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An Investigation into the Conditions Leading to Monsoon Onset over Kerala

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Abstract

Monsoon onset over 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). The columnar water vapour content and sea surface temperature and evaporation are all examined to look into the conditions leading to MOK from -7 pentads. We have also looked into the role of Monsoon Hadley Cell (MHC) using the NCEP/NCAR Reanalysis dataset. The role of the cross equatorial flow and low level jet at 850 hPa has also been explored. The importance of the Madden Julian Oscillation in initiating the MOK has also been studied using the outgoing longwave radiation data. An analysis of sea surface temperature over Arabian Sea and Bay of Bengal for contrasting MOK's, showed that, the AS warm pool plays a crucial role on MOK. Contrary to the popular notion that the moisture builds up only two to three weeks in advance, our study showed 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 thought of as a potential predictor for MOK. The 850 hPa winds strengthen in the extreme southern peninsula and Sri Lanka about 3 pentads prior to MOK. The evaporation rates over the southern Arabian Sea shows a dramatic increase with onset of MOK. The MHC can be thought of as useful predictor for extreme monsoon onsets (early or delayed).

1. Introduction

The mean date of monsoon onset for Kerala is around 1 June, according to meteorological records, 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 calendar (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, which is situated in the southwest part of the Indian subcontinent (figure 1) is the gateway for the Indian summer monsoon. This season gives about 80% of the mean annual rainfall, plays a crucial role in the Indian economy, as agriculture, power generation and drinking water are dependent upon 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

Of these, the MOK and its systematic northward progression play an important role as an early or delayed MOK can have a profound influence on the agricultural production over the entire Indian subcontinent. The objectives of the present study are

1. To study the air sea interaction processes over the Indian Ocean leading to MOK using a recently released high resolution HOAPS 3 dataset (Andersson, 2007).
2. To look into the role of the cross equatorial flow and low level jet leading to MOK.
3. To bring out the role of Monsoon Hadley Cell and Madden Julian Oscillation on 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) has summarized many of these studies in a Forecasting Manual of India Meteorological Department. In order to arrive at a uniform set of onset dates, Ananthakrishnan and Soman (1988) analysed the daily rainfall over a dense network of rain gauge stations in Kerala, and determined the onset dates for south Kerala and north Kerala separately. The MOK as defined by Ananthakrishnan and Soman (1988) is the first day of transition from light to heavy rain spell category 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 the kinetic energy increases over the southeast Arabian Sea by an order of magnitude just prior to the MOK. Based on 1979-1982 data, Pearce and Mohanty (1984) suggested that the 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 required about two to three weeks pre-conditioning by the atmosphere over the AS.

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

Joseph et al (1994) has critically reviewed the literature on monsoon onset over Kerala. They studied the temporal and spatial evolution of tropical deep convection and associated with MOK using composite pentad (5 days) mean maps of outgoing longwave radiation (OLR) using data of 10 years, in each of which the date of MOK is very close to 1 June. They found that at pentad -8 (i.e 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 -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 of 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 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) have examined the 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 to 10 days prior to MOK.

Fasullo and Webster (2003) suggested that a method based on the VIMT would be better 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 in identifying the withdrawal dates of the monsoon and could help in distinguishing between the actual MOK and the bogus MOK (Flatau et al., 2001).

Jospeh et al (2003) have looked into the role of Monsoon Hadley Cell (MHC) and MOK using the NCEP/NCAR Reanalysis data. They have used meridional wind 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 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 ($V_{850}-V_{200}$) is taken as the intensity of the MHC and was found to increase rapidly about 10 days prior to MOK.

Ramesh Kumar (2004) using the satellite derived precipitation over the Indian Ocean found that there is a Pre Monsoon Rainfall Peak about 6 pentads prior to MOK and have shown that this has some predictive value for MOK. Simon et al (2006) have looked into the conditions leading to the MOK using satellite data. The study revealed that the water vapour build up over the Western Arabian Sea by about two and half weeks can be thought of as useful parameter for predicting the MOK.

Joseph et al (2006) in a recent study have looked into the summer monsoon onset processes over south Asia and formulated an objective three-step method for MOK. The date on which zonal wind 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 and OLR. And finally they checked whether on the MOK date there was widespread convection (low OLR) around Kerala.

2. Data

The new version of the **Hamburg Ocean Atmosphere Parameters and Fluxes from Satellite** dataset, **HOAPS-3** (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 the fluxes. Except for the NODC/RSMAS Pathfinder SST data set, 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 data set and a new procedure to synthesize the defective 85 GHz channels on DMSP-F08. Previous improvements in HOAPS-II, such as the utilization of multi-satellite averages, inter-satellite calibration, and an efficient sea ice detection procedure are kept, resulting in homogeneous and reliable spatial and temporal fields. In the present study, we have used the pentad mean sea surface temperature and integrated columnar water vapour, evaporation and rain rate at a resolution of $0.5^\circ \times 0.5^\circ$ for the period 1988 to 2003. More details of this dataset can be had from Andersson et al., (2007).

We have used the NCEP/NCAR Reanalysis data (Kalnay et al.,1996) daily winds at standard pressure levels on a $2.5^\circ \times 2.5^\circ$ 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 have an equal influence from observations and model calculations and are classified as B class variable. More details of the reanalysis data can be obtained from Kalnay et al., (1996). The zonal and meridional winds at 850 hPa have been used for studying the characteristics of the low level jet on the MOK. We have also used the meridional winds at 850 hPa and at 200 hPa averaged over two regions (see figure 1) in identifying the strength of the Monsoon Hadley Cell (MHC) on the MOK. The increased convection in 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 gives the regions used for averaging the upward and downward branches of the Hadley cell circulations. The figure also depicts three other boxes which we have used for averaging the SST's in the AS & BB and also peninsular region for looking at the role integrated columnar water vapour prior to MOK.

The outgoing longwave radiation (OLR) for the present study is taken from 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 gives 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/late 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, 12 years the onset has been normal. The mean onset dates for different composites are also given in the table.

3. Results and Discussion

From the previous studies, it is quite clear that the air sea interaction processes over north Indian Ocean plays a major role prior to MOK. We now look at some of the parameters using the composite method for different types of MOK (listed in table 1) such as sea surface temperature, integrated columnar water vapour, evaporation, cross equatorial flow and low level jet using the different datasets listed in table 2.

