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STUDY OF INDIAN SUMMER MONSOON RAINFALL ON DECADAL SCALES VIS-À-VIS CIRCULATION PATTERNS

*K Muni Krishna and S Ramalingeswara Rao
Department of Meteorology and Oceanography, Andhra University
Visakhapatnam-530003, India

ABSTRACT

The decadal variations of all India summer monsoon seasonal rainfall during 1871-2000 are studied. Two extreme decades, one positive (1951-60) and another negative (1981- 1990) in the recent decades are considered depending upon the values of all-India monsoon seasonal rainfall. For these two decades, the synoptic features are studied for the parameters like mean seasonal values of air temperatures, zonal wind and meridional wind at two levels, 850hPa and 150hPa and latent heat flux in domain of 30^oE-120^oE and 30^oS-40^oN. The frequency of Bay of Bengal cyclonic systems during June through September is also studied. During good (poor) monsoon decade there is an enhancement (a reduction) in the intensity of easterly jet and frequency of Bay of Bengal cyclonic systems during June through September. It is also observed that the strength of the monsoon trough is pronounced/reduced during active/poor monsoon situations. Bay of Bengal and Arabian Sea play an important role in transporting moisture towards Indian main land and deciding the behaviour of Indian summer monsoon.

Keywords: Summer monsoon, rainfall, circulation, latent heat flux.

INTRODUCTION

The Indian summer monsoon is very important in all its aspects namely onset, withdrawal and variability because it is a rain giving monsoon. Quite many studies have been carried out on all these aspects in the past, but far more is yet to be done because we lack in correct understanding of their details. The Indian summer monsoon is a part of global circulation, which gives abundant amount of rainfall, which is crucial not only for agriculture and drinking purposes, but also for generation of hydroelectric power. The rainfall is not homogenous over the entire country. The seasonal summer monsoon rainfall is maximum over the west coast (200-290 cm) and northeastern parts (153-222 cm) of India, moderate over the central parts (70-120 cm) of India and minimum over northwestern (25-45 cm) parts (Shukla, 1987). If one part receives good amount of rainfall, another may suffer from drought conditions. The rainfall is not uniform with respect to the time also. There are some wet spells and dry spells during the monsoon season. Proper management of the abundant amounts of the rainfall occurred during the active monsoon periods or wet spells is very much essential to overcome the problems arising during the dry spells. The spatial and temporal variability of the rainfall play an important role on the economy of India.

A strong cross equatorial low level jet stream is one among the monsoon elements. It exits with its core close to 850hPa level over Indian Ocean and south Asia (Joseph and Raman, 1966; Findlater, 1969) and brings the moisture generated by trade winds over the south Indian Ocean and the evaporative flux from Arabian Sea to the areas of rainfall production over south Asia. The cyclonic vorticity north of this jet in the atmospheric boundary layer is a dynamic forcing for the generation of vertical upward air motion and rainfall and for the genesis of depressions in north Bay of Bengal (Joseph and Simon, 2005). During active monsoon period the core of the Jet passes eastward through peninsular India in between 12.5^oN and 17.5^oN. But in the break monsoon this moves southeastward from the central Arabian Sea and by-passing India passes eastward between latitudes 2.5^oN and 7.5^oN (Joseph and Sijikumar, 2004). The presence of a strong jet over peninsular India favors the formation of monsoon depressions in the north Bay of Bengal (Sikka, 1977). Generally the monsoon depressions form over the north Bay of Bengal north of 18^0N during the period June through September and move in west-north-westerly direction along the Ganges valley up to the central parts of the country before weakening generally (Rao, 1976). Rainfall is quite high to the left of their tracks. If they take more northern track over northern India, the Ganges plains receive good rains with corresponding deficiency over central India and northern peninsula. When they follow more southern course over central India, the central parts of India and Gujarat get good rain with the corresponding deficiency over the north. The wind convergence is strong in the southwestern sector of depression area (Subbaramayya, 1961). The absence of these depressions in July and August causes the rainfall deficit upto 40% over different parts of India (Raghavan, 1967; Dhar and Rakhecha, 1976).

*Corresponding author email: kailasam15@yahoo.co.in

Several authors suggested that baroclinic instability is responsible for the generation of the monsoon depressions (Shukla, 1977, 1978; Mishra and Salvekar, 1980; Moorti and Arakawa, 1985; Aravequia *et al*., 1995). They considered the baroclinic instability of the zonal wind with easterly shear associated with tropical easterly jet. They showed that higher (lower) wind shear leads to higher (lower) growth rates with or without the cumulus heating. Thus an increase or decrease of the easterly shear in the earlier / later period leads to monsoon depressions with higher/lower growth rates. Disturbances with weak growth rates may not sustain the frictional dissipation and may not develop. This may explain the decrease in the number of monsoon cyclonic systems when the shears are weak and increase when the shears are strong (Srinivas Rao *et al*., 2004).

