

Conditions leading to monsoon onset over Kerala and the associated Hadley cell

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सार – एशियाई ग्रीष्मकालीन मानसून और भूमंडलीय वायुमंडल एवं महासागर के परिप्रेक्ष्य में केरल में मानसून का आरंभ एक महत्वपूर्ण घटना है। इससे उष्णकटिबंधीय हिंद महासागर तथा पश्चिमी प्रशांत महासागर में भूमध्यरेखा के उत्तर में तीव्र एवं वृहद संवहनी ताप स्रोत के आरंभ होने और तापस्रोत को नमी प्रदान करने वाले तीव्र निम्नस्तरीय जेट प्रवाह, दोनों को केरल में मानसून के आरंभ के समय में लगभग 100 दिनों की अल्पावधि मिलने का संकेत मिलता है। उपग्रह के आँकड़ों का उपयोग करते हुए अब हम इस ताप स्रोत के धीमे विकास का मानीटरन करने में सक्षम हैं जो पहले भूमध्यरेखा के निकट बड़े समुद्र सतह तापमान प्रवणता (दक्षिण उत्तर दिशा में) से बनती है और फिर धीरे धीरे दक्षिणी पूर्वी अरब सागर में वार्म पूल की ओर बढ़ जाती है। मानसून हैडले सेल, इस वृहद संवहनी ताप स्रोत से संबद्ध है, जो दक्षिणी पूर्वी अरब सागर में केरल में मानसून के आरंभ के समय विशेष रूप से तीव्र होता है।

मानसून हैडले सेल की आरोही ब्रांच इस ताप स्रोत पर तथा अवरोही ब्रांच उपउष्णकटिबंधीय दक्षिणी हिंद महासागर पर स्थित है। मानसून हैडले सेल की V850 निम्न स्तरीय ब्रांच 850 हैक्टापास्कल पर तीव्र रेखांशिक दक्षिणाभिमुखी प्रवाह है जो भूमध्यरेखा से देशांतर 35° पू. और 55° पू. के मध्य से पार करती है। ऊपरी स्तर की V200 पर ब्रांच 200 हैक्टापास्कल रेखांशिक उत्तराभिमुखी प्रवाह है जो दक्षिणी हिंद महासागर के 45° पू. और 75° पूर्वी देशांतर के मध्य होती है। मानसून हैडले सेल की (V850–V200) पर ली गई तीव्रता केरल में मानसून के आरंभ से 10 दिन पहले की अवधि के दौरान बढ़ी हुई पाई गई है।

ABSTRACT. Monsoon onset over Kerala (MOK) is an important event in relation to the Asian Summer Monsoon and the global atmosphere and Ocean. It marks the beginning of an intense and large convective heat source north of the equator over the tropical Indian and west Pacific oceans and an intense low level jet stream that feeds moisture to the heat source, both having a life span of about 100 days from MOK. Using satellite data we are now able to monitor the slow evolution of this heat source which first forms near the equator over an area with large SST gradient (in the south-north direction) and slowly moves towards the warm pool over the southeast Arabian Sea.

A Monsoon Hadley cell (MHC) is associated with this large convective heat source which is particularly strong over the south-east Arabian Sea at MOK. The ascending branch of the MHC is over this heat source and its descending branch is over the subtropical south Indian ocean. The low level branch of the MHC called V850 is a strong meridional southerly flow at 850 hPa crossing the equator between the longitudes 35° E and 55° E. The upper level branch V200 is a meridional northerly flow at 200 hPa over the south Indian ocean between longitudes 45° E and 75° E. The intensity of the MHC taken as (V850 -V200) is found to increase rapidly during the 10 day period prior to MOK.

Key words – Monsoon onset, Monsoon Hadley cell, Convective heat source, Low level jet stream, Warm pool, Sea surface temperature, Remote sensing.

1. Introduction

The long term mean date of Monsoon Onset over Kerala (MOK) varies between 30 May and 2 June according to different estimates (Ananthakrishnan and Soman, 1988). The standard deviation of the date of MOK is about 8 days. Joseph *et al.* (1994) has given a critical review of the literature on monsoon onset over Kerala.

The date of MOK has been determined operationally by the India Meteorological Department every year for last more than 100 years. These are subjective estimates based primarily on the nature of the daily rainfall reported by observatory stations of Kerala. At the time of monsoon onset, rainfall is found to be widespread spatially and persistent from one day to the next. Accompanying such rainfall, lower tropospheric westerly wind (the monsoon