3.1. Sea surface temperature

A warm pool (SST > 28°C) exists in the western Pacific and eastern Indian Ocean. The warmest area of this warm pool is centered around 140°E to 180°E, where the SST exceeds 29°C in this central region. This is called the western Pacific warm pool. Sadler et al., (1987) have shown that, the tropical Indian Ocean north of equator warms rapidly from March onwards, and by May a large area in the north Indian Ocean attains SST more than 29.5°C, this area can be called 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. The SST's continue to rise until the MOK over the north Indian Ocean in May - June, but in the southwest Pacific, SST has a decreasing trend in May - June. Further, the Indian Ocean warm pool attains temperatures more than 30°C around the time of MOK (Seetharamayya and Master, 1988 ; Jospeh, 1990). A region of high SST as the Indian Ocean warm pool can create large scale moisture convergence, with its deep convective clouds, heating of the tropospheric column above, lowering of the surface pressure and strengthening of lower tropospheric westerly winds associated with the MOK (Joseph et al., 1994). Ramesh Kumar and Schluessel (1998) have shown that an early peaking of SST in the AS will help in the development of a low pressure over this area and thus creating an intense inter-hemispheric pressure gradient and strong cross equatorial flow, and conditions conducive for an early onset over the Indian subcontinent.

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) (figure 2). In case of normal MOK, the AS warm pool reaches maximum development in about 3 to 4 pentads prior to MOK (normal MOK composite) and the warm pool reaches maximum development only two pentads prior to MOK (in late composite) can be seen from figure 2.

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

3.2 Integrated columnar water vapour:

The integrated columnar water vapour (IWV) has been found to be a useful parameter for identifying the MOK by several authors (Pearce and Mohanty, 1984; Simon et al., 2006). We have used the IWV of the HOAPS 3 dataset for looking into the gradual build up of moisture conditions leading to MOK by averaging it over the peninsular box shown in figure 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 the peninsular India is clearly seen in figure 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 two to three weeks early (Pearce and Mohanty, 1984; Simon et al., 2006).

The spatial distribution of the IWV for composites of early, normal and delayed onsets also depicts (figure 5) this PMWP about 7 pentads prior to MOK in the AS. This could be the source of moisture needed for PMRP. Then the IWV further increases and reaches about 3 to 4 pentads prior to MOK as mentioned by Pearce and Mohanty (1993) and Simon et al., (2006). The PMWP occurring about 7 to 8 pentads prior to MOK can be a potential predictor for MOK. More study is needed in this direction.

3.3 Evaporation

There have been several studies regarding the source of moisture for the southwest monsoon rainfall, with the Arabian Sea and cross equatorial flow being considered major sources. Now it is widely recognized that the inter-hemispheric cross equatorial flow plays a major role on the monsoon activity over the Indian subcontinent. Evaporation over the Indian Ocean is one of the least studied parameter 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 Indian Ocean on a better spatial and temporal scale for studying the MOK. Further these estimates are highly scattered and mostly based on ship observations and are available only on a monthly basis, hence not were suitable. Schluessel (1996) has estimated the evaporation rates over the ocean using satellite data and Schulz et al., (1997) has further validated these estimates on a global scale.

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

The evaporation rates of the have been computed using the bulk parameterization method of Fairall et al., (1996). Figure 6 gives the evaporation rates over the Indian Ocean about 7 pentads earlier to MOK for the three different composites. The most interesting aspect is the substantial increase in the evaporation rates over the southern AS and south Indian Ocean (SIO) during the MOK pentad during the early MOK composite. This clearly shows that the southern AS evaporation plays a major role on the MOK. During the normal MOK composite also, similar features are observed with lower values of evaporation over the southern AS and SIO. In case, of delayed MOK, the evaporation over the AS is not does not increase as dramatically as in the case of early MOK composite. Further, 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 the 850 hPa winds from the NCEP/NCAR Reanalysis data to monitor the cross equatorial flow (CEF) and low level jet (LLJ) as they are found to play a major role on MOK. Further, the westerly mean monsoon current is strongest close to 850 hPa (Joseph and Sijikumar, 2004). We have looked into the role of the CEF & LLJ winds about 3 pentads earlier up to MOK for the three composites, namely, early, normal and delayed MOK. In the case of an early MOK composite (figure 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 (figure 8), we see there is strengthening and deepening of the westerly winds from -3 pentads to MOK (0 pentad) over the extreme south peninsula and Sri Lanka. Further, we see In case of a delayed MOK composite (figure 9), the LLJ does not extend from the south eastern 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

The convection in the southeast Arabian Sea and 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 (Joseph et al., 2003). The strength of the lower branch of the MHC is taken as the average meridional wind at 850 hPa in m/s over the region (35° E - 55° E and 10° S - 10° N, let us call this as V850) and shown in figure 1(box d). The upper branch of the MHC is taken as the average meridional wind at 200 hPa over the region (45° E - 75° E and 20° S to equator, let us call this as V200) and shown in figure 1 (box e). The intensity of the MHC is given by difference of the lower branch of MHC and upper branch of MHC (V850-V200).

Figure 10 gives 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 pentad (in case of normal composite) to 3 pentads (in case of early and delayed composites) prior to MOK. Hence we feel that it has more predictive value for extreme (early or delayed) onsets over Kerala.

3.6 Madden Julian Oscillation

The time longitude analysis of NOAA-CIRES OLR data along 5° S - 5° N, showed that MOK was over one week late in the year 1997. This appears to be associated with the Madden-Julian Oscillation (MJO, $OLR < 230$ W/m²) which has been particularly strong this spring (figure 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 the onset looked nearer to 17-18 May (Ananthkrishnan and Soman, 1991) rather than the MOK declared by IMD,(i.e 19th May).

4. Summary and Conclusions:

The air sea interaction parameters over the Indian Ocean are 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 earlier to MOK, to look into the conditions leading to different types of MOK. We also looked into utility of MHC using the NCEP/NCAR reanalysis wind data. It was found that they have much better predictive value in case of extreme MOK's (such as early or delayed). An analysis of the strength of 850 hPa winds showed that the westerly winds strengthened almost 3 pentads prior to MOK over the extreme peninsula and Sri Lanka region during both early and normal MOK composites. The evaporation rates showed dramatic increase over the southern AS with the MOK . The PMWP occurs about 40 days prior to MOK, and can be a potential parameter for predicting the MOK with a lead time of 40 days. More study is needed in this direction.

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Table captions

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.

Table 2: Different datasets used in the present study

Figure captions

Figure 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)

Figure 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

Figure 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 .

Figure 4: Composite mean integrated columnar water vapour (in Kg/m²) for the period 1989 to 2003 for the peninsular box mentioned in figure 1, with respect to MOK as 0.

Figure 5: Pentad mean integrated columnar water vapour (in Kg/m²) 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/m² and above are plotted at intervals of 5 Kg/m²

Figure 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.

Figure 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.

Figure 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.

Figure 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.

Figure 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.

Figure 11: Madden Julian Oscillation (MJO) of outgoing longwave radiation averaged [5°N – 5°S] from NOAA-CIRES. The contours are from 130 W/m² to 290 W/m² with an interval of 10 W/m². Values lower than 230 W/m² indicate MJO.