According to the results of Bhalme and Mooley (1980) India experienced frequent large-scale droughts in summer monsoon during 1891-1920 and 1961-1975 and only a few in the intervening period. They found the following conditions for large-scale droughts: (1) Weak meridional pressure gradients, (2) Larger northward seasonal shifts of the monsoon trough, (3) Larger number of days in the breaks of the monsoon, (4) Smaller frequency of depressions and shorter westward extent of depression tracks, and (5) Abnormally low 200-hpa surface in May in the latitude belt 15^0-30^0N along 70^0E. Opposite features were reported in large-scale floods. Awade *et al*. (1985) reported larger northward transport of momentum in the upper troposphere across 30^0N in good monsoon years than in poor monsoon years in both pre-monsoon and monsoon months. In good monsoon years there is large divergence in the momentum transport in sub-tropics, while there is large convergence in middle latitudes. In poor monsoon year, there is large divergence of sensible heat in sub-tropics and large convergence in the middle latitudes in mid troposphere.

After approaching the Indian coastline as a southwesterly current the monsoon air is deflected to northeastern region of India and northern parts of Burma. Subsequently, it flows along the plains of northern India and southern periphery of the Himalayas as an easterly current. The flow of air is around a quasi-permanent zone of low pressure over the plains of northern India. This is referred to as the monsoon trough. Its axis is oriented in northwest-southeast direction and runs parallel to the southern edge of Himalayas representing a line of symmetry between westerly or southwesterly winds to the south and easterly or southeasterly winds to its north. It passes through Delhi, Allahabad and Kolkatta. Active phases of monsoon occur when its axis is to the south of its normal position and its eastern end dips into Bay of Bengal. In such a situation there is heavy rain over plains of northern India, the central parts of India, and along the west coast. An extension of the axis into the Bay of Bengal is often the precursor of a Bay depression. Once a depression is formed, it is followed by an increase in rainfall intensity over those parts of central India that lie to south of the axis (Das, 1987).

The monsoon current picks up copious moisture by evaporation from the Arabian Sea and the Indian Ocean. This moisture is essential not only for the monsoonal rainfall but also important as a driving force for monsoon as the latent heat release in the monsoon trough strengthens the monsoon circulation. More moisture transport leads to active monsoon conditions which are indicated by dense multilayered and convective clouds over central parts of the country, over the eastern Arabian Sea and Bay of Bengal and strong low level (westerly/southwesterly) flow over the Arabian Sea often with a low level jet of strength, 25-30 m/s below 850 mb level (Keshavamurthy and Sankara Rao, 1992).

The summer monsoon climate exhibits variability in a variety of time scales, intraseasonal variability, interannual variability, intradecadal variability etc. Various components of the Asian summer monsoon also exhibit significant interdecadal variability (Joseph, 1976; Parthasarathy and Mooley, 1978; Bhalme and Mooley, 1980; Mooley and Parthasarathy, 1984; Kripalani *et al.*, 1997; Mehta and Lau, 1997; Chang *et al.*, 2001, 2000; Parthasarathy *et al.*, 1991; Wu and Wang, 2002). Folland *et al*. (1986) have found low frequency variability of global sea surface temperature (SST) on this time scale. The gradient in SST between northern and southern hemispheres also seems to vary on this time scale.

The Indian monsoon is known to have gone through alternating epochs of above normal and below normal conditions, each lasting about three decades (Krishna Murthy and Goswami, 2000). The interdecadal variability is evident in various monsoon parameters such as all India monsoon rainfall (Partharasathy *et al*., 1994; Kripalani and Kulkarni, 1997; Kripalani *et al*., 1997; Webster *et al.*, 1998), the frequency of cyclones in Indian monsoon region (Joseph, 1976), homogeneous monsoon rainfall covering the northwestern and central parts of India (Partharasathy *et al.*, 1993) and circulation features such as the April position of the 500 hPa ridge (Kripalani *et al*., 1997).

The behaviour of the interdecadal epochs of the monsoon may have great socioeconomic impact in South Asia region. A strong monsoon is associated with anomalous ascent around 25°N and weak monsoon is associated with anomalous ascent near the equator (Goswami *et al.*, 1999).

Monsoon rainfall fluctuates around mean causing runs of wet and dry years. The drought and wet decades occur in runs rather than scatter randomly. In the same manner the decadal rainfall amounts also fluctuate around mean causing runs of wet monsoon decades and dry monsoon decades. These fluctuations were persistent.

In view of the importance of rainfall the authors examined the decadal variability of all-India summer monsoon rainfall in terms of circulation patterns over India and neighbourhood and cyclonic activity over the Bay of Bengal, which are connected well with the rainfall activity.

MATERIALS AND METHODS

Data and Methodology

The all-Indian summer monsoon rainfall (June-September) is the area-weighted average of the rainfall of 29 meteorological sub-divisions (Parthasarathy *et al.*, 1994). They have not included the hilly regions due to sparse rain gauge network. Later this data was updated by Indian Institute of Tropical Meteorology and kept in their web site (www.tropmet.res.in). This data set during 1871 to 2000 is considered. Another data set used in this paper, including air temperatures, zonal wind and meridional wind at two standard levels, 850 hPa and 150 hPa and latent heat flux covering a 50-year (1951-2000) period, for the domain 30^{o}E-120^{o}E and 30^{o}S-40^{o}N are taken from the National Centers for Environment Prediction-National Center for Atmospheric Research (NCEP/NCAR) re-analysis datasets (Kalnay *et al.*, 1996).

