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An investigation into the conditions leading to monsoon onset over Kerala

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With 11 Figures

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Summary

Monsoon onset over the Kerala (MOK) coast has been studied using the recently released high resolution **H**amburg **O**cean **A**tmosphere **P**arameters and Fluxes from **S**atellite data (HOAPS 3). Columnar water vapour content, sea surface temperature and evaporation have been utilised to examine the conditions leading to MOK from −7 pentads. The role of monsoon hadley cell (MHC) has also been assessed using the NCEP/NCAR Reanalysis dataset. In addition the role of the cross-equatorial flow and low level jet at 850 hPa has also been explored, as has the importance of the Madden Julian Oscillation in initiating the MOK, the latter using outgoing longwave radiation data. An analysis of sea surface temperature over the Arabian Sea (AS) and Bay of Bengal for contrasting MOKs, showed that the AS warm pool plays a crucial role in MOK. Contrary to the popular notion that moisture builds up only 2–3 weeks in advance of MOK, our study has shown that the integrated columnar water peaks around 35–40 days (almost around the same time as that of the pre-monsoon rainfall peak) prior to MOK and can be a potential predictor of MOK. The 850 hPa winds strengthen over the extreme southern peninsula and Sri Lanka about 3 pentads prior to MOK, and the evaporation rates over the southern Arabian Sea show a dramatic increase with onset of MOK. The MHC can be a useful predictor for extreme monsoon onsets (early or delayed).

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1. Introduction

The mean date of monsoon onset for Kerala is around 1 June, according to meteorological records, and it coincides almost exactly with the middle of the Malayalam month of *Edavam*, which is the tenth month of the Kollam era of the Kerala regional calender (Ananthakrishnan and Soman 1991). Traditionally the southwest monsoon is known in Kerala as *Edavapadi*, which literally means the middle of the month Edavam. This shows that the near regularity of the onset of the southwest monsoon around 1 June was known to the people of Kerala from ancient times.

Kerala State, situated in the southwest part of the Indian sub-continent (Fig. 1), is the gateway for the Indian summer monsoon. The monsoon generates about 80% of the mean annual rainfall, and plays a crucial role in the Indian economy as agriculture, power generation and drinking water are dependent up on it. There are three important aspects which make each monsoon unique: namely, a) the monsoon onset date over Kerala (MOK), b) the amount of monsoon rainfall during the season, and c) the frequency and intensity of active, weak or break phases in monsoon conditions within the season.

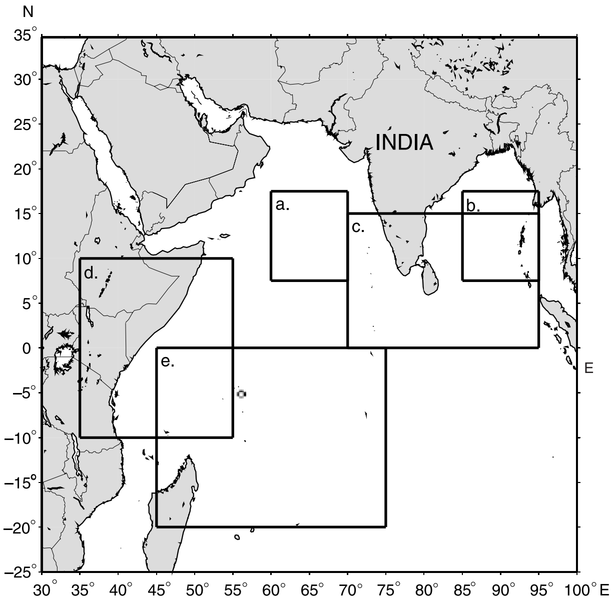

Fig. 1. Study areas used for averaging various parameters. See text for more details. a) Arabian Sea, b) Bay of Bengal, c) Peninsular box, d) lower branch of monsoon Hadley cell (V850), e) upper branch of monsoon Hadley cell (V200)

The MOK and its systematic northward progression are important as an early or delayed MOK can have a profound influence on agricultural production over the entire Indian sub-continent. The objectives of the present study are:

1. To study the air–sea interaction processes over the Indian Ocean leading to MOK using the recently released high resolution Hamburg Ocean Atmosphere Parameters and fluxes from Satellite data (HOAPS) 3 dataset (Andersson et al. 2007).
2. To analyze the role of the cross-equatorial flow and low level jet leading to MOK.
3. To identify the influence of the Monsoon Hadley Cell and Madden Julian Oscillation on the MOK.

There have been several studies relating to the synoptic features present during the onset phase of the summer monsoon over India. Ananthakrishnan et al. (1967) summarised many of these studies in a Forecasting Manual of the India Meteorological Department (IMD). In order to arrive at a uniform set of onset dates, Ananthakrishnan and Soman (1988) analysed daily rainfall over a dense network of rain gauge stations in Kerala, and determined the onset dates for north and south Kerala separately. The MOK, as defined by Ananthakrishnan and Soman (1988), is the first day of transition from light to heavy rain with a condition that the average daily rainfall during the first 5 days after the transition should not be less than 10 mm.

Krishnamurti et al. (1981) showed that kinetic energy over the southeast Arabian Sea increases by an order of magnitude just prior to the MOK. Based on 1979–1982 data, Pearce and Mohanty (1984) suggested that monsoon onset over South Asia was associated with a gradual moisture build up over the Arabian Sea (AS) followed by a rapid intensification of the AS winds. The whole process of monsoon onset thus requires about 2–3 weeks pre-conditioning by the atmosphere over the AS.

Soman and Krishnakumar (1993) studied the climatological structure of the atmosphere during the onset phase of the summer monsoon using a vanety of meteorological parameters from Indian stations such as rainfall, wind, relative humidity and vertically integrated moisture transport (VIMT) and outgoing longwave radiation. Their study showed that relative humidity builds up suddenly in the vertical a few days prior to MOK. Vertically integrated moisture transport at individual stations increases sharply with respect to the south Kerala onset. Convective activity was also found to increase rapidly over the southeast Arabian Sea and east Bay of Bengal with the approach of MOK.

Joseph et al. (1994) - critically reviewed the literature on monsoon onset over Kerala. They studied the temporal and spatial evolution of tropical deep convection associated with MOK using composite pentad (5 days) mean maps of outgoing longwave radiation (OLR) over a 10 year period in each year the date of MOK was very close to 1 June. They found that at pentad −8 (i.e., 8 pentads or 40 days before MOK) organised deep convection was present in a band around the equator east of about 70° E, extending into the west Pacific Ocean. By pentad −7 the convection in the western Pacific decreased considerably and in the Indian Ocean it organised into a super cloud cluster and moved slightly northwards. 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 AS resulting in MOK at pentad 0. The rapid break in convection over the western Pacific at pentad −2 and −1 is a characteristic feature of MOK. At MOK the intense convective zone extends from the southeast Arabian Sea to the south China Sea. Thus, prior to MOK, active convection develops over the southeast Arabian Sea over a period of 2–3 weeks.

Simon and Joshi (1994) examined moisture changes prior to the MOK using the NOAA/TOVS satellite data parameters such as mid- and upper tropospheric water vapour and scale height of water vapour. Their study, using the pentad averaged values in the western Arabian Sea, showed an increase in scale height of water vapour and mid-tropospheric moisture (700–500 hPa) about 8–10 days prior to MOK.

