

## On the Relative Roles of El Nino and Indian Ocean Dipole Events on the Monsoon Onset over Kerala

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### Abstract

Inter annual variations of the monsoon onset over Kerala (MOK) have been studied using data from over sixty years (1948-2009) of NCEP/NCAR Reanalysis and outgoing longwave radiation (OLR). The sea surface temperature (SST) fields over the North Indian Ocean associated with the MOK have been examined in association with El Nino and Indian Ocean Dipole (IOD) events which originate in the Pacific and Indian Ocean respectively. An analysis of the tropical convective maximum (TCM) showed significant differences in its strength and location during the El Nino, IOD, early, normal and delayed MOK composites. Further, we also looked into the role of the convective systems formed over the Arabian Sea and Bay of Bengal on MOK.

The most significant features during early (delayed) MOK years is the abnormal persistence of westerlies (easterlies) several days prior to MOK and enhanced (suppressed) deep convection over the south eastern Arabian Sea and the southern Bay of Bengal. Moisture builds up over peninsular India several pentads prior to MOK during La Nina, negative IOD and concurrent La Nina and negative IOD years as compared to the El Nino, positive IOD and concurrent El Nino and positive IOD years indicating its significant role on MOK. The monsoon Hadley cell and Walker circulations are weaker (stronger) during a delayed (early) MOK. Further the sea surface temperature anomalies in the western Pacific are negative (positive) during delayed (early) MOK.

## 1. Introduction

The tropical Indian Ocean forms the major part of the largest warm pool on Earth, and its interaction with the atmosphere plays an important role in shaping climate on both regional and global scales (Schott, Xie and Mc Creary, 2009). In addition to the Indian summer monsoon, two important phenomena which influence the Indian Ocean are the El Niño and Southern Oscillation (popularly known as ENSO) and the recently discovered Indian Ocean Dipole. Ashok et al., (2001) have shown that the IOD and ENSO have complementarily affected the Indian summer monsoon rainfall during the past four decades. Using an AGCM, these authors showed that the ENSO-induced anomalous circulation over the Indian region is either countered or supported by the IOD-induced anomalous meridional circulation cell, depending upon the phase and amplitude of the two major tropical phenomena in the Indo-Pacific sector.

El Niño is a coupled climate phenomenon characterized by anomalous warming of the upper layers of the central to eastern tropical Pacific Ocean, followed a season or so later by large scale warming in the tropical Indian Ocean, whereas La Niña typically shows the opposite sea surface temperature (SST) anomalies. The Indian Ocean Dipole (IOD) is also a coupled ocean-atmosphere phenomenon but it originates in the Indian Ocean (Saji et al., 1999; Webster et al., 1999) and manifests itself as a basin scale mode of sea surface temperature (SST) and wind anomalies occurring on interannual time scales. A positive phase of the IOD causes an anomalous cooling of SST in the eastern tropical Indian Ocean (off Java Island), bringing droughts in the Indonesian and Australian region. On the other hand, the western tropical Indian Ocean (off the east coast of Africa) tends to experience an anomalous warming of SST, which activates atmospheric convection and brings increased rainfall. A negative phase of IOD, in contrast, involves anomalously high SSTs in the eastern Indian Ocean and low SSTs in the west, bringing more rain to the Indonesia and Australia region and less to the East African countries. . Saji and Yamagata (2003) and Ashok et. al., (2004) showed that the IOD exerts a major impact on seasonal climatic conditions in the countries around Indian Ocean. However, like ENSO, the IOD may induce unusual circulation and rainfall patterns not only over the Indian Ocean rim countries but also globally. Earlier studies (Saji and Yamagata, 2003; Ashok et. al., 2004) have shown that the dipole mode exerts a major impact on seasonal climatic conditions in the countries around Indian Ocean

The intensity of the IOD is represented by the difference in SST anomalies between a western equatorial Indian Ocean ( $50^{\circ}$  E- $70^{\circ}$  E and  $10^{\circ}$  S- $10^{\circ}$  N) box and a south eastern equatorial Indian Ocean ( $90^{\circ}$  E- $110^{\circ}$  E and  $10^{\circ}$  S- $0^{\circ}$  N) box, the so-called Dipole Mode Index (DMI) (Saji et al., 1999). These boxes are shown in Figure 1. The DMI is positive (negative) during a positive (negative) IOD event.