The frequencies of the cyclonic systems generated over the Bay of Bengal during June through September for the period 1881-2000 are obtained from the published report of the India Meteorological Department (1979) and from the weather reports published in Mausam journals, India Meteorological Department.

The average seasonal monsoon rainfall amounts in different decades starting from 1871 to 2000 are evaluated. From these values the extreme events are obtained. If any value exceeds or equal to mean+one standard deviation, the corresponding decade is considered as extreme positive decade. If any value precedes or equal to mean-one standard deviation, the corresponding decade is considered as extreme negative decade. One positive and another negative extreme decades are considered. For these two extreme decades, the mean monsoonal thermal patterns, circulation patterns, zonal and meridional wind anomalies in the lower (850 hPa) and upper (150 hPa) troposphere are studied. The frequency of cyclonic systems generated in the Bay of Bengal is also studied.

RESULTS AND DISCUSSION

Figure 1 clearly indicates that the decadal variation of summer monsoon rainfall during the period 1871-2000. Rainfall fluctuates around the mean value of 85.1cm. However, decadal mean values are showing changing dry/wet monsoons. In the beginning the values showed a positive trend from 1871-1880 to 1881-1890. After that there was a sharp decrease up to 1900-1910. Then the rainfall increased gradually with time and reached peak value in the decade 1940-1950. After that there was a decreasing tendency up to 1980-1990. Monsoon was very active during 1871-1900 and 1930-1960 and poor during 1900-1920 and 1980-1990. During the period of study 1871-2000, India experienced very heavy rainfall amounts during 1880-1890 and 1940-1950 and very less amounts during 1900-1920. From this it was observed that wet/dry monsoon conditions were prevailed for three consecutive decades. In the recent decades 1980-1990 experienced less amount of rainfall (about mean-1 standard deviation). NCEP/NCAR data is available only from 1950 onwards and so the authors wish to study the thermal as well as circulation features which are responsible for the good monsoon activity during 1951-60 and for the poor monsoon activity (1981-1990) (Fig.1).

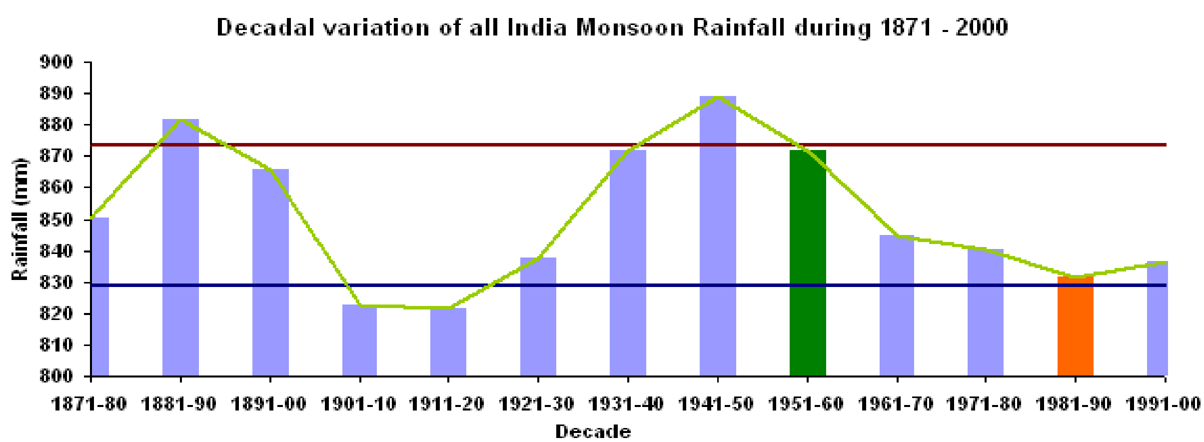

Fig. 1. Decadal variation of All-India Monsoon Rainfall during 1871-2000. Brown line indicates mean+SD, blue line indicates mean-SD green, orange bars indicate good and poor monsoon decades respectively.