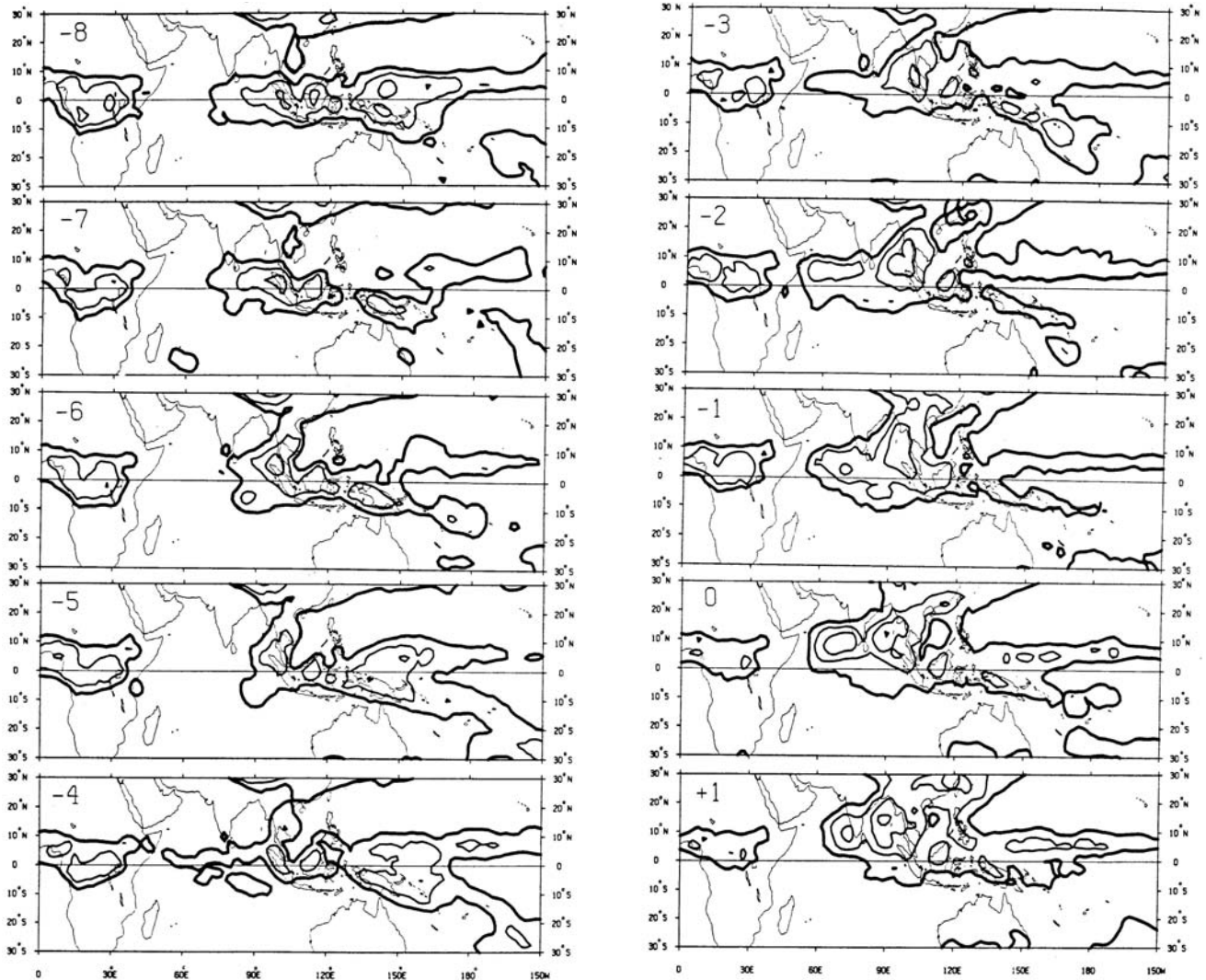


Fig. 1. Pentad mean OLR in Wm^{-2} for pentads -8 to $+1$ as a composite of 10 years 1975, 1976, 1977, 1980, 1981, 1982, 1984, 1985, 1986 and 1987 whose MOK is between 28 May and 4 June (Mean 31 May). Only contours of 240 Wm^{-2} and less at intervals of 20 Wm^{-2} shown. MOK is at the middle of 0-Pentad

current) is strong and deep and the relative humidity of the air is high from the surface to at least 500 hPa (Rao, 1976). In this study we have used dates of MOK as determined by IMD whose extremes are 11 May in 1918 and 18 June in 1972.

Joseph *et al.* (1994) studied the temporal and spatial evolution of the tropical deep convection associated with MOK using composite pentad (5 days) mean maps of Outgoing Long wave Radiation (OLR) using data of 10 years. This is given in Fig. 1 taken from Joseph *et al.* (1994). At MOK, in an east-west elongated box area around Kerala, OLR is very low, showing the formation of an east west Maximum Cloud Zone (MCZ) as studied by Sikka and Gadgil (1980). Joseph *et al.* (1994) found that at pentad -8 (8 pentads or 40 days before MOK) there is