Fasullo and Webster (2003) suggested that a method based on VIMT would be more effective at identifying the MOK than the subjective estimates of IMD or the rain based method of Ananthakrisnan and Soman (1988). In addition, they suggested that the VIMT method would help to identify the withdrawal dates of the monsoon and to distinguish between an actual and a bogus MOK (Flatau et al. 2001).

Joseph et al. (2003) examined the role of the Monsoon Hadley Cell (MHC) in MOK using NCEP/NCAR Reanalysis data. They used meridional wind speed at 850 hPa averaged over the region 35° E–55° E; 10° S–10° N as a measure of the lower branch of the Hadley Cell, and meridional wind speed at 200 hPa averaged over the region 45° E–75° E; 20° S and equator as a measure of the upper limb of the Hadley Cell. The difference (V850–V200) represents the intensity of the MHC and was found to increase rapidly about 10 days prior to MOK.

Ramesh Kumar (2004), using satellite derived precipitation over the Indian Ocean, found that there is a pre-monsoon rainfall peak (PMRP) about 6 pentads prior to MOK and that this has some predictive value for MOK. Simon et al. (2006) examined the conditions leading to the MOK using satellite data. The study revealed that water vapour build up over the western Arabian Sea by about 2:5 weeks can be a useful parameter for predicting the MOK.

In a recent study, Joseph et al. (2006) investigated summer monsoon onset processes over South Asia and formulated an objective three-step method for MOK identification. The date on which zonal wind speed at 850 hPa, averaged over the box bounded by the latitudes 5° N–10° N and longitudes 70° E–85° E, reached 6 m/s at 600 hPa was taken as MOK. Then, the MOK was checked for bogus onsets using 850 hPa wind speeds and OLR. And finally, they checked whether or not there was widespread convection (low OLR) around Kerala on the MOK date.

2. Data

The new HOAPS-3 dataset (Andersson et al. 2007) contains updated global fields of precipitation and evaporation over the global ocean and all basic state variables needed for the derivation of fluxes. Except for the NODC/RSMAS Pathfinder sea surface temperature (SST) dataset, all variables are derived from SSM/I passive microwave satellite data over the ice free global ocean. HOAPS-3 covers the time span from 07/1987 to 12/2005, resulting in a climatology containing 18 complete years of data. Thorough evaluation of the HOAPS-II climatology resulted in the development of a new precipitation-algorithm, improving the global freshwater balance in HOAPS. Other changes in HOAPS-3 are the integration of the Version 5 NODC/RSMAS Pathfinder SST dataset and a new procedure to synthesise the defective 85 GHz channels on DMSP-F08. Previous improvements in HOAPS-II, such as the utilisation of multi-satellite averages, inter-satellite calibration, and an efficient sea-ice detection procedure are retained, resulting in homogeneous and reliable spatial and temporal fields. In the present study, we have used pentad mean SST and integrated columnar water vapour, evaporation and rain fall rate at a resolution of 0.5° × 0.5° for the period 1988 to 2003. More details of this dataset can be found in Andersson et al. (2007).

We have used NCEP/NCAR Reanalysis data (Kalnay et al. 1996) daily winds at standard pressure levels on a 2.5° × 2.5° grid resolution. Note that the values of the variables derived from the reanalysis have varying degrees of influence from observations and models. The variables u (zonal component of the wind) and v (meridional component of the wind) have a stronger influence from the observations than the model and are classified as A class variables. Other variables such as relative humidity are influenced equally by observations and model calculations and are classified as B class variables. More details of the reanalysis data can be obtained from Kalnay et al. (1996). Zonal and meridional winds at 850 hPa have been used to study the characteristics of the low level jet on the MOK. We have also used meridional winds at 850 hPa and at 200 hPa averaged over two regions (see Fig. 1) to identify the strength of the influence of the Monsoon Hadley Cell (MHC) on the MOK. Increased convection over the southeast Arabian Sea and its surrounding area prior to MOK gives rise to a local Hadley circulation, with an upward motion near the area of convection and a downward motion in the south Indian Ocean. Figure 1 presents the regions used for averaging the upward and downward branches of the Hadley Cell circulations. The figure also depicts three other boxes which have been used to average the SSTs in the Arabian Sea (AS) and Bay of Bengal (BB) and also the peninsular region with the aim of examining the role of integrated columnar water vapour prior to MOK.

The outgoing longwave radiation (OLR) used in the present study is the interpolated OLR data provided by the National Oceanic and Atmospheric Administration – Cooperative Institute for Research in Environmental Sciences (NOAA–CIRES), Climate Diagnostics Center, Boulder, Colorado, from their website http://www.cdc.noaa.gov (Gruber and Krueger 1984).

Table 1 presents the onset dates according to IMD for the study period. We have classified arbitrarily the years as early or delayed in which the dates of monsoon onset are earlier/later than one week (7 days). There were two early (1990 and 2001) and two delayed (1997 and 2003) onsets in our study period (1988–2003). Thus, out of 16 years, in 12 years the onset was normal. The mean onset dates for different composites are also given in Table 1.

Table 1. Monsoon Onset dates over Kerala for different years along with the mean monsoon dates used for different composites, namely, early, normal and delayed using the India Meteorological Department MOK dates

Early		Normal		Delayed	
Year	MOK date (IMD)	Year	MOK date (IMD)	Year	MOK date (IMD)
1990	19 May	1988	26 May	1997	9 June
2001	23 May	1989	3 June	2003	8 June
		1991	2 June		
		1992	5 June		
		1993	28 May		
		1994	28 May		
		1995	5 June		
		1996	3 June		
		1998	2 June		
		1999	25 May		
		2000	1 June		
		2002	29 May		
Mean date	21 May		1 June		9 June

3. Results and discussion

From previous studies, it is quite clear that air–sea interaction processes over the north Indian Ocean play a major role prior to MOK. In this section we will examine some of the parameters using the composite method for different types of MOK (listed in Table 1). The different datasets from which the parameters e.g., sea surface temperature, integrated columnar water vapour, evaporation, cross-equatorial flow and low level jet, are taken are listed in Table 2.