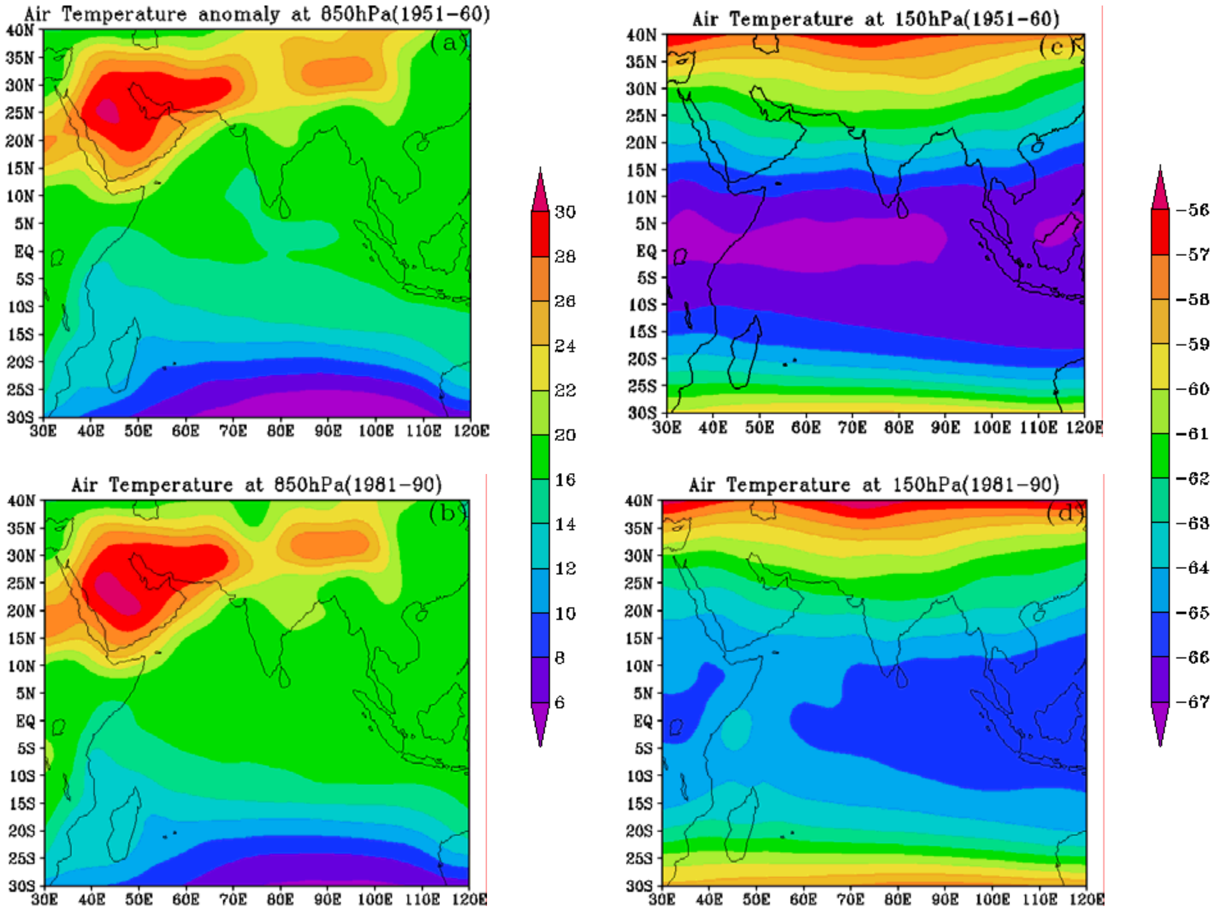

Fig. 2. Monsoon seasonal (JJAS) thermal patterns of the atmosphere at 850 hPa and 150 hPa for good (a, c) /poor (b, d) monsoon decades (Temperatures in ^{o}C).

Thermal patterns

850hPa: The thermal features in good and poor monsoon decades resemble some important differences. Over the Bay of Bengal, Arabian Sea and India the north-south temperature gradient is more during good monsoon decade (1951-1960) when compared to the poor monsoon decade (Fig. 2a and b).

150hPa: Thermal distribution at 150 -hPa over India and neighboring areas for 1951-1960 and 1981-90 are depicted in figures 2c and d. There are few differences between these two patterns over southern India; the upper troposphere is relatively cool during good monsoon (1951-1960) when compared to poor monsoon (1981-1990) decade. Temperatures over southern India during good monsoon decade are relatively less by 1° to 1.5°C. The feature is clearer over tropical Indian Ocean with a temperature difference of 2°C-2.5°C.

Circulation patterns

850hPa: The authors wish to note differences between the circulation features associated with active and poor monsoon decades. In active monsoon decades the cross equatorial flow and the low level jet across the western coast of India exhibited maximum intensity (Fig. 3a and b).

In good monsoon decade the cross-equatorial flow is strongly spreading over a wide area. The intensities are about 10 m/s. The low level jet is also strengthened. The speed is about 16 m/s., which is present in between 50°E to 65°E and 5-12°N over the Arabian Sea, the speed gradually decreases towards north. In the Bay of Bengal, the wind speeds are in between 6-10 m/s. While in the case of poor monsoon decade the cross equatorial flow is weaker, wind speeds are less when compared to the good. The strength of the low level jet is also decreased. 16 m/s contour is concentrated over a small area only when compared to the good monsoon. Over the Bay of Bengal there is no appreciable change in the wind speeds. Over land area there is a difference in the speeds. During good monsoon decade, the wind speeds are ranging from 11 m/s in the south to 2 m/s in the north. During poor monsoon, winds with relatively low intensity exist over southern peninsula (Fig. 3a and b).