organized deep convection in a band around the equator east of about 70°E and extending into the west Pacific Ocean. By pentad -7 the convection in the western Pacific has decreased considerably and in the Indian Ocean it has organized into a super-cloud-cluster and moved slightly northwards. At pentad -6 it is possible that a pair of cyclones has formed, one on either side of the equator in the Indian Ocean. By pentad -5 the Indian Ocean is practically free of convection, but the convective activity has increased over the equatorial west Pacific Ocean. At pentad -4 an elongated narrow band of convection formed close to the equator in the Indian Ocean. This band grew rapidly in area and intensity and moved north steadily, particularly over the Arabian Sea resulting in MOK at pentad 0. The rapid break-up of convection over the western Pacific at pentad -2 and -1 is a characteristic

feature of MOK. At MOK the intense convective zone extended from the southeast Arabian Sea to south China. It may be noted that cumulonimbus convection is associated with OLR 240 Wm^{-2} and lower OLR signifying more convection. Thus preceding MOK, active convection develops over the south east Arabian Sea and adjoining equatorial Indian Ocean over a period of 2-3 weeks culminating in the monsoon onset over Kerala. Studying the monsoon onset over south Asia of the 4-years 1979-82, Pearce and Mohanty (1984) found that the period prior to monsoon onset consists of two main phases: (a) a moisture buildup phase over the Arabian Sea during which synoptic and meso scale transient disturbances develop and (b) a rapid intensification of the Arabian Sea winds and a substantial increase in latent heat release, essentially a large scale feed back process. Phase (b) follows phase (a). Thus in their study also monsoon onset requires a long period of preparation by the atmosphere of the order of 2 to 3 weeks.

Joseph *et al.* (2000, 2002) made an attempt to define MOK uniquely. At MOK an east-west cloud band of intense cumulonimbus convection passes through Kerala and the monsoon westerly current – the Low Level Jetstream (LLJ) of Joseph and Raman (1966) and Findlater (1969) – over Kerala is strong and deep. They found that the LLJ at MOK crosses the equator close to the east African coast (near longitude 40° E). About 6-8 pentads earlier a similar cloud band passes through Kerala with associated strong and deep lower tropospheric westerly winds and widespread rainfall. This has been called the Pre Monsoon Rain Peak (PMRP) by Joseph and Pillai (1988). At PMRP the LLJ crosses the equator between longitudes 60° E and 70° E . Associated with MOK there is a large area of deep convection over the south-east Arabian Sea which is absent at PMRP. Instead there is a large area of convection over the south Bay of Bengal at PMRP. There are other differences as well. The area of intense convection over the south Bay of Bengal at PMRP moves to north Bay of Bengal and then to the western Pacific Ocean. In contrast the convective cloud band at MOK moves north to the Himalayas and takes the monsoon rains to the whole of India. Particularly in the years of delayed MOK, PMRP occurs in early May giving widespread and heavy rainfall over Kerala. Joseph *et al.* (2000, 2002) has described in detail how to distinguish between PMRP and MOK.

A large region of the tropical oceans with SST greater than 28° C (called warm pool) lies in the tropical regions of the western Pacific and Indian Ocean. Beginning in March the tropical Indian Ocean north of the equator warms very rapidly in the annual cycle and by May a large area there attains SST greater than 29° C . This area is called the Indian Ocean warm pool. The

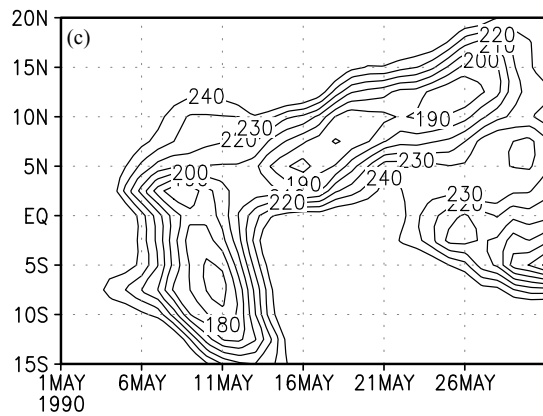
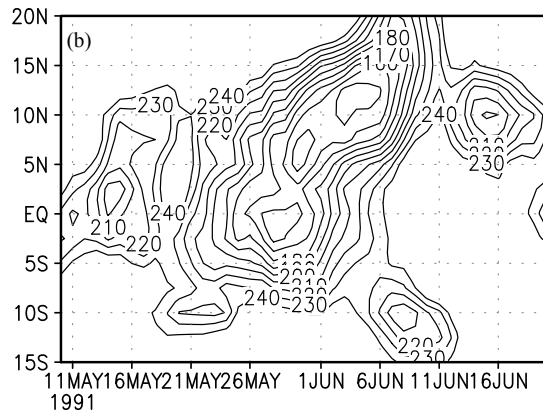
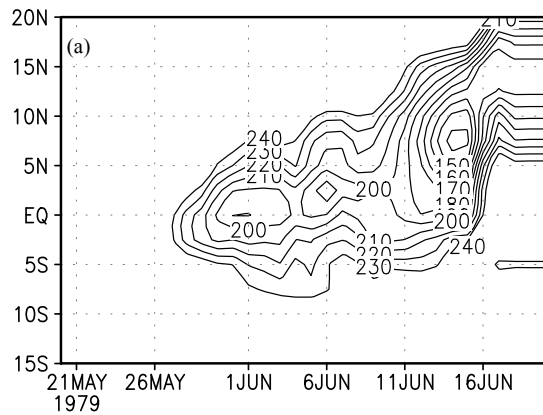
Indian Ocean warm pool shows seasonality both in spatial extent and intensity with peak values in excess of 30° C occurring in the south eastern Arabian Sea in May – the Arabian Sea Warm Pool [Seetharamayya and Master (1984), Joseph(1990a,b), Vinayachandran and Shetye (1990), Shenoy *et al.* (1999), and Rao and Shiva Kumar (1999)]. The Arabian Sea warm pool appears to play an important role in the onset process of the summer monsoon. The Arabian Sea warm pool collapses dramatically with the onset of summer monsoon (Rao, 1990).