3.1 Sea surface temperature (SST)

A warm pool (SST > 28 °C) exists in the western Pacific and eastern Indian Oceans. The warmest area of this warm pool is centred around 140° E to 180° E, where the SSTs exceed 29 °C in this

Table 2. Different datasets used in the present study

Name of dataset	Variables used	Resolution	Data period
HOAPS	sea surface temperature evaporation integrated columnar water vapour	pentad, 0.5° × 0.5°	1988–2003
NCEP/NCAR reanalysis	zonal and meridional winds at 850 hPa meridional wind at 200 hPa	daily, 2.5° × 2.5°	1988–2003
NOAA–CIRES	OLR	daily, 2.5° × 2.5°	1988–2003

central region. This is called the western Pacific warm pool. Sadler et al. (1987) have shown that the tropical Indian Ocean north of the equator warms rapidly from March onwards. By May, a large area in the north Indian Ocean attains SSTs above 29.5 °C, and this area can be called the

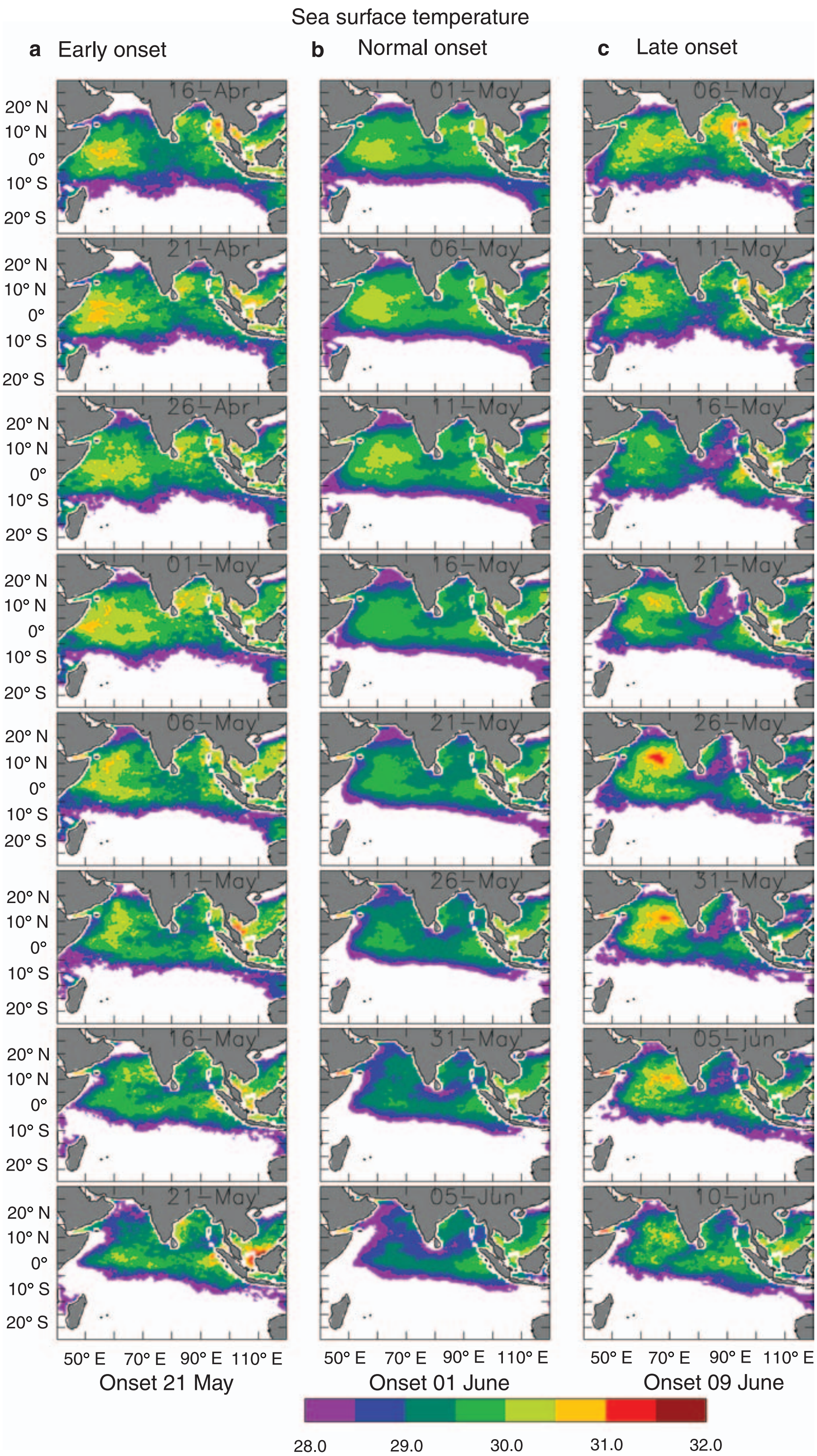

Fig. 2. Pentad mean sea surface temperature (in °C) for pentads (−7, −6, −5, −4, −3, −2, −1 and MOK) for composites (**a**) early, (**b**) normal and (**c**) delayed MOK. Only contours above 28 °C and above are plotted at intervals of 0.5 °C

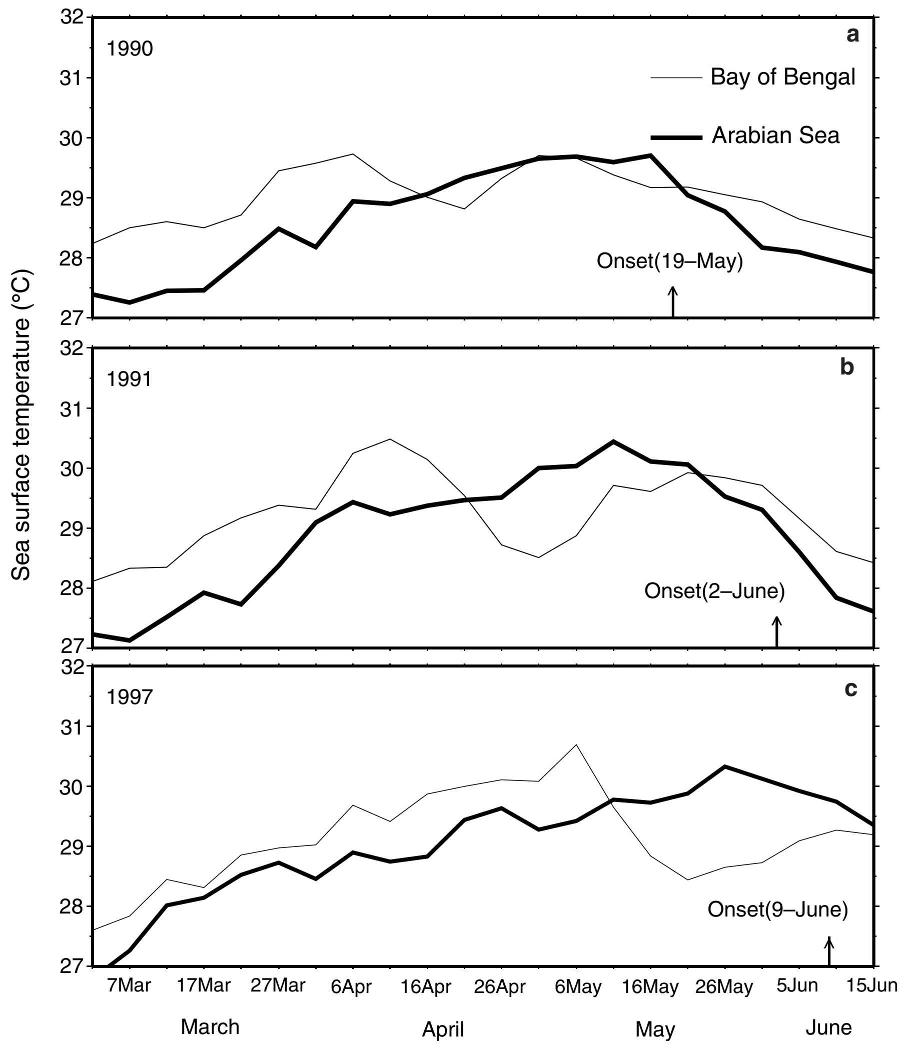

Fig. 3. Pentad mean sea surface temperature (in °C) for AS & BB for three contrasting MOK Years: (**a**) early MOK – 1990, (**b**) normal MOK – 1991 and (**c**) delayed MOK – 1997