150hPa: The circulation patterns in the upper troposphere (150-hPa) infer the differences between the poor monsoon

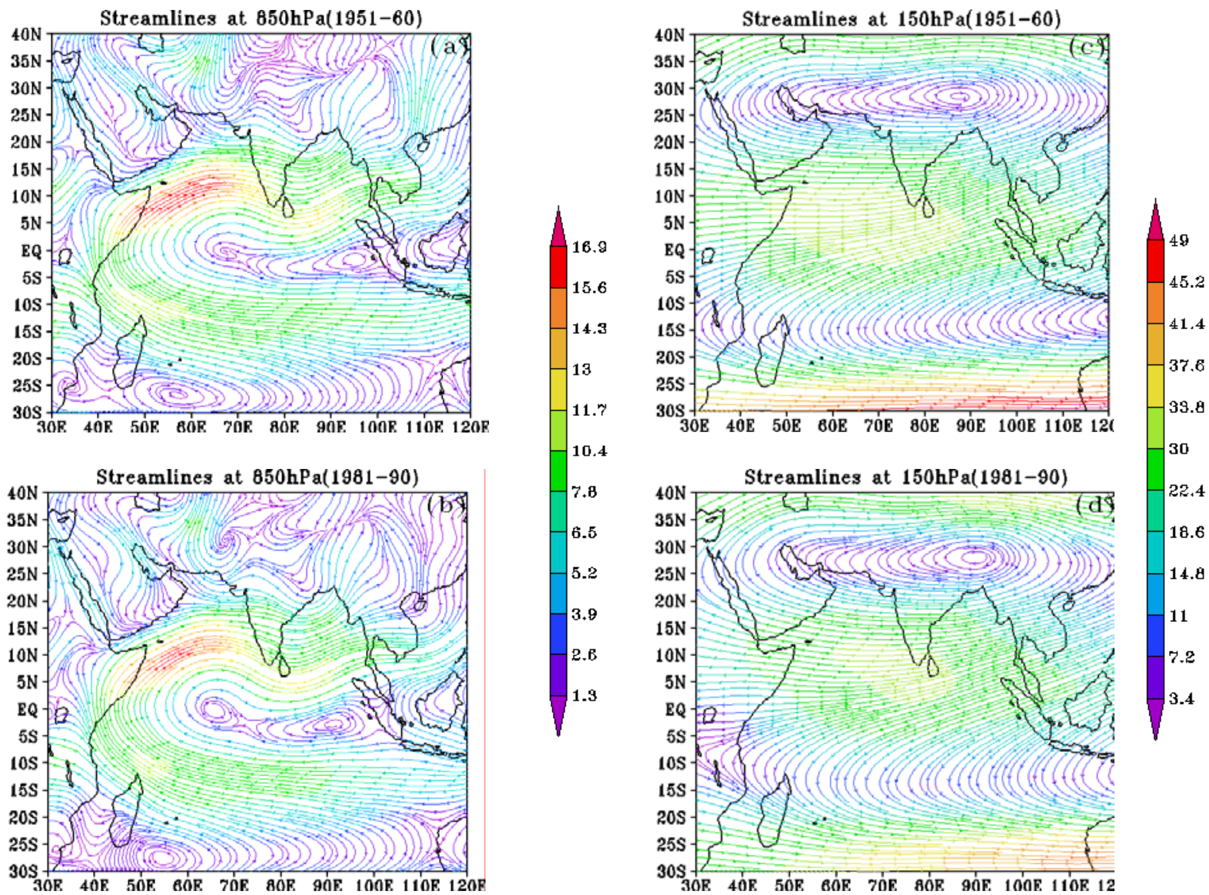

Fig. 3. Monsoon seasonal (JJAS) circulation patterns of the atmosphere at 850 hPa and 150 hPa for good (a, c)/poor (b, d) monsoon decades (wind speed in m/s).

and good monsoon decades. Generally the easterlies are dominant in the upper troposphere. The maximum in the easterlies is concentrated in the southern latitudes. The core of maximum easterlies is known as easterly Jet stream. First time Koteswaram (1958) discovered the existence of easterly Jet. In the good monsoon case the wind speeds over the southern tip and adjoining ocean areas are exceeding 30 m/s covering wider area 40°E-90°E and equator to 10°N. Over the land area (India) the wind speeds are less when compared to oceanic regions, they are varying from 30 m/s over southern tip to 5 m/s at 25°N.

In the poor monsoon the area under 30 m/s contour is very much reduced and limited to the region 55°E to 85°E and equator to 10°N. There is no appreciable changes over India when compared to good monsoon (Fig. 3c and d).

Anomalies: The wind anomalies are obtained by subtracting the long term (50 year) means from the corresponding actual values.