In this paper we have studied the development of deep convection over the Arabian Sea warm pool and the consequent strengthening of the lower tropospheric monsoon current leading to monsoon onset over Kerala. Recent literature has shown a non-linear relation between SST and deep convection over the tropical oceans. In the range of SST $27\text{-}29^\circ \text{ C}$, convection increases approximately linearly with SST. Convection reaches a maximum around 29.5° C . Further increase in SST produces decrease in convection. Regions of SST greater than 30° C are generally associated with clear sky conditions [Gadgil *et al.* (1984), Graham and Barnett (1987), Zang (1993), Lau *et al.* (1997)]. A study by Lindzen and Nigam (1987) is important in this context. They have shown that in the low latitude regions of the Pacific Ocean, SST gradient is more important than SST in relation to excitation of deep convection.

In section 2 the data used in this paper has been discussed. Section 3 describes the development of deep convection and the strengthening of the monsoon current over south east Arabian Sea and adjoining equatorial Indian Ocean and its association with sea surface temperature, prior to the monsoon onset over Kerala during a year of delayed MOK (1979, date of MOK is 13 June), a year of normal MOK (1991, date of MOK is 1 June), and a year of early MOK (1990, date of MOK is 19 May). Section 4 describes the monsoon Hadley circulation associated with the development of deep convection prior to monsoon onset. Composites showing the slow increase in the strength of the Hadley cell in cases of delayed, normal and early monsoon onsets are discussed in section 5. Conclusions of the study are summarized in section 6. This section suggests possibility of using the slow intensification of convection and the monsoon Hadley cell for the medium range prediction of monsoon onset.

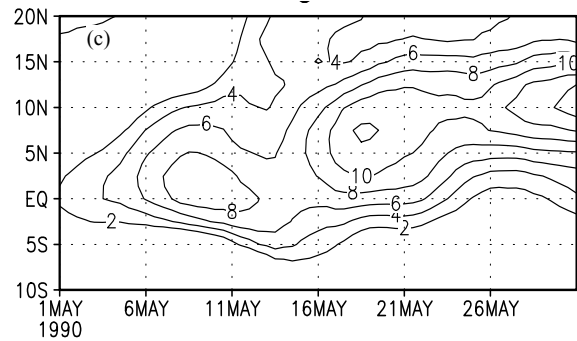
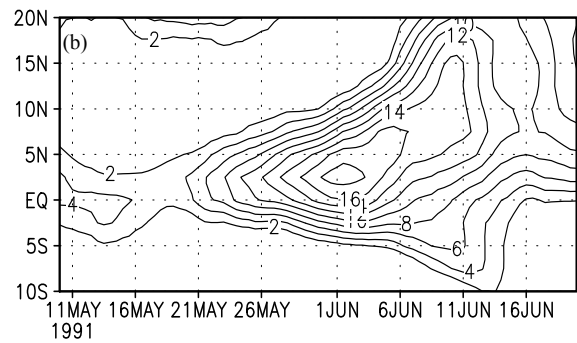
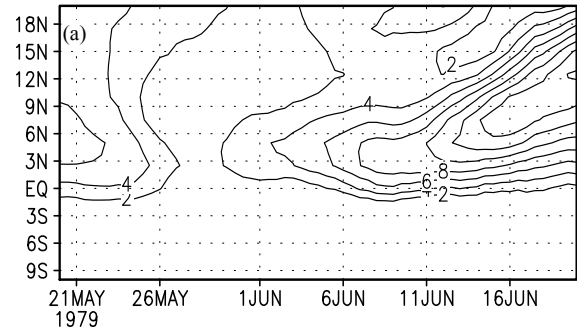
2. Data used

The basic data set used in this study are all obtained from the NCEP/NCAR reanalysis data CDs (Kalnay *et al.*, 1996). Specifically the data used are (i) 850 hPa and