Indian Ocean warm pool (Joseph et al. 1994). By April, the warmest area north of the equator is located in the north Indian Ocean, but for the global oceans the warmest area continues to remain south of the equator in the western Pacific Ocean. SSTs continue to rise until the MOK over the north Indian Ocean in May–June, but in the southwest Pacific, SSTs have been decreasing in May–June. Furthermore, the Indian Ocean warm pool attains temperatures higher than 30 °C around the time of MOK (Seetharamayya and Master 1988; Joseph 1990). A region of SSTs as high as those of the Indian Ocean warm pool can create large scale moisture convergence, with deep convective clouds, heating of the tropospheric column above, lowering of the surface pressure and strengthening of lower tropospheric westerly winds associated with the

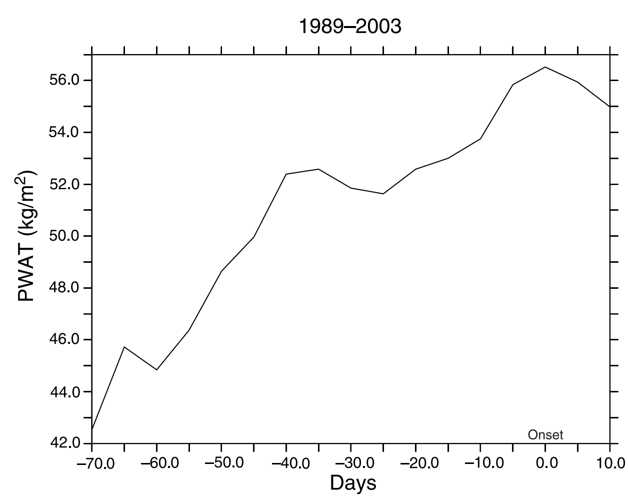

Fig. 4. Composite mean integrated columnar water vapour (in kg/m^2) for the period 1989–2003 for the peninsular box mentioned in Fig. 1, with respect to MOK as 0

MOK (Joseph et al. 1994). Ramesh Kumar and Schluessel (1998) have shown that an early peaking of SSTs in the AS will help in the development of low pressure over this area and thus in creating an intense inter-hemispheric pressure gradient, strong cross-equatorial flow, and condi-

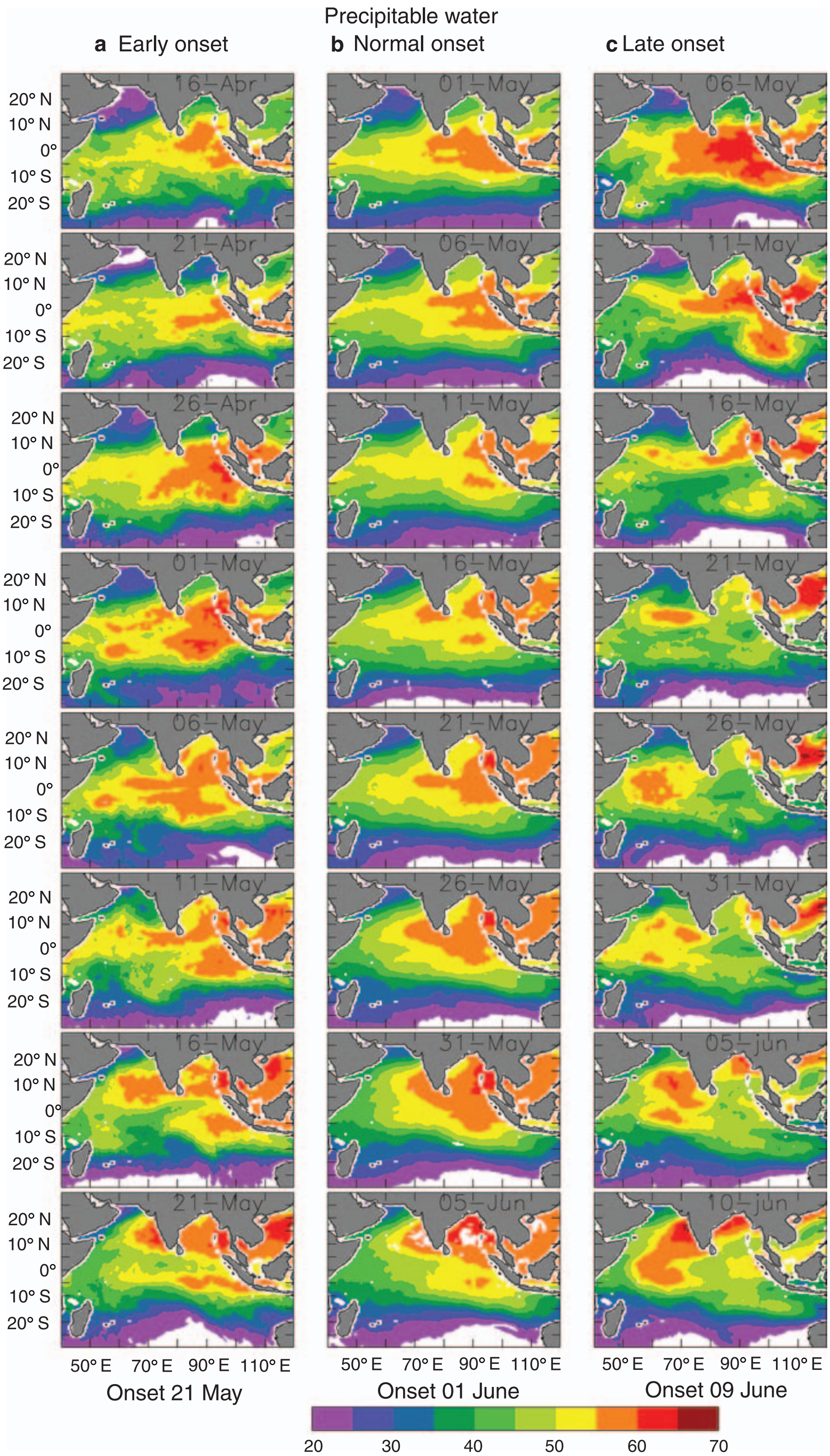

Fig. 5. Pentad mean integrated columnar water vapour (in kg/m^2) for pentads (−7, −6, −5, −4, −3, −2, −1 and MOK) for composites (**a**) early, (**b**) normal and, (**c**) delayed MOK. Only contours above 20 kg/m^2 and above are plotted at intervals of 5 kg/m^2

tions conducive for an early onset over the Indian sub-continent.