Anomaly U wind* at *850-hPa: The U wind anomaly in good monsoon decade showed positive values over south and central Arabian Sea and the major part of the India, south of 20^0N (Fig. 4a and b). This indicates that a strong westerly belt is perceived during good monsoon decade, which helps to enhance monsoon activity by picking up the moisture from south and central Arabian Sea. Over northern India anomaly easterly belt is seen. Generally over the north India the deflected monsoon (southeasterly belt) persists. The presence of easterly anomalies indicates that the deflected monsoon also has greater strength during good monsoon years. In the poor monsoon situation the reverse is true. The presence of easterly belt in the most parts of the Arabian Sea (except a small region over the north) and south of 25^oN indicates the existence of weak westerlies over these regions. This indicates that the moisture transport from the Arabian Sea will be diminished due to the presence of weak westerlies. At the same time over the north India, north of 25^oN the anomalies are positive, which indicates that the deflected monsoon is also weak. From the above anomalies and their patterns we may come to conclusion that the strength of (1) the westerlies over the Arabian Sea and the India south of 20^oN and (2) deflected monsoon over northern India will be a key factor for deciding the monsoon behaviour. If the strength of these two branches is reduced, it will result in poor moisture transport causing

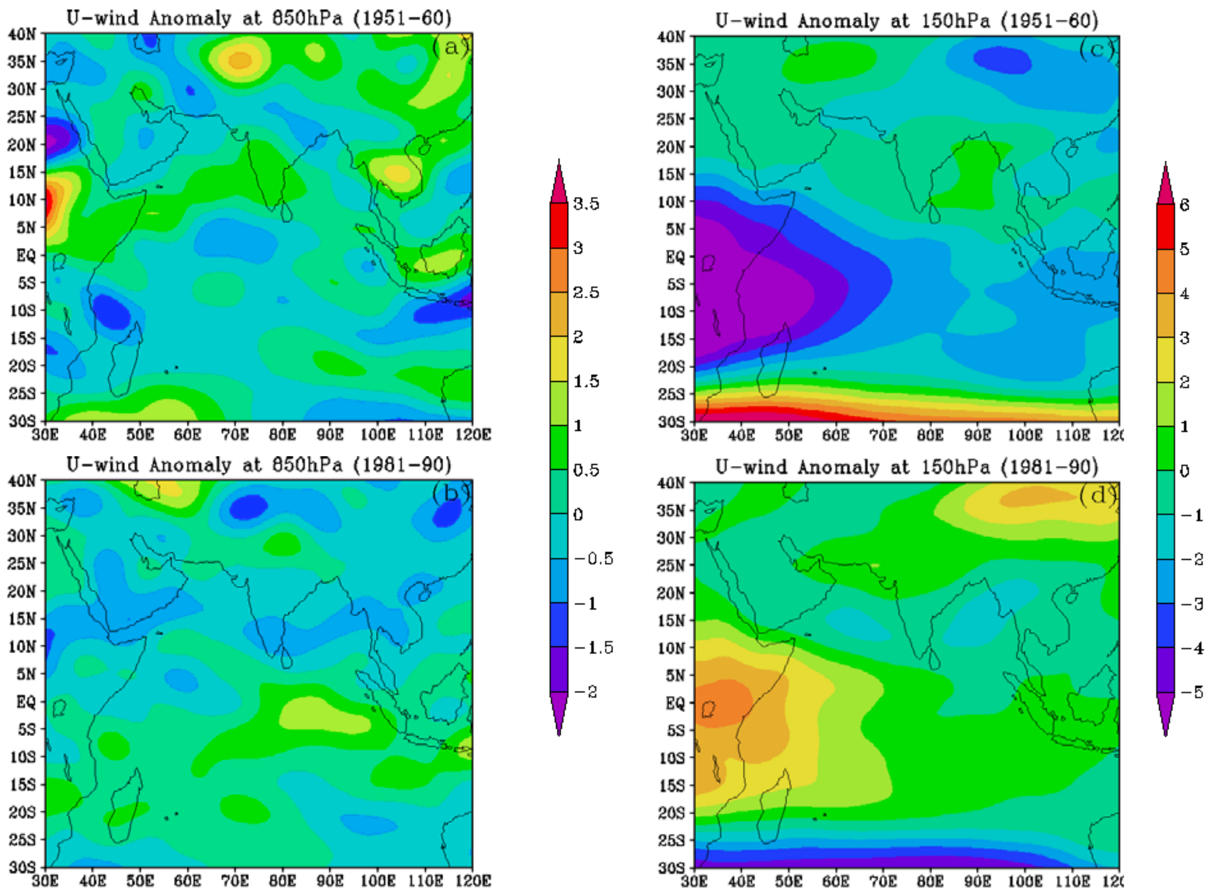

Fig. 4. Monsoon seasonal (JJAS) zonal wind anomaly of the atmosphere at 850 hPa and 150 hPa for good (a, c) /poor (b, d) monsoon decades (anomalies are in m/s).