Table 1

Mean date of Monsoon Onset used for different composites, namely, early, normal and delayed

Early		Normal		Delayed	
Year	MOK date MOK date (IMD)	Year	MOK date (IMD)	Year	
(IMD)					
1990 June	19 May	1988	26 May	1997	9
2001 June	23 May	1989	3 June	2003	8
		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 June	21 May		01 June		9

Table 2

Different datasets used in the present study

Name of dataset Period	Variables used	Resolution	Data
HOAPS 2003	Sea surface temperature Evaporation Integrated Columnar water vapour	pentad, 0.5° X 0.5°	1988-
NCEP/NCAR Reanalysis 2003	Zonal and Meridional winds at 850 hPa Meridional wind at 200 hPa	daily, 2.5° X 2.5°	1988-
NOAA-CIRES 2003	OLR	daily, 2.5° X 2.5°	1988-

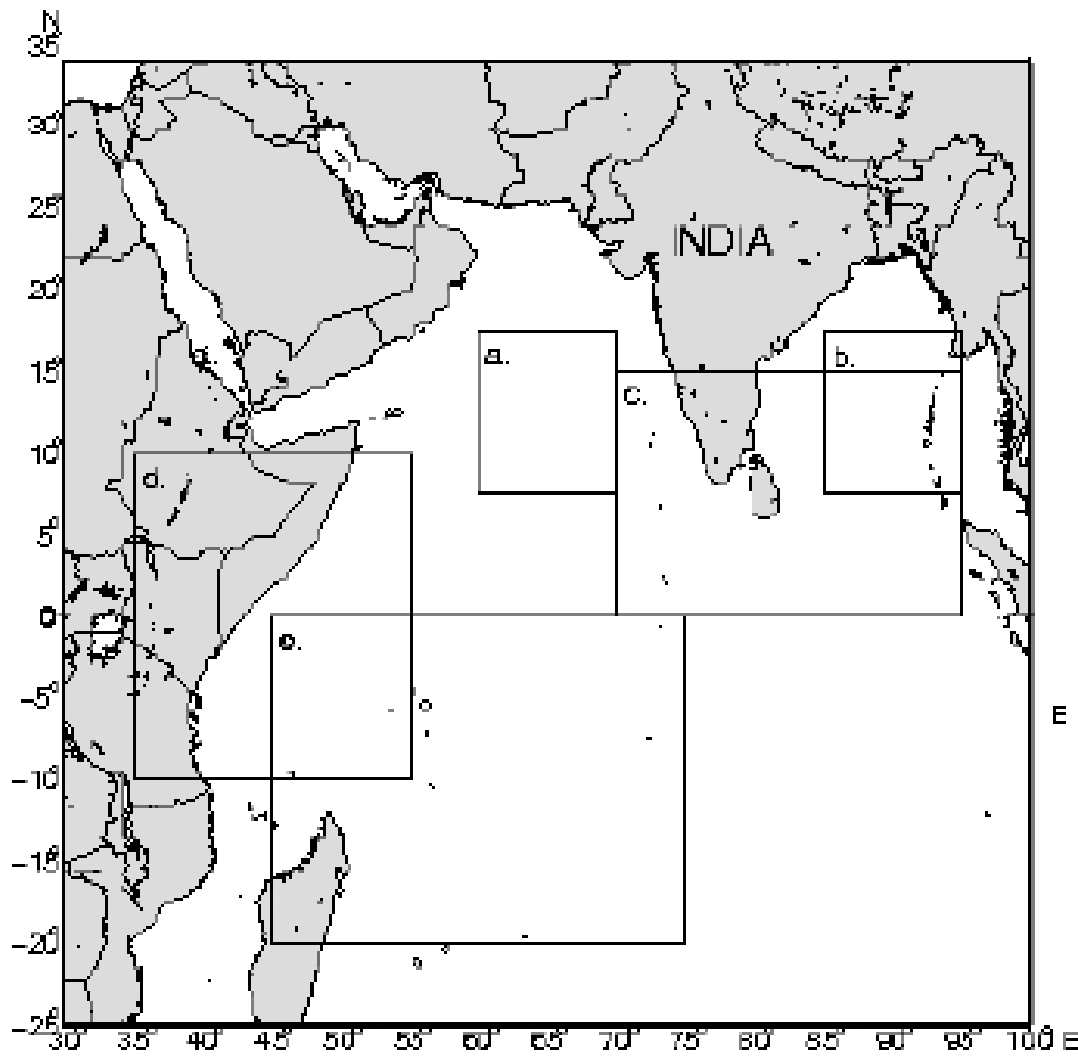


Figure 1

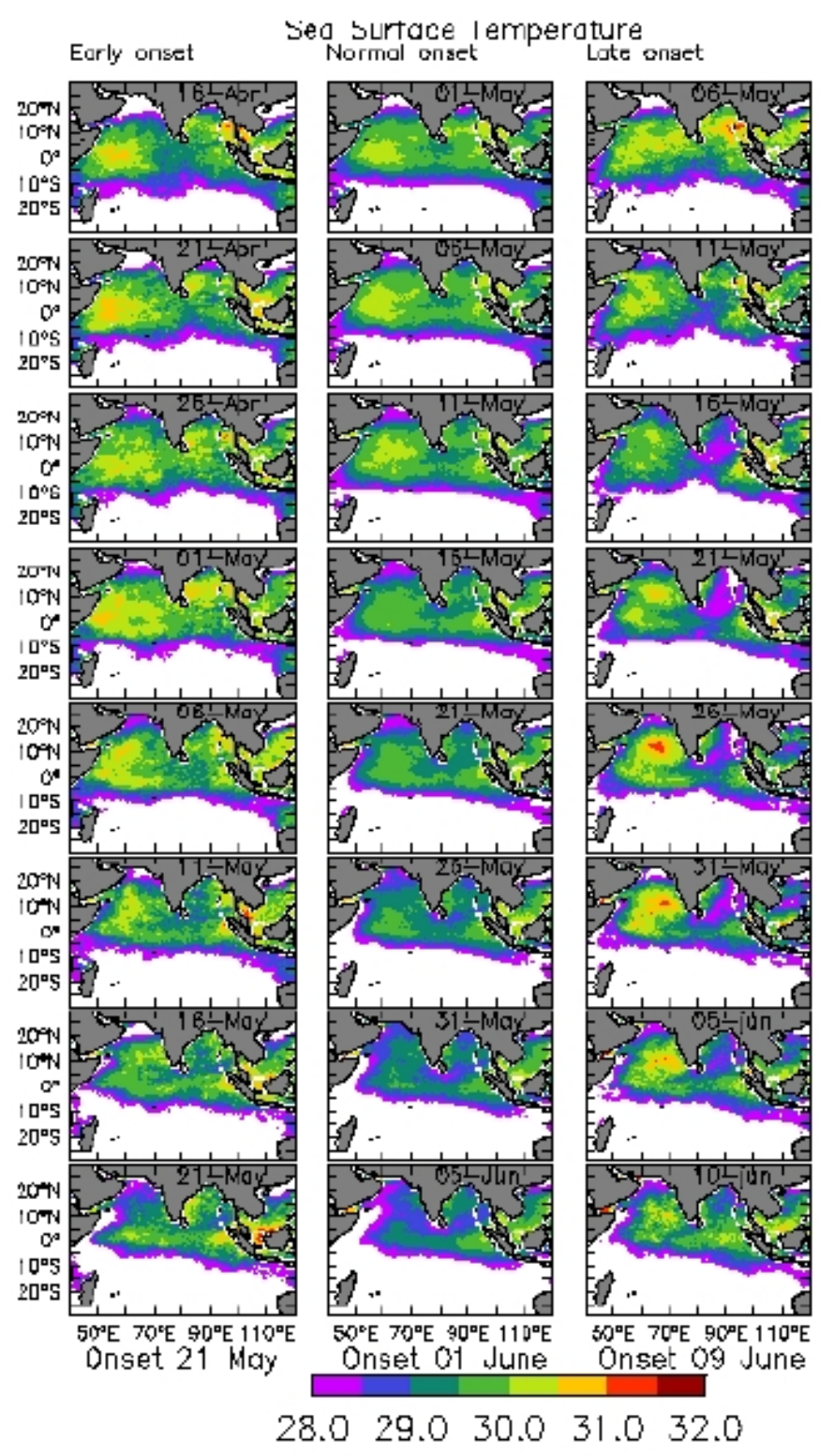


Figure 2

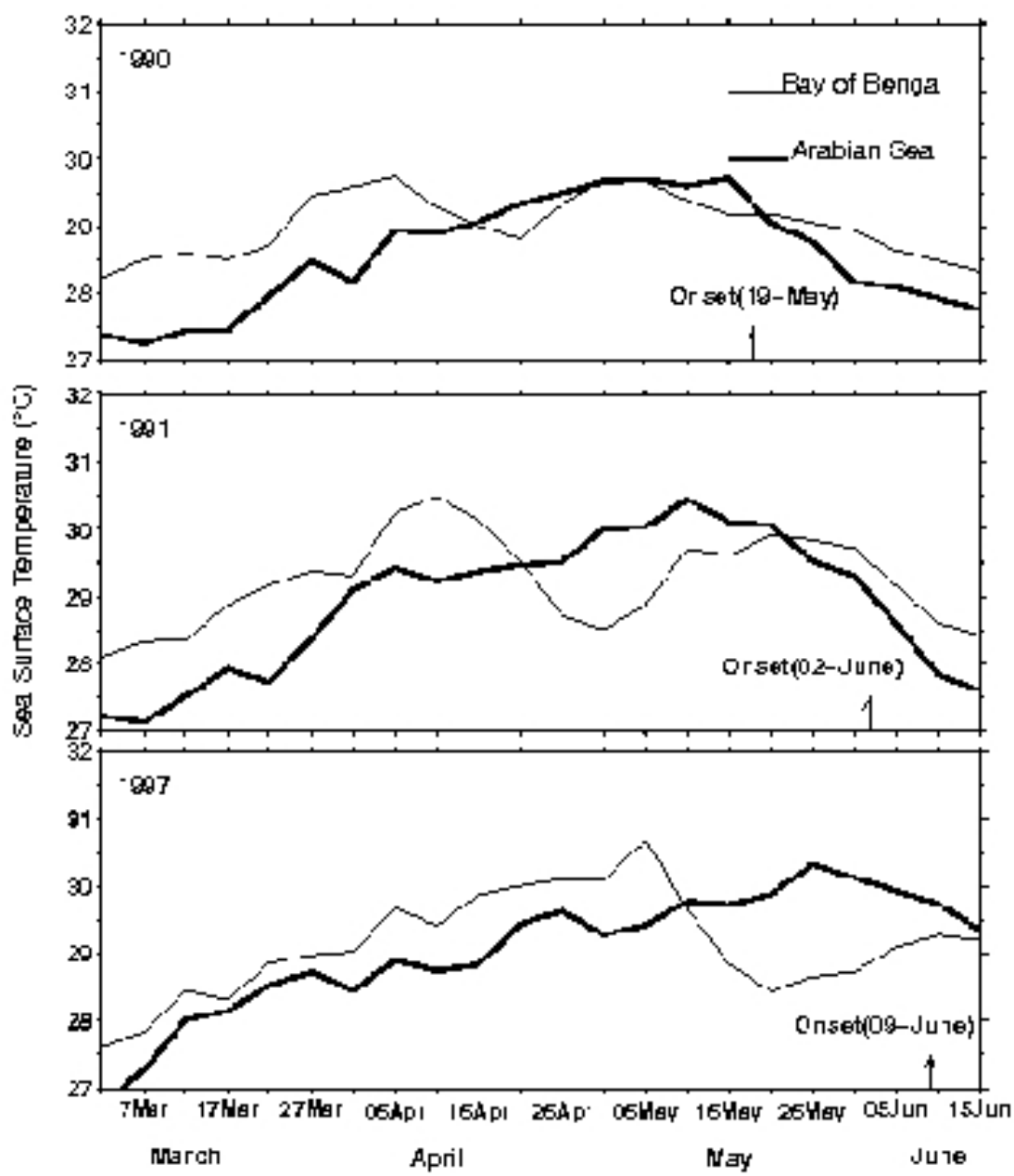