The warm pool of AS reaches maximum development about 4 pentads prior to MOK (in early MOK composite) which agrees well with the findings of Ramesh Kumar and Schluessel (1998) (Fig. 2). In the case of a normal MOK, the AS warm pool reaches maximum development in

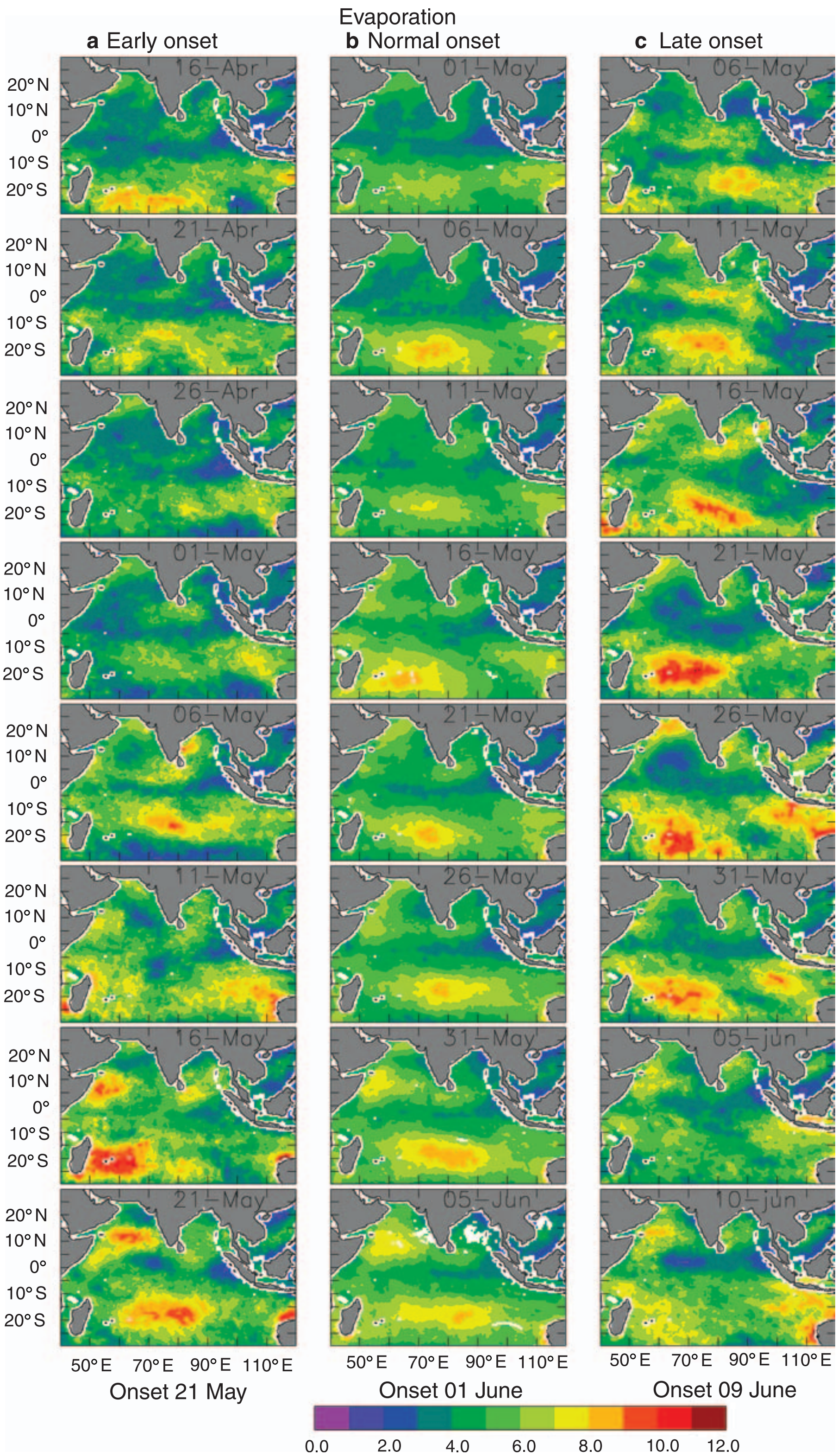

Fig. 6. Pentad mean evaporation (in mm/day) for pentads (−7, −6, −5, −4, −3, −2, −1 and MOK) for composites (**a**) early, (**b**) normal and (**c**) delayed MOK. Contours are plotted at intervals of 1 mm/day

about 3–4 pentads prior to MOK (normal MOK composite) and the warm pool reaches maximum development only two pentads prior to MOK (in the late composite), as can be seen from Fig. 2.

Figure 3 depicts the SST distribution over the AS and BB from 1 March to 15 June for three contrasting MOKs, namely, early, normal and delayed. From the figure it can be seen that, in the case of the early MOK (1990), the AS warm pool peaks about a couple of pentads earlier than for a normal year (1991), and in the case of the delayed MOK, AS warm pool development is also delayed. Our results of early and delayed MOK are in good agreement with those of Joseph et al. (1994) who attribute it to the delayed movement of equatorial convective cloud maximum to the north Indian Ocean.

3.2 Integrated columnar water vapour (IWV)

Integrated columnar water vapour has been found by several authors to be a useful parameter for identifying the MOK (Pearce and Mohanty 1984; Simon et al. 2006). We have used the IWV of the HOAPS-3 dataset to examine the gradual build up of moisture conditions leading to MOK by averaging over the peninsular box shown in Fig. 1 (box c). This figure is drawn using data from about 14 pentads (70 days) prior to MOK and 2 pentads (10 days) after (with MOK date shown as 0 in the figure). The gradual build up of moisture over peninsular India is clearly seen in Fig. 4, after superposing the onset dates of all the years for the study period. From the figure it can be seen that the moisture builds up gradually from about 14 pentads before MOK, and there is a distinct, pre-monsoon precipitable water peak (PMWP) around 40 days prior to MOK, contrary to popular belief that the moisture peaks only 2–3 weeks before the onset (Pearce and Mohanty 1984; Simon et al. 2006).

The spatial distribution of the IWV for composites of early, normal and delayed onsets also depicts (Fig. 5) this PMWP about 7 pentads prior