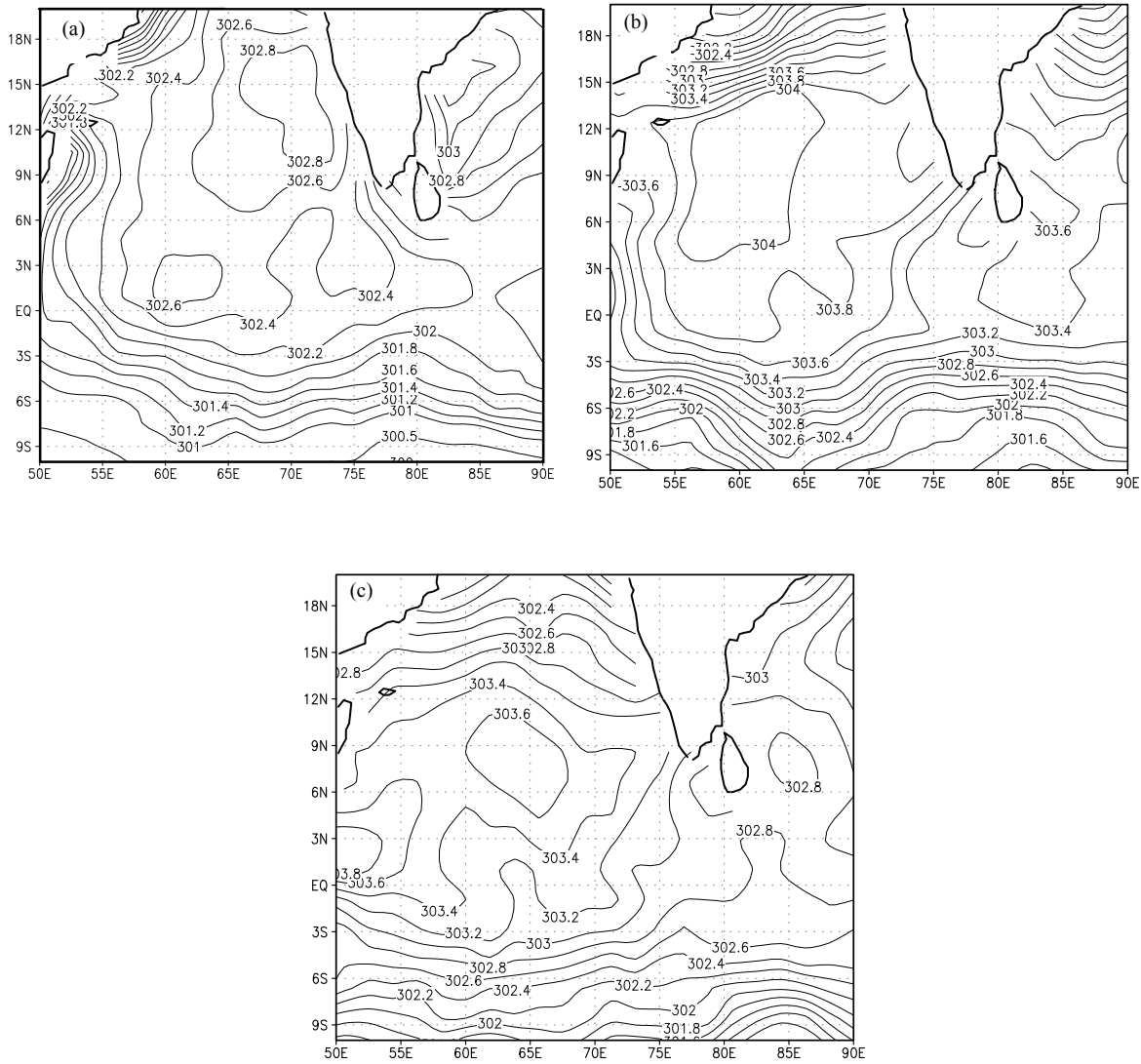
Figs.2(a-c). Hovmuller diagram of mean OLR between longitudes 65° E and 75° E, in Wm^{-2} for (a) a case of delayed MOK (1979) (b) a case of normal MOK (1991) and (c) a case of early MOK (1990). Isolines of OLR are at intervals of $10 Wm^{-2}$

200 hPa wind data (U and V components in ms^{-1}) on a 2.5° latitude-longitude grid, twice daily. These data have a rating A, which means that they are strongly influenced



Figs. 3(a-c). Hovmuller diagram of the mean zonal wind between longitudes 65°E and 85°E, in ms^{-1} for (a) a case of delayed MOK (1979) (b) a case of normal MOK (1991) and (c) a case of early MOK (1990). Isolines of zonal wind are at intervals of $2 ms^{-1}$

by the observed data and the influence of the model used to derive the grid point value is minimal, (ii) Outgoing long wave radiation is obtained from the AVHRR aboard the NOAA Polar Orbiting Spacecraft (Gruber and Kruger, 1984). These data are in Wm^{-2} and each value represents the areal average OLR flux for a $2.5^\circ \times 2.5^\circ$ box. (iii) Sea Surface Temperature (SST) data set is on a nearly $1.9^\circ \times 1.9^\circ$ latitude-longitude grid taken from the NCEP SST analysis. The analysis is produced both daily and weekly, using 7 days of *in-situ* data (ship and buoy) and bias-corrected satellite SST data.