Figure 3

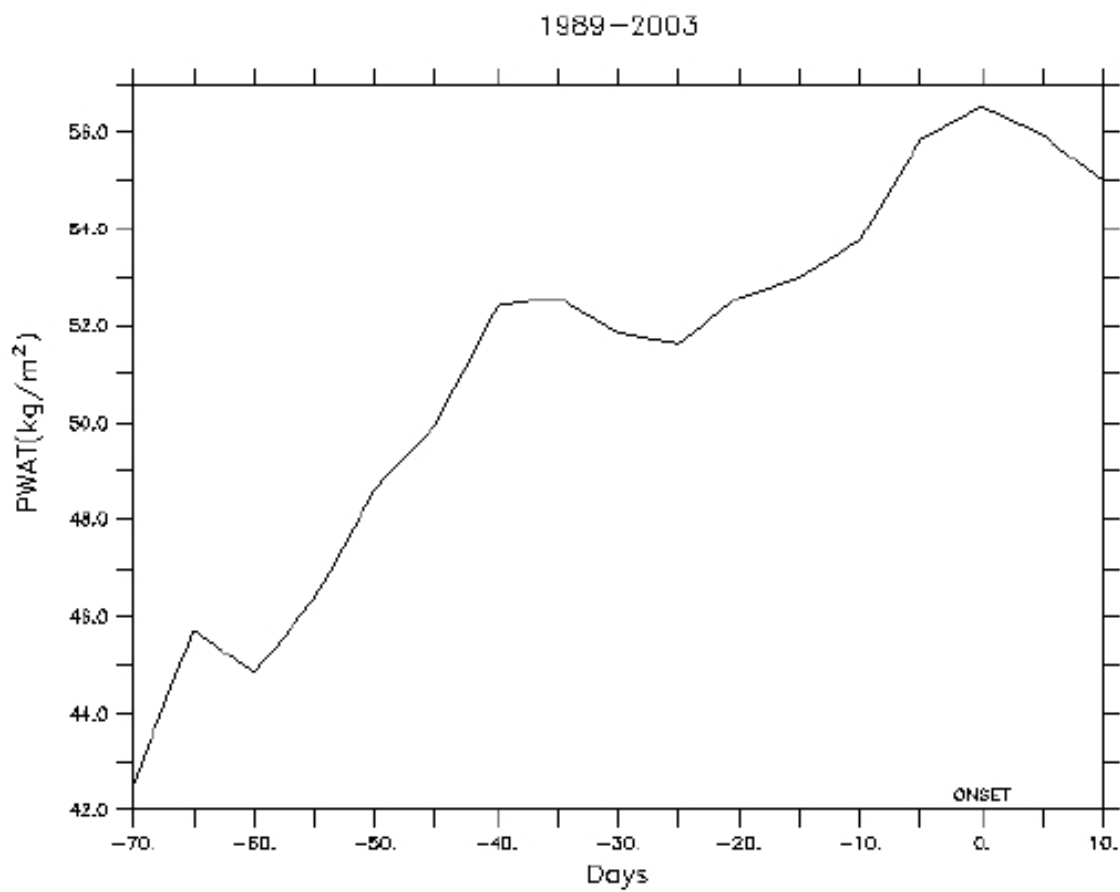


Figure 4

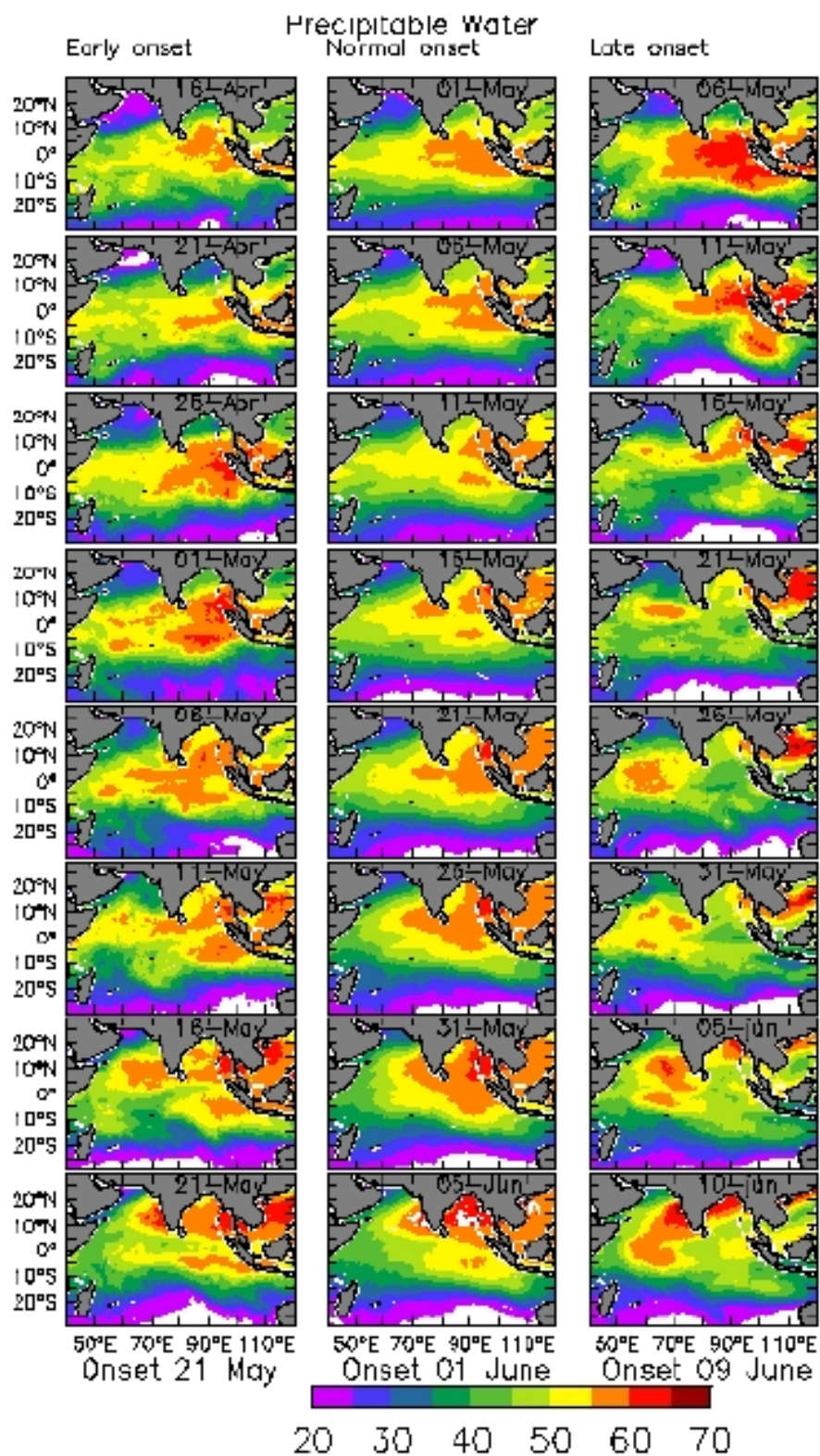


Figure 5

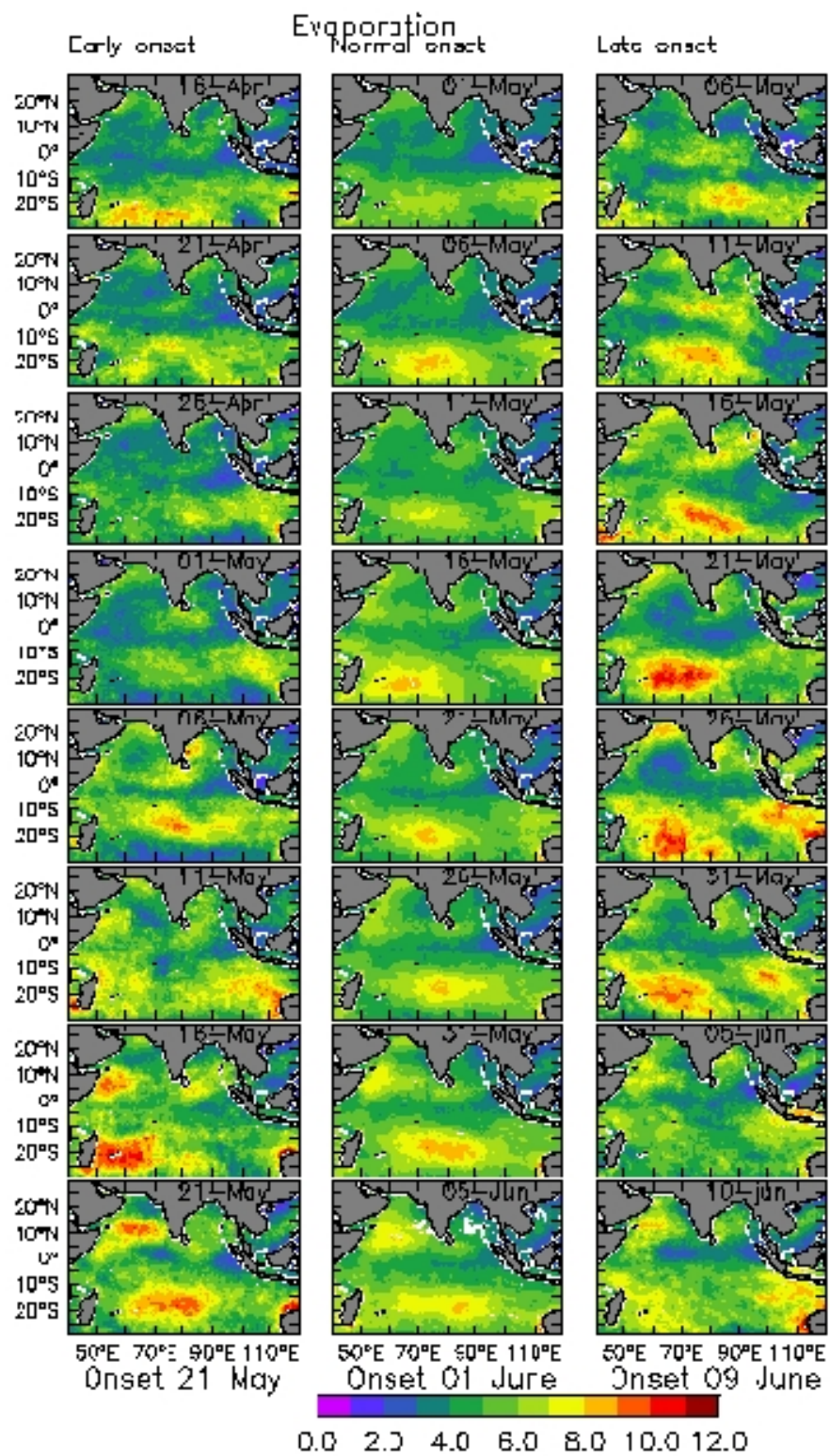


Figure 6

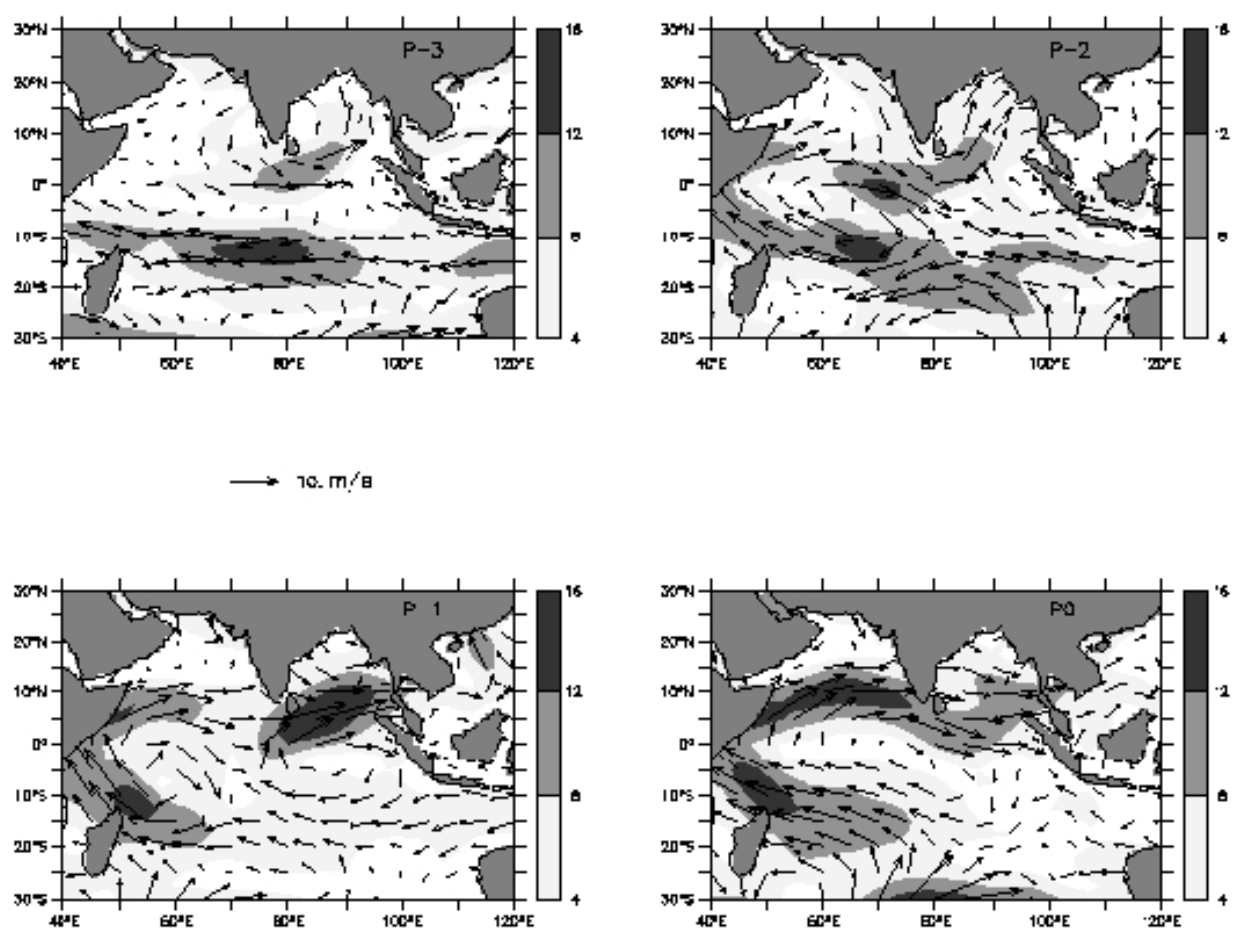