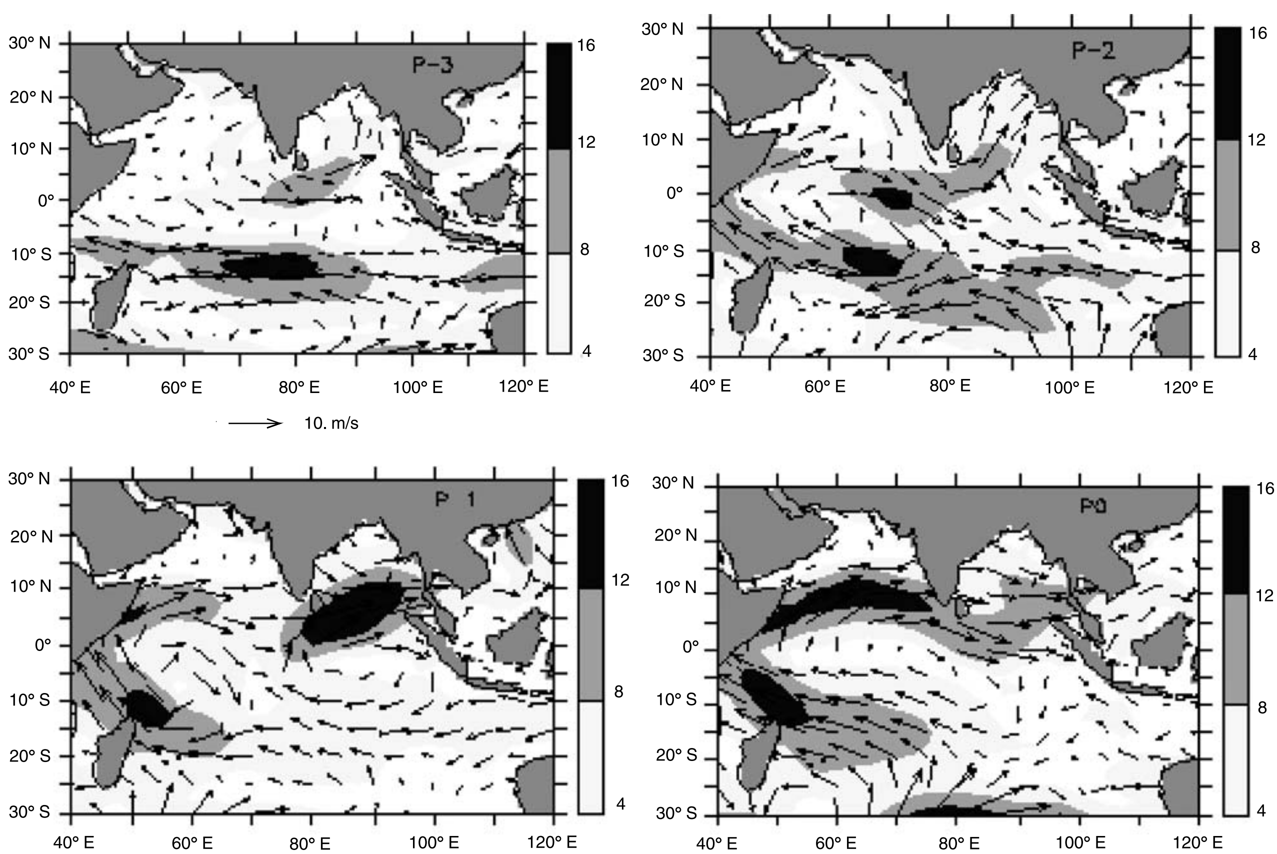

Fig. 7. Pentad mean 850 hPa wind (in m/s) for pentads (−3, −2, −1 and MOK) for early monsoon composite. Only contours of 4 m/s and above at intervals of 4 m/s are shown

to MOK in the AS. This could be the source of moisture needed for PMRP. Then the IWV further increases and reaches about 3–4 pentads prior to MOK, as mentioned by Pearce and Mohanty (1993) and Simon et al. (2006). The PMWP occurring about 7–8 pentads prior to MOK can be a potential predictor of MOK. More study is needed in this direction.

3.3 Evaporation

There have been several studies regarding the source of moisture for southwest monsoon rainfall, with the Arabian Sea and cross-equatorial flow being considered major sources. Now it is widely recognised that the inter-hemispheric cross-equatorial flow plays a major role in monsoon activity over the Indian sub-continent. Evaporation over the Indian Ocean is one of the least studied parameters in the context of MOK. The major reason for this could be that reliable estimates of evaporation are not available over the vast oceanic regions, especially over the Indian Ocean on spatial and temporal scales high enough for the study of the MOK. Furthermore, these estimates are highly scattered, mostly based on ship observations, and are available only on a monthly basis, hence were not suitable. Schluessel (1996) estimated evaporation rates over the ocean using satellite data and Schulz et al. (1997) further validated these estimates at the global scale.

The newly released high resolution HOAPS-3 dataset provides reliable evaporation estimates on a higher spatial ($0.5^\circ \times 0.5^\circ$) and temporal (pentad) resolution (Andersson et al. 2007).

Evaporation rates have been computed using the bulk parameterisation method of Fairall et al. (1996). Figure 6 presents the evaporation rates over the Indian Ocean about 7 pentads prior to MOK for the three different composites. The most interesting aspect is the substantial increase

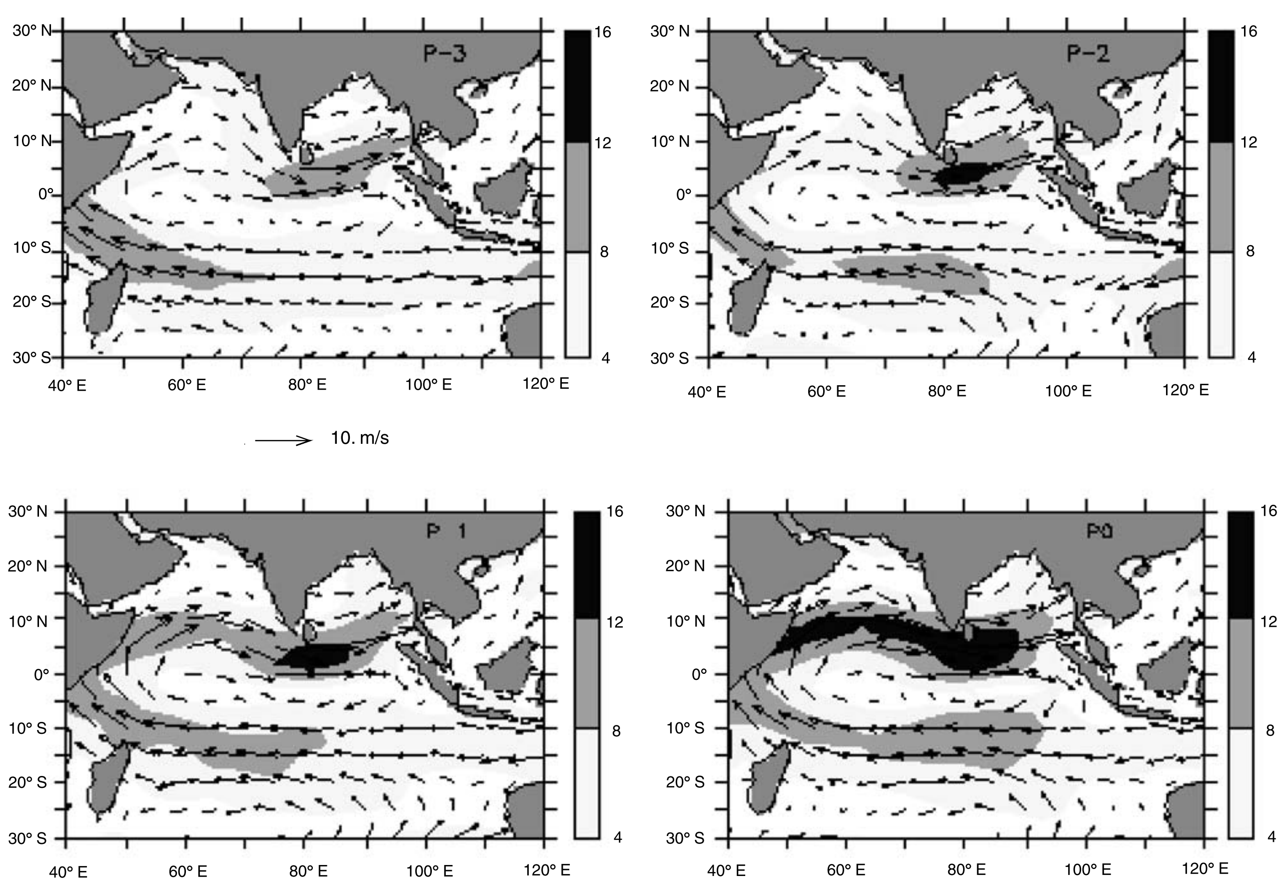

Fig. 8. Pentad mean 850 hPa wind (in m/s) for pentads (−3, −2, −1 and MOK) for normal monsoon composite. Only contours of 4 m/s and above at intervals of 4 m/s are shown

in evaporation rates over the southern AS and south Indian Ocean (SIO) during the MOK pentad during the early MOK composite. This clearly shows that southern AS evaporation has a major influence on the MOK. During the normal MOK composite similar features are observed with lower values of evaporation over the southern AS and SIO. In the case of delayed MOK, evaporation over the AS does not increase as dramatically as in the case of the early MOK composite. Furthermore, there is substantial increase in evaporation in the southeastern Indian Ocean from the previous pentad.

