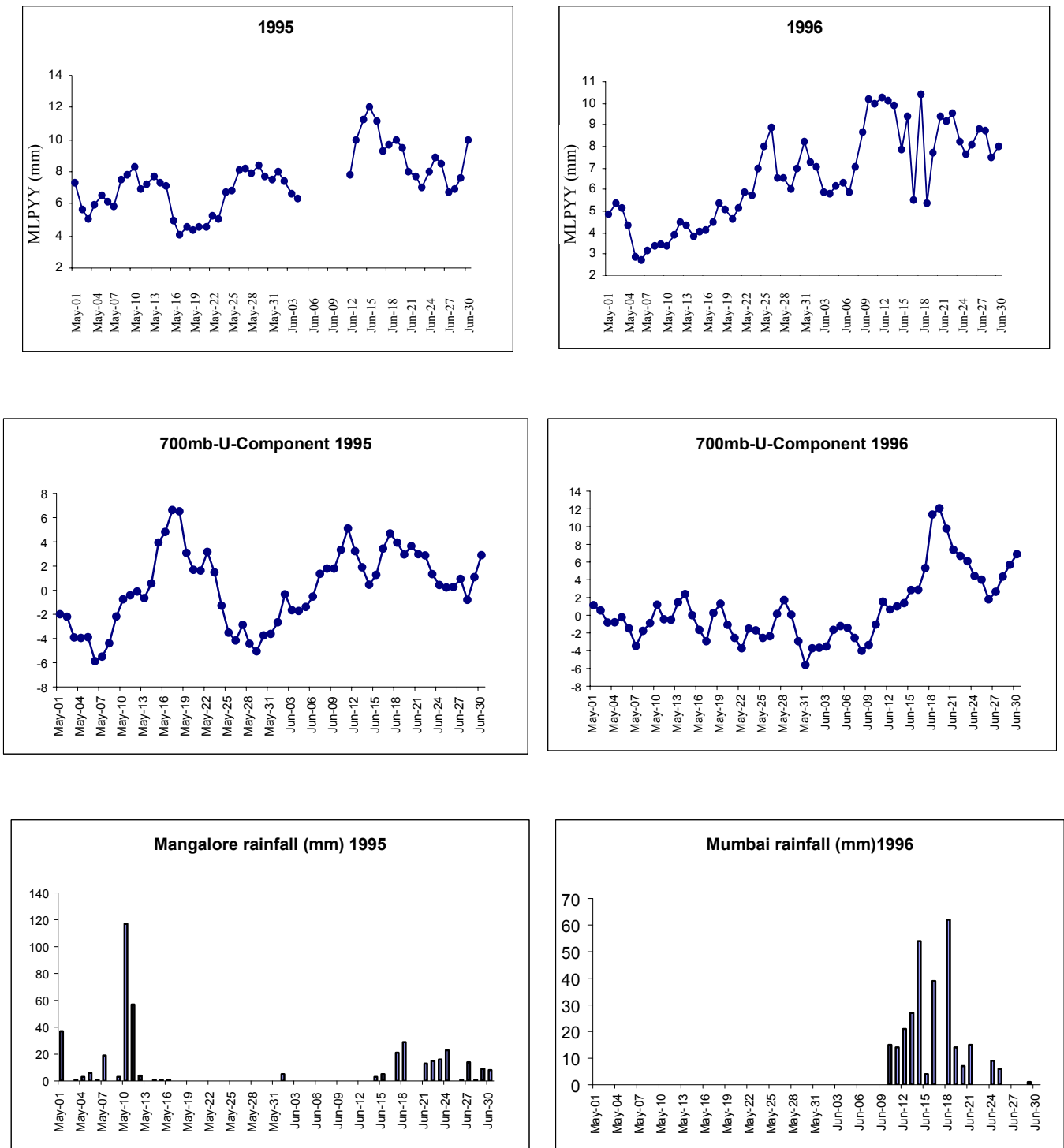
Fig. 5. Variation of middle level water vapour (700-500 hPa) and U-component of wind   over Eastern Arabian Sea and its association
with heavy rainfall events over the west coast of India during 1995 and 1996

(1000 hPa – 700 hPa, 700 hPa – 500 hPa, and 500 hPa – 300 hPa) along with the total water vapour averaged over the East Arabian Sea are presented for 1995 in Fig. 2. Significant changes are taking place in the amount of water vapour during onset. As per India Meteorological Department, monsoon onset took place on 8 June over Kerala coast in 1995. Water vapour content in the three layers increases during onset time and it remains relatively high during the peak summer monsoon months. Around the onset time, sudden increase in water vapour is seen in all the three layers with about 25% increase in the lower level and 100% increase in both middle and upper levels around the onset time. Total water vapor content of the atmosphere also showed similar increasing trend from 36 mm to 51 mm (about 41%) during onset.