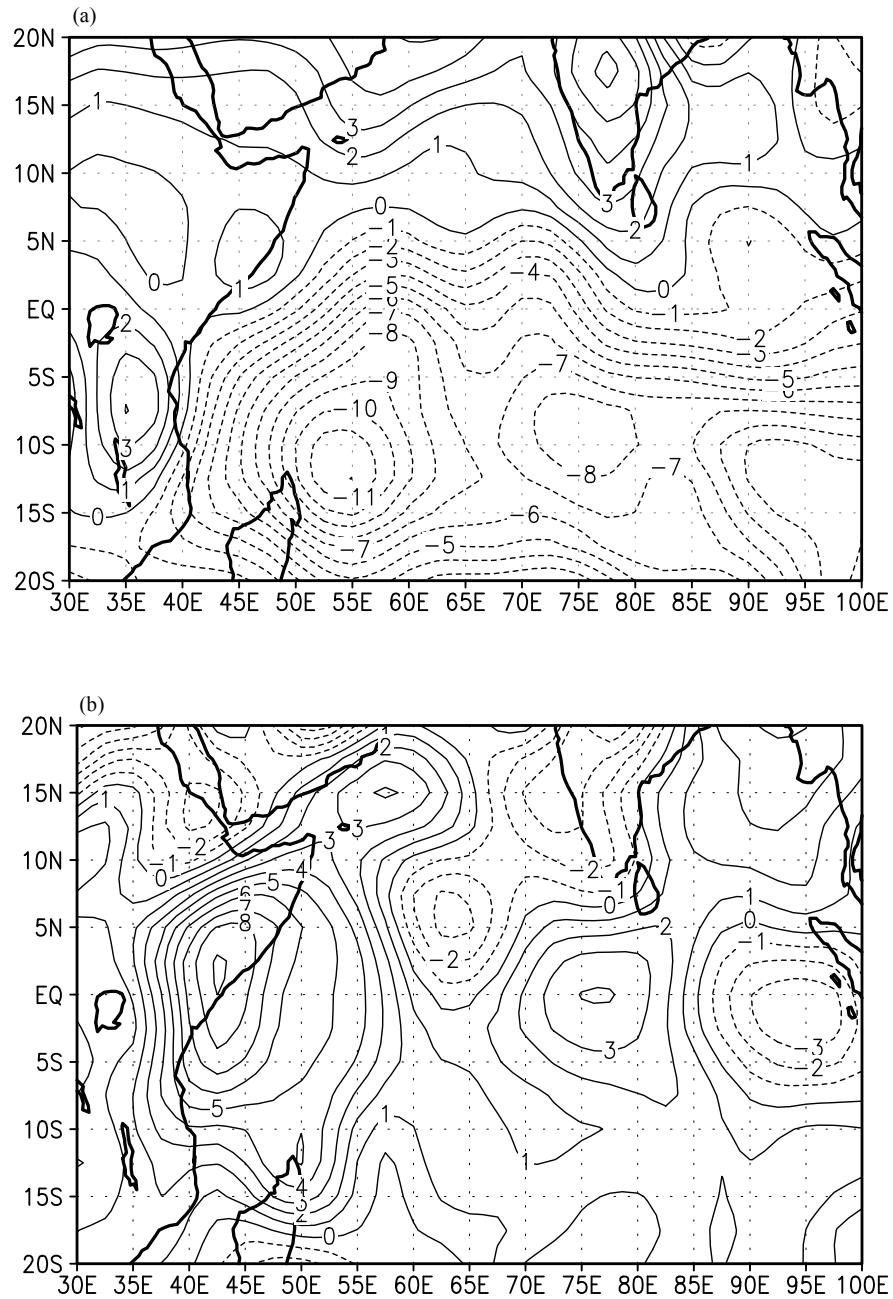
Figs. 4(a-c). Pentad mean SST about 2 weeks prior to MOK in °K, for (a) 29 May – 2 June, 1979 (b) 17 – 21 May, 1991 and (c) 4 – 8 May, 1990. Isotherms of SST are at 0.2° K intervals

3. Deep convection associated with monsoon onset of Kerala

Fig. 2(a) gives the Hovmuller diagram of the mean OLR between longitudes 65° E and 75° E for 1979, a year of delayed MOK (13 June). The variation of mean OLR from 20 May to 20 June is shown. Convection begins near the equator with OLR of 200 Wm⁻², by the end of May. As time advances the convection intensifies and the area of maximum convection moves north to latitudes 5°N-10° N. At the time of MOK, OLR reaches very low value of less than 150 Wm⁻². Fig. 4(a) gives the mean isotherms of SST during the pentad, 29 May – 2 June, 1979, Fig 4(b) gives the same for 17 – 21 May 1991 & Fig 4 (c)

gives the same for 4 – 8 May, 1990. All these are about 2 weeks prior to MOK. It is seen from the figure that the convection near the equator, which began by the end of May, developed over an area where SST had large north-south gradient. The mechanism suggested by Lindzen and Nigam (1987) is presumably at work. At this time the maximum SST (center of the warm pool) was around the latitude 12° N considerably to the north of the area of convection. Even during the 8-12 June 1979, convection was over an area south of the axis of the warm pool.