3.4 Low level jet and cross-equatorial flow

We have used 850 hPa winds from NCEP/NCAR Reanalysis to monitor the cross-equatorial flow (CEF) and low level jet (LLJ) as they are found to play a major role in MOK. Furthermore, the westerly mean monsoon current is strongest close to 850 hPa (Joseph and Sijikumar 2004). We have analysed the role of the CEF and LLJ winds about 3 pentads before MOK for the three composites, namely, early, normal and delayed MOK. In the case of an early MOK composite (Fig. 7), it can be seen that CEF developed only about one pentad prior to MOK and LLJ was present only during the MOK. In the normal composite case (Fig. 8), there is a strengthening and deepening of the westerly winds from −3 pentads to MOK (0 pentad) over the extreme south peninsula and Sri Lanka. Furthermore, in the case of a delayed MOK composite (Fig. 9), the LLJ does not extend from the southeastern Arabian Sea to the equatorial Indian Ocean region south of Sri Lanka and is also very weak as compared to the early and normal MOK composites.

3.5 Monsoon hadley cell (MHC)

Convection in the east and southeast Arabian Sea gives rise to a local Hadley circulation

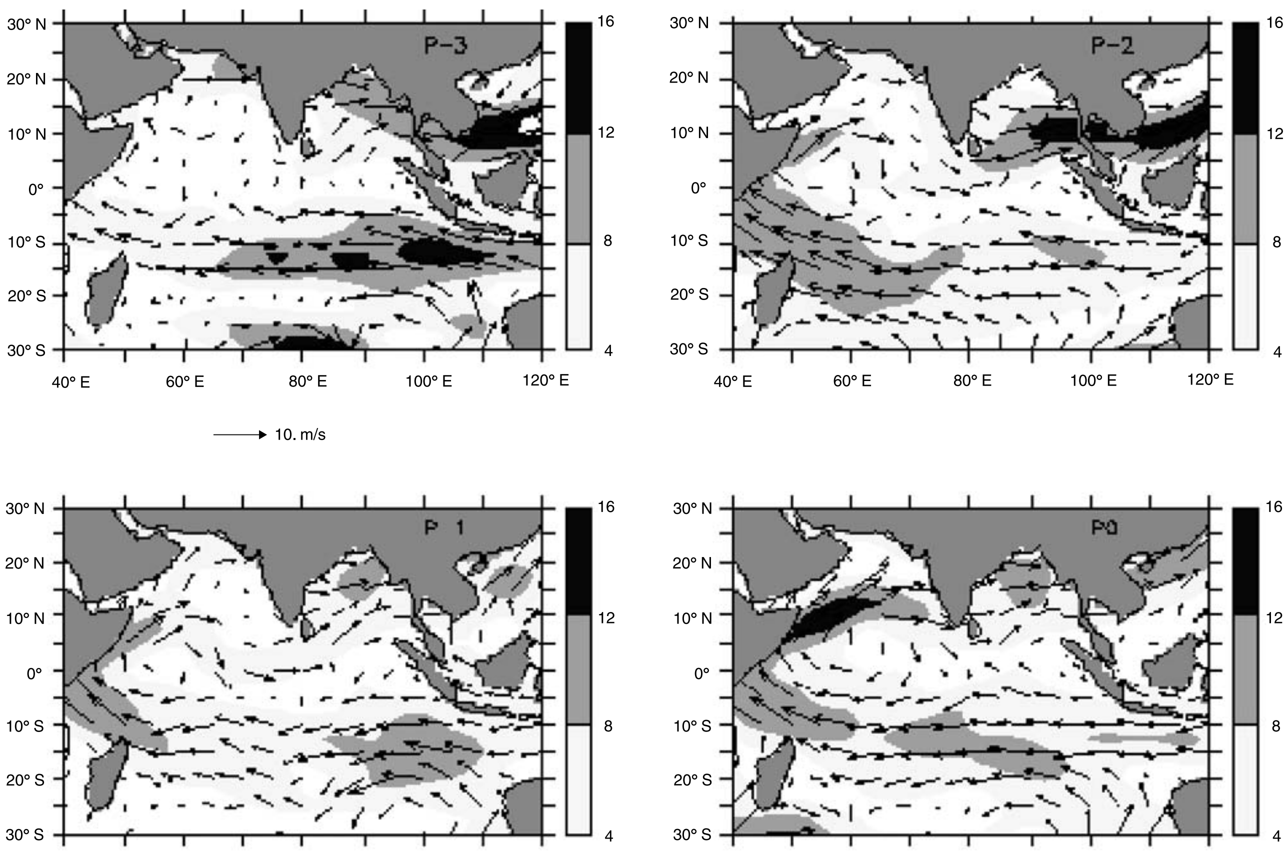

Fig. 9. Pentad mean 850 hPa wind (in m/s) for pentads (−3, −2, −1 and MOK) for delayed monsoon composite. Only contours of 4 m/s and above at intervals of 4 m/s are shown