In Fig. 3, the time-latitude plots of water vapour in the upper, middle, lower levels and total water vapour content over the Arabian Sea (50° -75° E) are presented for 1995. These plots show clear northward propagation during the onset and its presence in the following monsoon season in all the levels. An initial water vapour maximum is seen in the first week of May which may be due to the bogus onset condition prevailed during this time (Flatau *et al.*, 2001). Delay of the real monsoon onset in 1995 by a week time may be due to the bogus onset conditions prevailed nearly one month earlier.

We have analyzed water vapour in all the three levels over Eastern Arabian Sea during May to September in 1995 and 1996, with the help of wavelet analysis to study the role of intraseasonal oscillations on the occurrence onset and the maintenance of the monsoon activity in the following four months. The Morlet wavelet transform is used for this purpose. Intraseasonal oscillations with periods of about 15-30 days and 30-60 days are seen in the middle level and upper level water vapour over the East Arabian Sea. Wavelet plot for 1995 is shown in   Fig. 4. Notable feature in this figure is the presence of only high frequency mode with period about 15-30 days before the monsoon onset and both high and low frequency modes with periods about 15-30 and 30-60 days after the real onset. Since the bogus onset and its northward movement are limited to the southern parts of Indian Peninsula (Joseph and Pillai, 1988; Flatau *et al.*, 2001), its signature in water vapour may be smoothed out when averaged in a big box. This may be a possible reason for the absence of low frequency signal before real onset in the wavelet analysis. All these modes are not seen clearly in the lower level (not shown), may be due to the weak variations (~25% only) in water vapour when compared to the variations in the middle and upper levels (~100%). Around onset date (8 June), all these modes are significant and in positive phase.

3.1.   *Rainfall events over the west coast of India and its association with water vapour*

In this section, the possible influence of middle level water vapour and the zonal wind speed at 700 hPa on the west coast precipitation is examined using rain guage data from few coastal stations, TOVS water vapour data and NCEP/NCAR reanalysis zonal wind data. In Fig. 5, the middle level precipitable water vapour, zonal wind at 700 hPa both averaged over the East Arabian Sea region and rainfall over west coast station Mangalore are presented for 1995. The box considered for spatial average is larger starting from few hundreds of km west of the coast in order to cover the zonal wind few hundred km away from the coast. It is to be remembered that the zonal wind speed decreases as it approaches near the coast due to upstream blocking effects. Middle level water vapour in 1995 shows three significant peaks during 8 -15 May, 25 May – 4 June and 12 – 20 June. Out of these three peaks, first and the last one led to heavy rainfall along the west coast as evidenced from Mumbai rainfall. Mangalore received 124 mm on 11 May, Panjim 180 mm on 14 June and Mumbai 42 mm on 16 June. Intensive rainfall activities over these stations may be attributed to the high moisture levels in the atmosphere and increased zonal winds as seen in Fig. 5. Though there is a peak in middle level water vapour during 25 May - 4 June, the zonal wind was easterly (negative). The west coast stations did not receive rainfall during this time may be due to the reversal in wind direction.

From 8 June 1996 the middle level water vapour increased from about 6 mm to a peak of about 10 mm on 13 June. The area averaged zonal wind in the EAS also showed an increase in speed from about 10 June with peak around 19 June. Mumbai recorded an increase in rainfall from 10 June with a peak (60 mm) on 18 June. Another coastal station Mahabaleswar recorded 30 cm rainfall on 19 June.

Similar relationship between west coast rainfall and increase in westerly wind/water vapour is found in other years also. This simple case study demonstrates the importance of both the atmospheric moisture content and zonal wind speed on the west coast rainfall activity. If either one or both of these parameter are changing that may be reflected in the west coast rainfall. If atmospheric moisture content is less in monsoon season (especially during break condition), more zonal wind and off shore lifting may be required for the occurrence of heavy rainfall. Grossman and Durran (1984) also pointed out that when convective activity is less along the west coast, more offshore lifting is required to produce convection.

4. Conclusions

The evolution of atmospheric moisture content in different levels *viz.*, lower, middle and upper levels during monsoon onset and the following monsoon season is studied using satellite measured water vapour data. They showed significant increase in the amount of water vapour in these levels before and after onset. The water vapour showed a significant increase of 100% in the upper and middle levels.

The time-latitude plot averaged over Arabian Sea (50°-75° E) for the three levels and total precipitable water vapour show first significant northward propagation during the real onset and its repetition till the end of monsoon season. An initial water vapour maximum is seen in the first week of May, which may be due to the bogus onset condition prevailed in 1995. Wavelet analysis of the middle and upper level water vapour suggested the presence of well-marked 15-30 days oscillation before and during onset time and 30-60 day oscillation only after the real onset in the EAS.

Few case studies were made to understand the possible influence of middle level water vapour content and zonal wind speed on the occurrence of heavy rainfall along the west coast of India. West coast generally received heavy rainfall when both moisture content and westerly wind are high.

Acknowledgements

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