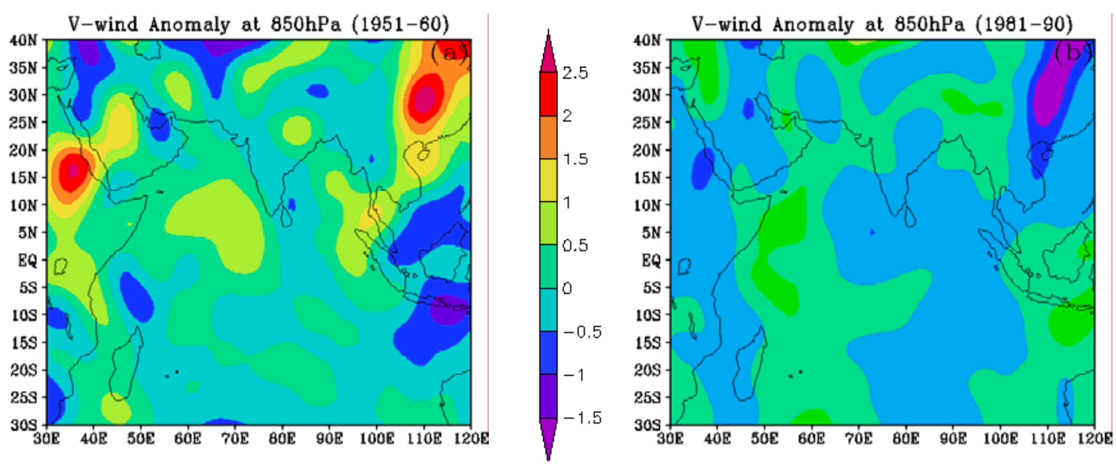

Fig. 5. Monsoon seasonal (JJAS) meridional wind anomaly of the atmosphere at 850 hPa for good (a) /poor (b) monsoon decades (anomalies in m/s).

the poor monsoon. If the two branches are intensified one can expect good monsoon situation due to the transport of more moisture (Fig. 4a and b).

Anomaly U wind at 150-hPa: Anomaly picture (Fig. 4c and d) indicates differences clearly between the poor and good monsoon situations. Easterly anomalies are dominant over equatorial Indian Ocean in good monsoon situation. This indicates that the easterly Jet is intensified in good monsoon situation. In the case of poor monsoon, over the equatorial Indian Ocean the anomalies are westerlies, which indicate the weakening of easterly Jet. From these observations one can say that the easterly jet plays an important role in deciding the activity of monsoon over the Indian subcontinent (Fig. 4c and d).

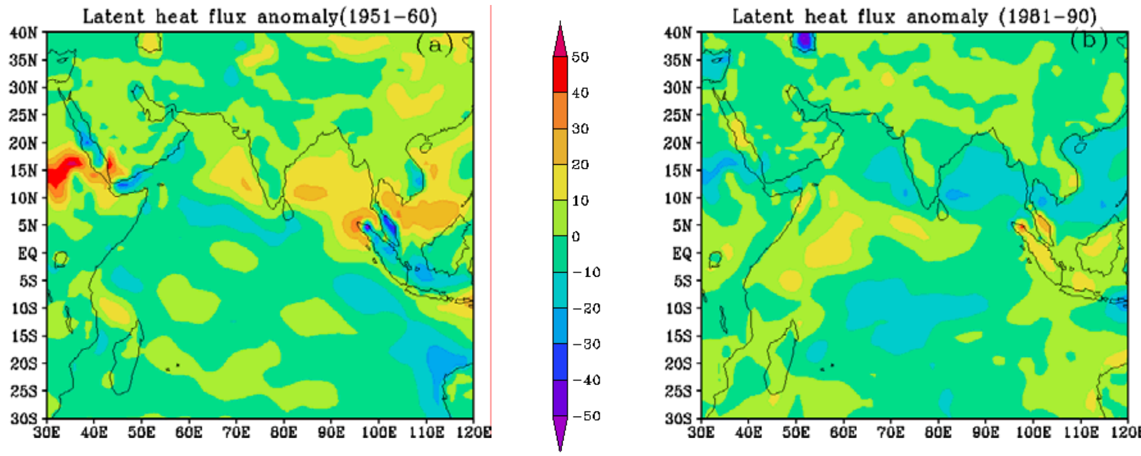

Fig. 6. Monsoon seasonal (JJAS) latent heat flux anomalies in good (a) and poor monsoon (b) decades (values are in w/m^2).

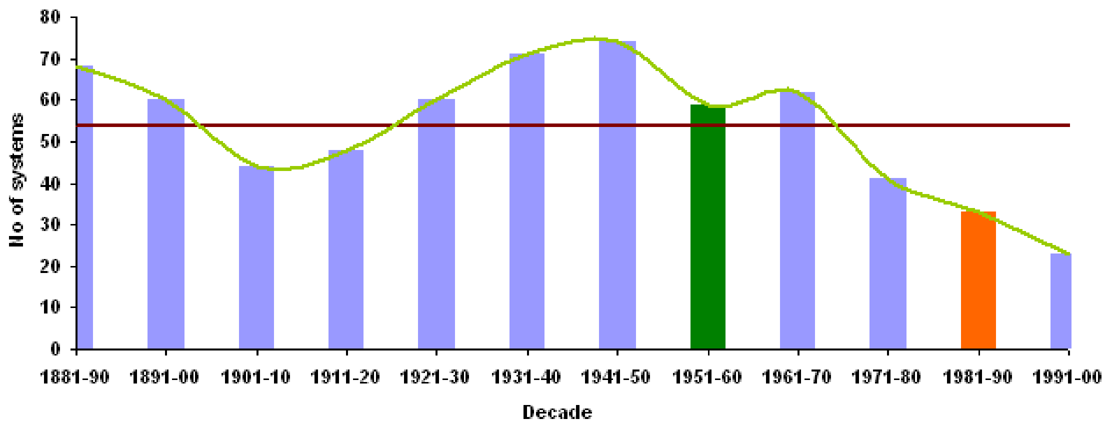

Fig. 7. Decadal variation of cyclonic systems formed in the Bay of Bengal during monsoon season. Brown line indicates mean.