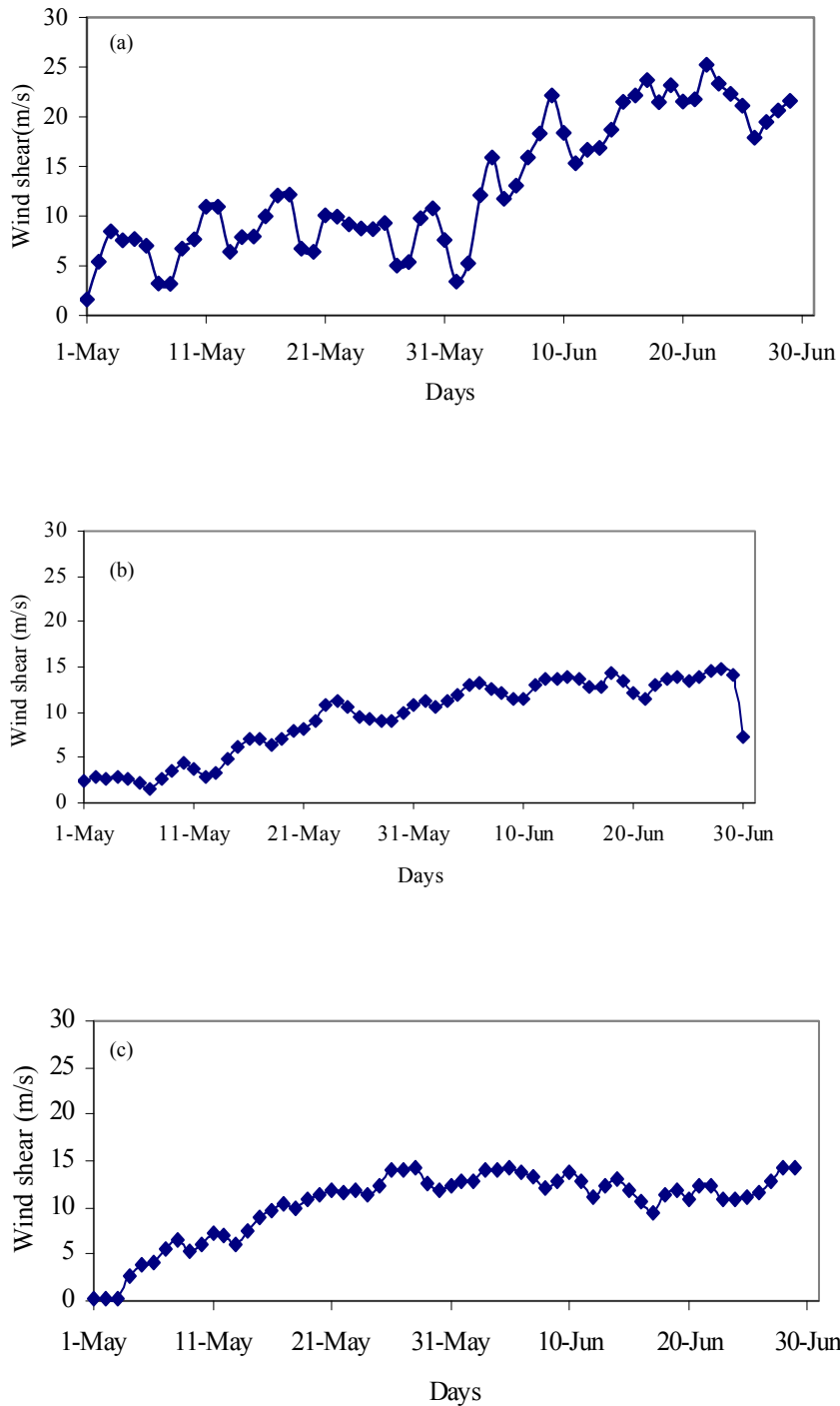
Fig. 3(a) gives a Hovmuller diagram of the 850 hPa zonal wind (U) between longitudes 65° E and 85° E for the period 20 May-20 June 1979. The zonal wind lags



Figs. 5(a&b). Isotachs of mean meridional wind in ms^{-1} during the pentad just prior to MOK (8-12 June, 1979) for (a) 200 hPa & (b) 850 hPa. Isotachs of meridional wind are at 1ms^{-1} intervals, positive is for southerlies and negative for northerlies

behind the OLR by several days. The wind is considered to be in response to the convective heat source shown by the OLR [Fig. 2(a)]. In a study by Sijikumar and Joseph (2002), it has been shown that the monsoon low level jet stream responds to the convective heat source with a lag of about 3 days, convection leading. After the convective heat source forms, the monsoon current gets accelerated,

which explains the observed lag. The zonal wind at 850 hPa is also strong near the equator first and the axis of maximum wind slowly moves north. Both the deep convection and strong 850 hPa zonal wind first began near the equator about 10 days before the onset of monsoon over Kerala and reached high values and higher latitudes of 5°N - 10°N , at the times of MOK.