Figure 7

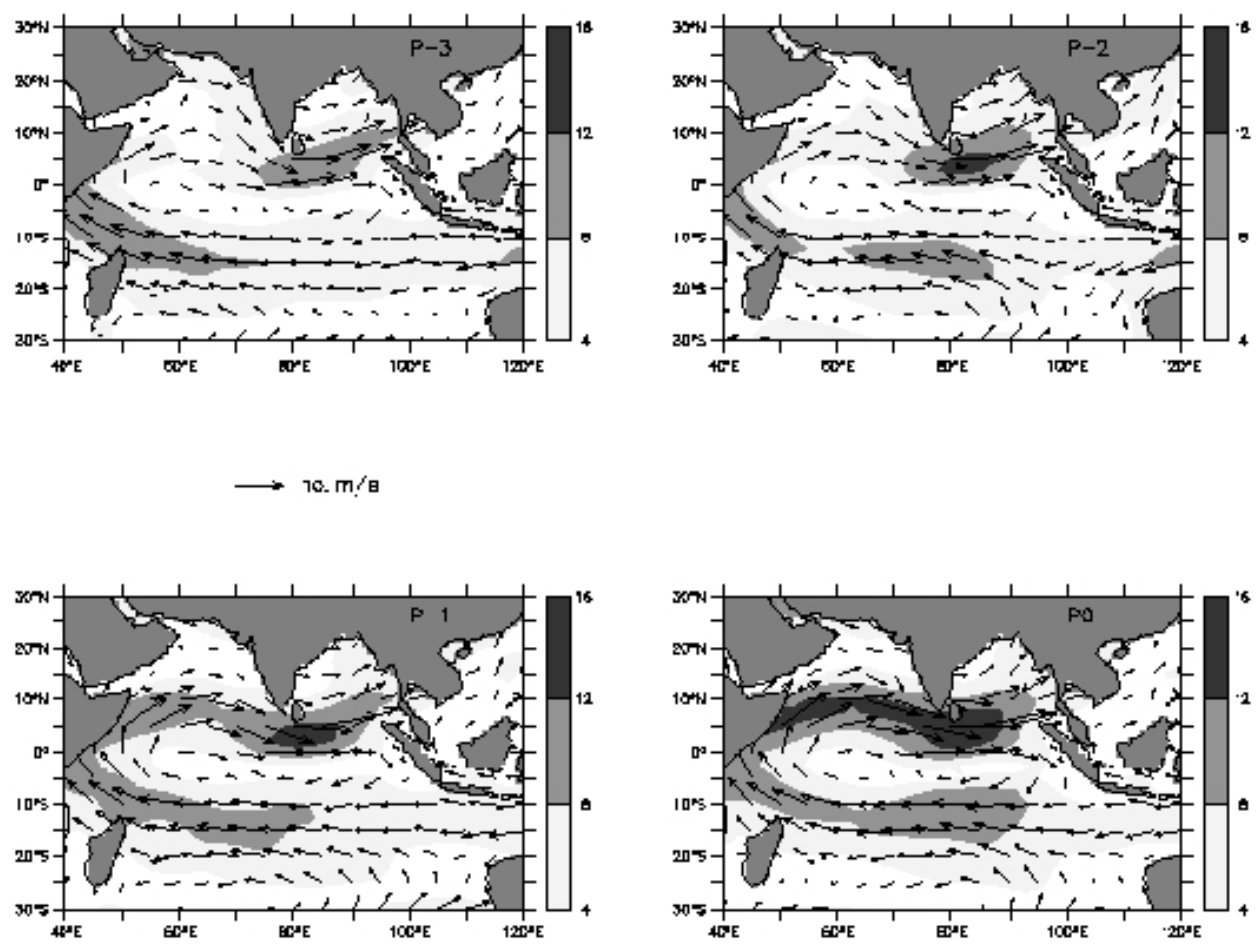


Figure 8

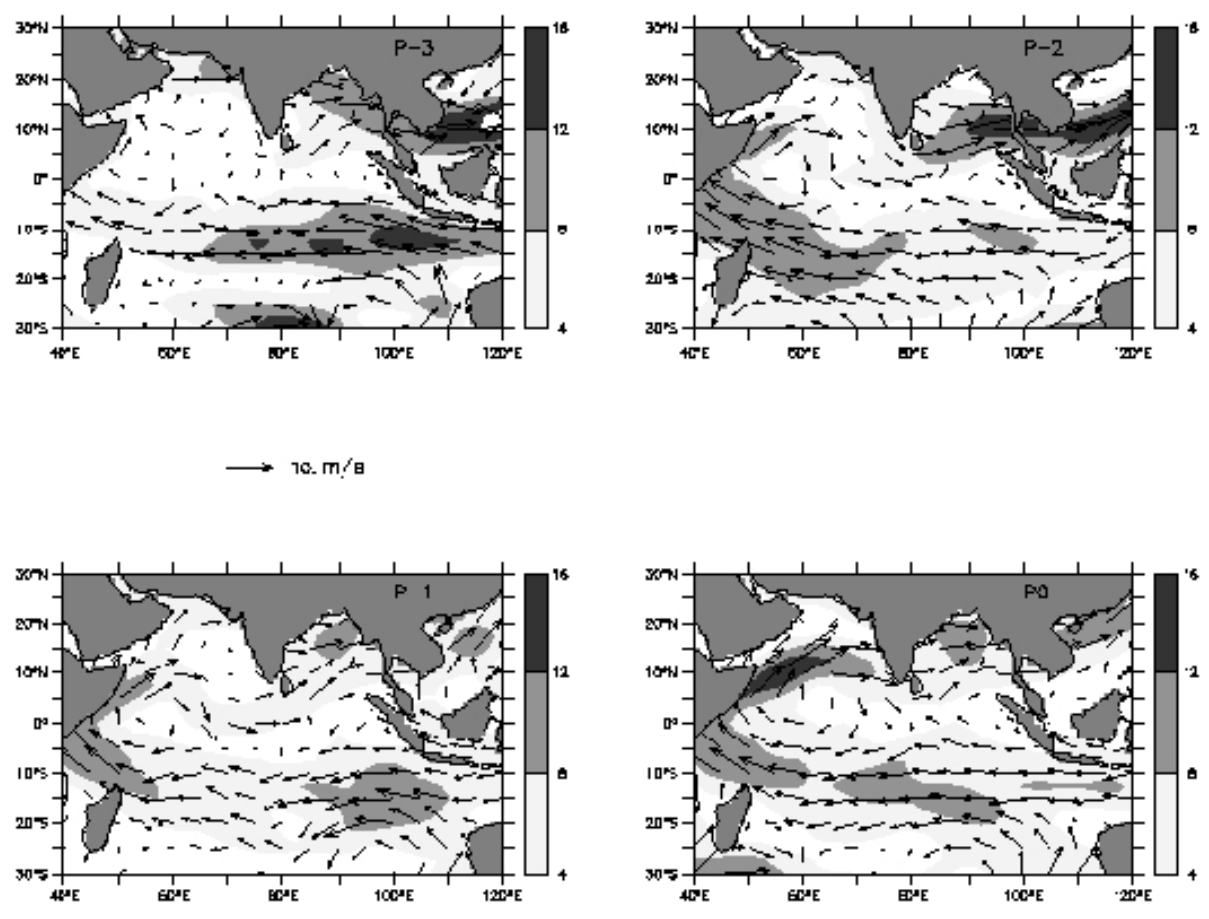


Figure 9

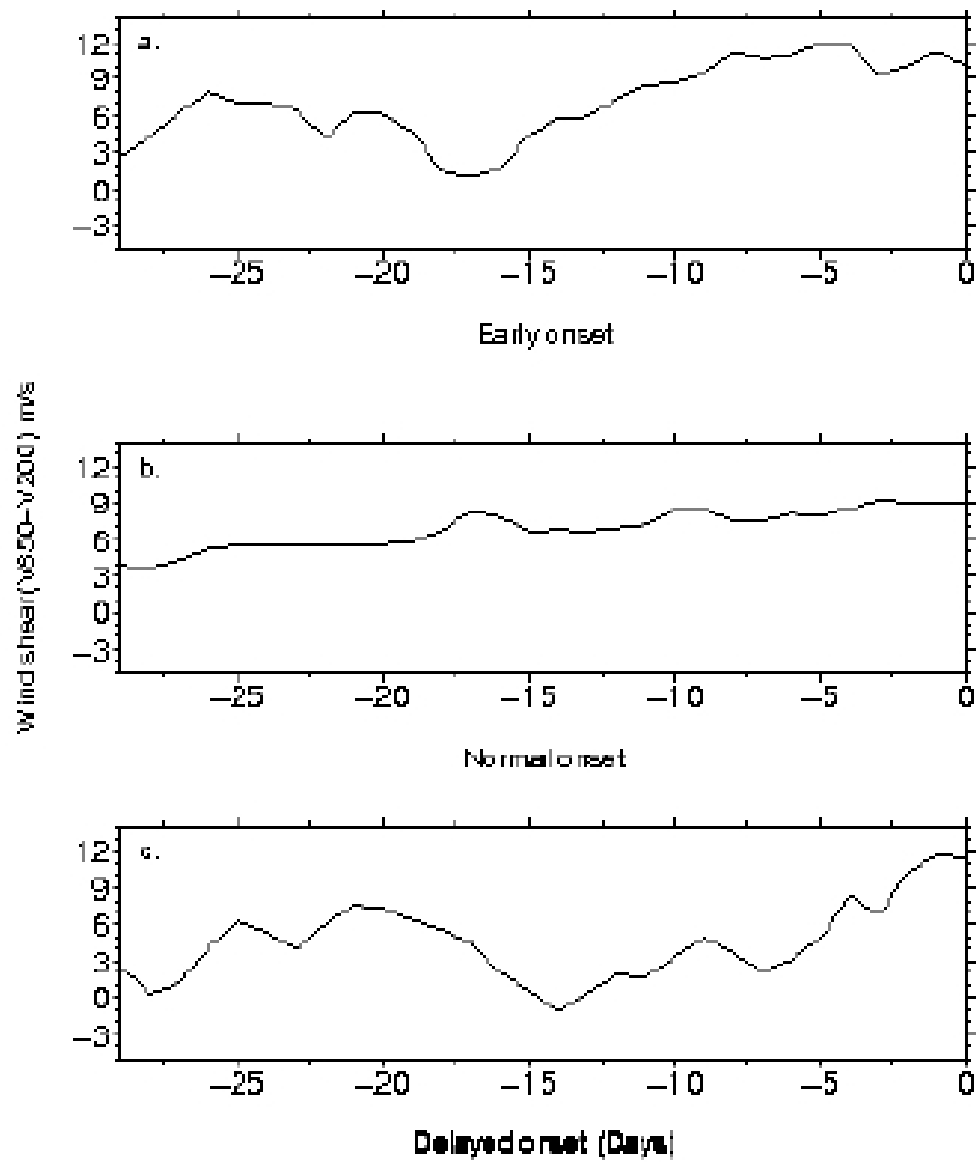


Figure 10

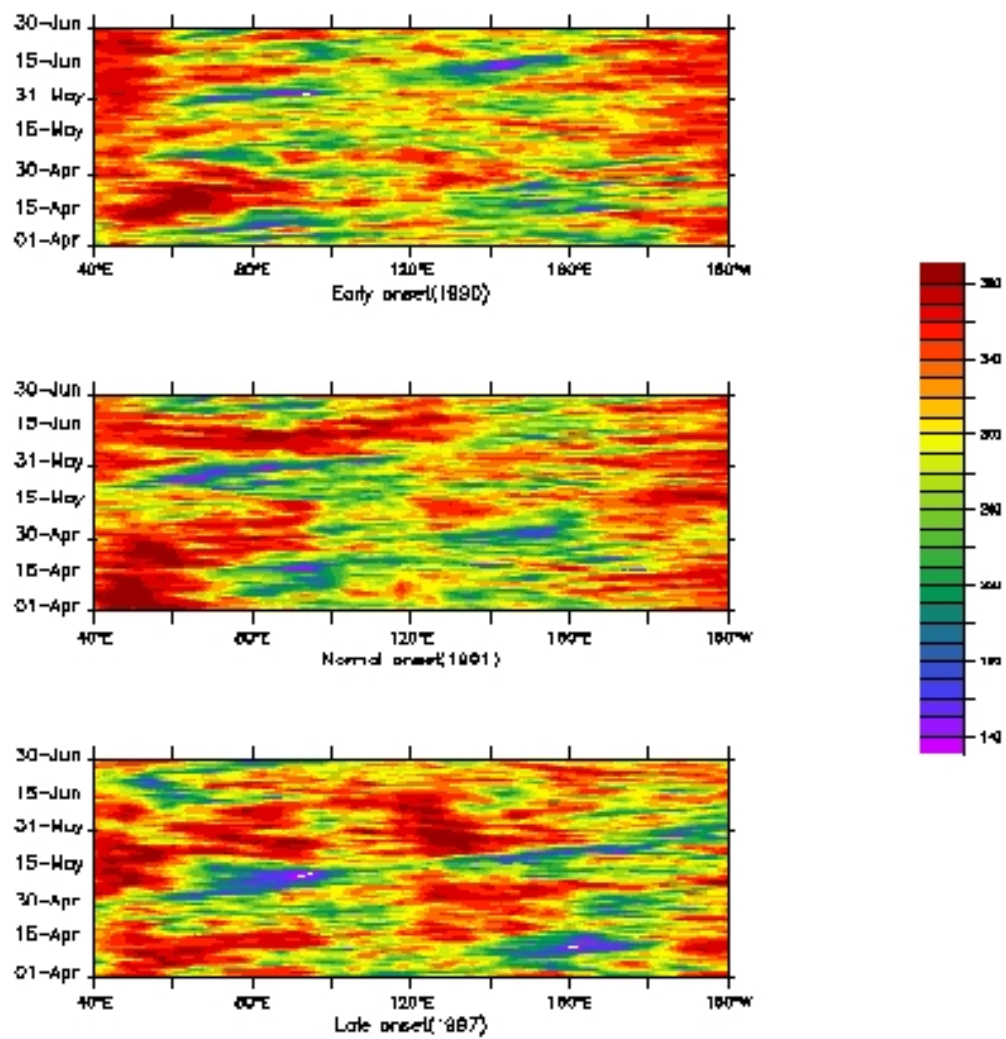


Figure 11