Anomaly V wind at 850- hPa: There are some differences between the anomalies of poor and good monsoons over the Arabian Sea. In good monsoon case, over Arabian Sea and adjoining northern parts of equatorial Indian Ocean, the anomalies are positive. Further the positive anomalies are extended from Sumatra to central parts of North India in SE-NW direction. In the case of poor monsoon, northerly anomaly is present over southeastern Arabian Sea, south and central Bay of Bengal, adjoining Indian mainland (Fig. 5a and b). This pattern indicates the strengthening/weakening of southerlies during good/poor monsoon. Northward transport of moisture from equatorial Indian Ocean is enhanced/reduced during good/poor monsoon.

Anomaly latent heat flux

The anomaly latent heat flux values are calculated by subtracting the long term mean (50 Year) mean values from the corresponding actual values. In good monsoon decade, the latent heat flux anomaly is positive over Eastern Arabian Sea and adjoining parts. The anomaly is high over southeastern Arabian Sea and the values range from 10 to 20 W/m². The anomaly is positive over the entire Bay of Bengal and the values lie in between 10 to 20 W/m² (Fig. 6a).

In poor monsoon decade, the latent heat flux anomaly is negative over southeastern parts of the Arabian Sea and adjoining area. The values lie in between -10 to -20 W/m². Over the Bay of Bengal also, negative values are present, particularly they are pronounced over south central parts of the Bay of Bengal (Fig. 6b).

Cyclonic systems

The cyclonic activity over the Bay of Bengal is more during good monsoon decade. The number of cyclonic systems (of all categories of systems, depressions, storms, severe storms) formed over Bay of Bengal is 33 during poor monsoon conditions. The number is doubled in the case of good monsoon (Fig. 7). The time series of frequency of cyclonic systems and rainfall indicates that they are positively related (Fig. 1). There is a decreasing trend in the frequency of cyclones in the recent four decades, which is closely connected with the tendency of rainfall.

CONCLUSIONS

In good monsoon decades, the westerly belt in the latitudes to south of monsoon trough and easterly belt in the latitudes north of the trough are quite pronounced at 850-hPa during June through September. This indicates that the trough is strengthened and inflow of air due to these two branches coming from the Arabian Sea and the Bay of Bengal enhances the transport of moisture to the monsoon trough. Ultimately this situation leads to formation of more rainfall over India during monsoon months. In poor monsoon decade opposite features are observed; weak westerlies/easterlies to the south/north of trough reduce the inflow of moisture from the regions of the Arabian Sea /the Bay of Bengal.

In good monsoon decade, the intensity of tropical easterly jet stream is enhanced and elongated in east-west direction occupying more area (covering southern tip of India and tropical equatorial Indian Ocean) during June through September. While in poor monsoon decade, it is observed that the strength of easterly jet stream is reduced and squeezed in east-west direction occupying less area.

In good monsoon decade, the cyclogenetic activity is enhanced over Bay of Bengal, while in the poor monsoon decade, the cyclogenetic activity is reduced. Bhaskar Rao *et al.* (2001) reported that total cyclonic systems indicated decreasing tendency after the 1970's which may be coinciding with the observation of global warming and climate change during last three decades. Bengtsson *et al.* (1996), reported that doubling of CO_2 reduces the number of cyclonic storms. The reduced cyclonic activity in the decade 1980- 90 is agreeing with the above two studies. Srinivasa Rao *et al*. (2004) also reported a decreasing trend in tropical cyclonic systems of the Bay of Bengal during monsoon and a significant negative correlation between the tropical easterly Jet strength and the number of tropical cyclonic systems.

From the results on the latent heat flux it can be concluded that both the Arabian Sea and the Bay of Bengal play an important role for the enhancement of evaporation in good monsoon decade. The enhanced water vapour is imported to Indian main land through both the branches, (a branch of monsoon current from the Arabian Sea and another from the Bay of Bengal). The latent heat is the hidden heat supplied by the water vapour and after copious rains are produced over northeast India, monsoon trough area and central India, the large amounts of latent heat will be released and it will be given to atmosphere. This heat enhances the north-south temperature gradient and hence monsoon meridional circulation and the zonal winds. So the winds get more strengthened in the upper troposphere and it may be responsible for the strengthening of tropical easterly jet stream at upper troposphere during good monsoon decade opposite features are observed for poor monsoon decade.

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