Figs. 6(a-c). Gives the progress with time of the daily strength of the Hadley cell (V850-V200) in ms^{-1} for composites of (a) Delayed (b) Normal and (c) Early monsoon onsets. The years of Delayed, normal and early onsets are given in Table 1. V850 and V200 are defined in the text

1991 is a year of normal monsoon onset (MOK, 1 June). Fig. 2(b) and Fig. 3(b) give respectively the Hovmuller diagrams of OLR and 850 hPa zonal wind, for

the period 10 May-10 June. In this case also convection has started 10 days earlier than the date of MOK, but slightly south of the equator and advanced northwards.

TABLE 1

Mean date of Monsoon onset

Year (Delayed onset)	MOK date (IMD)	Year (Normal onset)	MOK date (IMD)	Year (Early onset)	MOK date (IMD)
1972	18 Jun	1963	31 May	1960	14 May
1979	13 Jun	1975	31 May	1961	18 May
1983	13 Jun	1976	31 May	1962	17 May
		1980	1 Jun	1969	17 May
		1981	31 May	1990	19 May
		1982	1 Jun		
		1984	31 May		
		1987	2 Jun		
		1989	3 Jun		
		1991	2 Jun		
		1996	3 Jun		
		1998	2 Jun		
Mean date of monsoon onset	15 Jun	Mean date of monsoon onset	1 Jun	Mean date of monsoon onset	17 May

Here also the wind lagged behind the convection. SST analysis shows that the initial onset of deep convection was over areas with large north-south SST gradient, as in 1979.

Fig. 2(c) gives the Hovmuller diagram of OLR for the year 1990, whose date of MOK is 19 May. The figure gives the OLR from 1-31 May. In this case the initial outbreak of convection is between the equator and 10° S, further south than in the other two cases. This could be due to the earlier calendar date of the onset. In the annual cycle, the equatorial cloudiness maximum (ITCZ) moves north from the southern hemisphere to the northern hemisphere across the equator during April-June. Fig. 3(c) shows the Hovmuller diagram of 850 hPa zonal wind.

4. Development of monsoon onset Hadley cell

The increased convection in the southeast Arabian Sea and to its east gives rise to a local Hadley circulation with upward motion over the area of convection and downward motion in the south Indian ocean, with a return current through the low level jet stream. Fig 5(b) gives the isotachs of 850 hPa meridional wind averaged over the period 5 days to 1 day prior to MOK of 1979. As a measure of the lower branch of the Hadley cell we have taken the average meridional wind in ms^{-1} over the box 35° E- 55° E and 10° S- 10° N. This is called V850. Fig. 5(a) gives the isotachs of the meridional wind of the

same period but at 200 hPa. The upper limb of the Hadley cell (V200) is taken as the average meridional wind over the box 45° E- 75° E and 20° S to Equator. (V850-V200) is taken as the index of the strength of the Monsoon Hadley Cell (MHC).

5. Composite monsoon Hadley cell during delayed, normal and early monsoon onsets

Figs. 6(a-c) gives the progress with time of the strength of the MHC for composites of delayed, normal and early onsets. The data regarding the date of monsoon onsets and their mean are given in Table 1. It is seen that in all the 3 cases, the MHC begins to strengthen about 10 days before the monsoon onset over Kerala and reaches high intensities at the time of onset. This feature it is hoped, should give us a method for medium range prediction of MOK. Since the MHC, as defined above has a climatological increase in strength in the annual cycle, for use in medium range prediction we have to calculate the anomalous MHC. This aspect will be taken care of in further studies.

6. Summary and conclusions

Monsoon onset over Kerala is preceded by the development of a large area of active deep convection over southeast Arabian Sea and further east to the west Pacific Ocean and the strengthening of the cross equatorial low level jet stream. Strong cross-equatorial

flow from south to the north in the lower troposphere and north to south in the upper troposphere leading to a strong monsoon Hadley cell is a characteristic feature of the monsoon onset. It is noted that the initial formation of deep convection is near the equator over an area of large north-south SST gradient and the convection intensifies and moves north towards the axis of the warm pool. Satellite data enables us to monitor the progress of these changes as all the parameters involved, OLR, SST and winds can be obtained from satellites. It is hoped that monitoring these changes particularly the intensity of the monsoon Hadley cell will enable us to predict monsoon onset on the medium time range (about 10 days ahead).

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