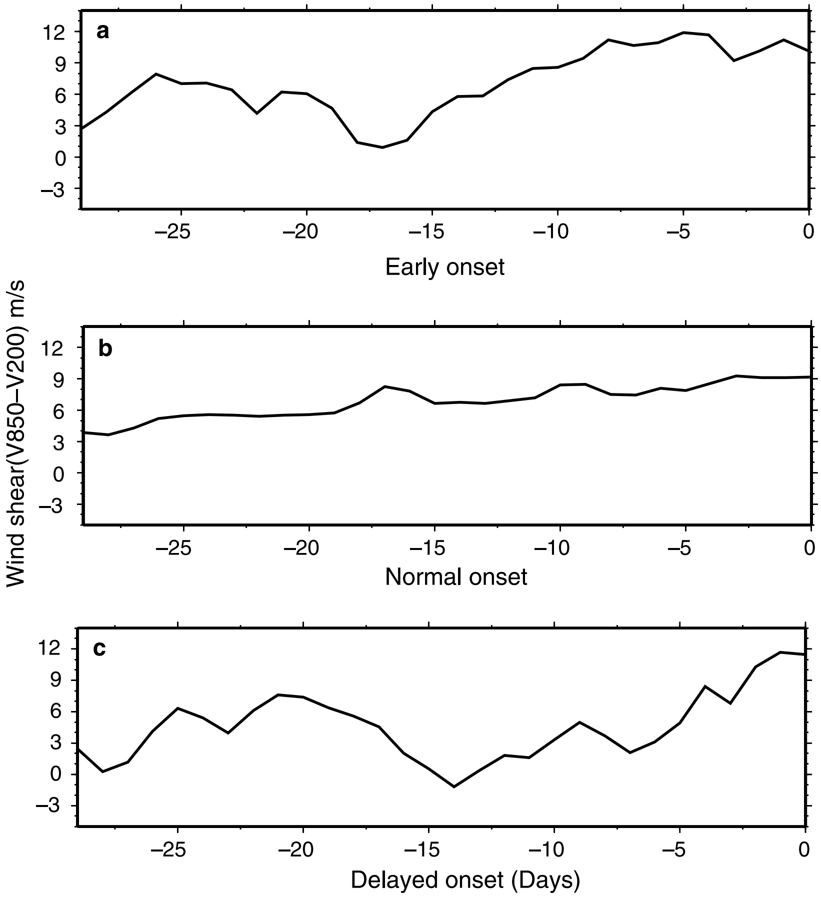

Fig. 10. Daily strength of monsoon Hadley cell (V850–V250) in m/s from −30 days to MOK, for composites of (**a**) early, (**b**) normal and (**c**) delayed. The years of early, normal and delayed are given in Table 1. V850 and V200 are defined in the text

with upward motion over the area of convection and downward motion over the southern Indian Ocean, with a return current through the low level jet stream (Joseph et al. 2003). The strength of the lower branch of the MHC is taken as the average meridional wind speed (m/s) at 850 hPa over the region 35° E–55° E and 10° S–10° N (let us call this V850) shown in Fig. 1 (box d). The upper branch of the MHC is taken as the average meridional wind speed at 200 hPa over the region 45° E–75° E and 20° S – equator (let us call this V200) shown in Fig. 1 (box e). The intensity of the MHC is determined by the difference between the lower and unner branches of the MHC (V850–V200).

Figure 10 presents the strength of MHC with the progress of time for the early, normal and delayed onset composites. It can be seen that MHC begins to strengthen about 2 pentads (in the case of the normal composite) to 3 pentads (in the case of the early and delayed composites) prior to MOK. Hence, we feel that it has predictive value for extreme (early or delayed) onsets over Kerala.

3.6 Madden Julian Oscillation (MJO)

The time-longitude analysis of NOAA–CIRES OLR data along 5° S–5° N, showed that MOK was over one week late in 1997. This appears to be associated with the Madden-Julian Oscillation (OLR $<230\,W/m^2$) which was particularly strong in the spring (Fig. 11). The active phase of the MJO crossed the Indian Ocean in mid-May, spawning an intense Bay of Bengal cyclone (15–19 May). At the normal onset date of 1 June, the suppressed phase of the MJO was in place and appears to have delayed the onset. In the early MOK case (1990), the MJO also developed well in advance and onset was closer to 17–18 May (Ananthakrishnan and Soman 1991) rather than the MOK date defined by the IMD (i.e., 19 May).

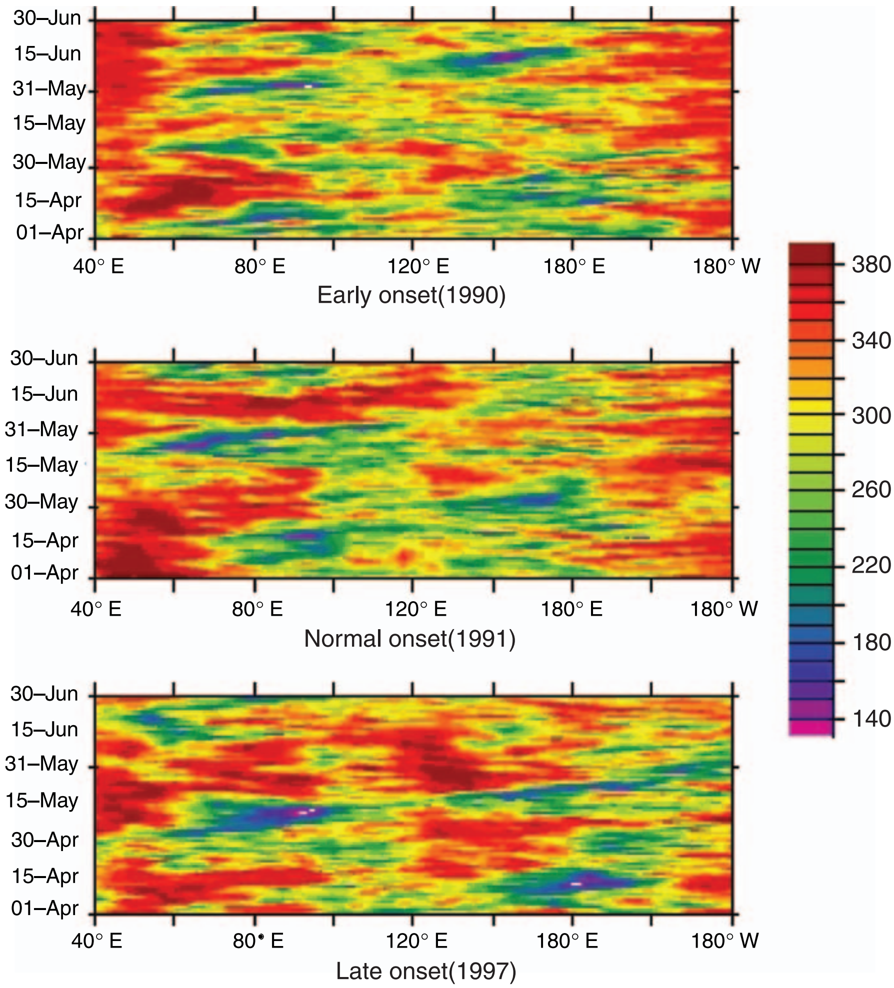

Fig. 11. Madden Julian Oscillation (MJO) of outgoing longwave radiation averaged (5° N–5° S) from NOAA–CIRES. The contours are from 130 W/m^2 to 290 W/m^2 with an interval of 10 W/m^2. Values lower than 230 W/m^2 indicate MJO

4. Summary and conclusions

Air–sea interactions over the Indian Ocean were studied for several years using a compositing technique for early, normal and delayed monsoon MOK. The recently released high resolution HOAPS-3 dataset parameters such as sea surface temperature, integrated columnar water vapour and evaporation are examined from 7 pentads before MOK, to identify the conditions leading to different types of MOK. We also looked into the utility of the MHC as a predict of MOK using NCEP/NCAR reanalysis wind data. It was found that parameters have a much better predictive value in the case of extreme MOKs (such as early or delayed) than for normal MOKs. An analysis of the characteristics of 850 hPa winds showed that westerly winds strengthened almost 3 pentads prior to MOK over the extreme peninsula and Sri Lanka region during both early and normal MOK composites. Evaporation rates showed a dramatic increase over the southern AS with the MOK. The PMWP occurs about 40 days prior to MOK, and could be a potential predictor of the MOK with a lead time of 40 days. More study is needed in this direction.

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