The tropical Indian Ocean gradually warms during an ENSO year (Reason et al., 2000), reaching a maximum during January-March, about one season after the SST anomaly in the central Pacific Ocean has peaked. This SST response in the Indian Ocean is so robust that it was even captured in earlier analyses of sparse ship observations (Weare, 1979). Soman and Slingo (1997) showed that the tropical convective maximum (TCM) over Indonesia and the western Pacific during the spring season (March to May) plays an important role in the monsoon onset over India. Their study showed that during El Niño, modulation of the Walker circulation by the warm SST anomalies in the central and east Pacific appears to delay the onset of the monsoon through its remote effect on the TCM. However, the cold SST anomalies in the western equatorial Pacific, which develop during the mature phase of El Niño, also influence the TCM and delay the onset of the monsoon. During La Niña, the local warm SSTs in the western equatorial Pacific modulate the strength and position of the TCM and tend to advance the time of monsoon onset.

Based on 1979-1982 data, Pearce and Mohanty (1984, hereafter referred to as PM84) suggested that the monsoon onset over South Asia was associated with a gradual moisture build up over the Arabian Sea followed by a rapid intensification of the Arabian Sea winds. The whole process of monsoon onset thus required about two to three weeks of pre-conditioning by the atmosphere over the Arabian Sea.

Joseph et al., (1994) 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 of which the date of MOK is very close to 1 June. 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 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 the South China Sea. Thus prior to MOK, active convection develops over the southeast Arabian Sea over a period of 2-3 weeks.

In their study (for the period 1870–1989), Joseph et al. (1994) showed that of the 22 years when the MOK was delayed more than 8 days, 16 cases were associated with a moderate or strong El Niño. Further, it was found that, of the 13 strong El Niños during the same period, 9 were associated with moderate to large delays in MOK. Their study further revealed that the delayed MOK is associated with warm SST anomalies at and south of the equator in the Indian and Pacific Oceans and cold SST anomalies in the tropical and subtropical oceans to the north during the pre-monsoon season (March to May). Given this association with Indian Ocean SST anomalies, it is likely that IOD events may also significantly impact on the MOK date.

Since there appear to be uncertainties in both the details of the pre-monsoon build up and the potential influence of ENSO and the IOD on this build up, the objectives of the present study are to assess:

a) whether the convective systems which form in the North Indian Ocean such as the Arabian Sea, Bay of Bengal or northwest Pacific Ocean play a significant role in altering the moisture build up needed over the Arabian Sea prior to MOK and also whether the circulation patterns get affected by these systems.

b) the impact of El Nino, La Nina, positive IOD and negative IOD and concurrent events on the TCM which in turn will modulate the monsoon onset over Kerala.

## **2. Data**

In order to look into the moisture and circulation features prior to the MOK, this study examines the NCEP/NCAR Reanalyses (Kalnay et al., (1996).) 850 hPa zonal and meridional winds, integrated columnar water vapour (IWV) from the high resolution satellite dataset HOAPS (Hamburg Ocean Atmosphere Parameters and Fluxes from Satellite data Version III ; Andersson et al., 2007). 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 a B class variable. More details of the re-analysis data can be obtained from Kalnay et al.,(1996).

Table 1 gives the years which are chosen for making the composites for early, normal and delayed MOK composites. These MOK dates were considerably more than one standard deviation away from the mean MOK for Kerala (IMD). Table 2 gives the data for the pure El Nino, pure La Nina, pure positive Indian Ocean Dipole and pure negative Indian Ocean pole years extracted from Meyers et al. (2007). Figure 1 gives the details of various regions used for computing the monsoon Hadley cell circulation, the regions used for computing the dipole mode index (DMI, see Saji et al., 1999 for more details). The Nino 3 region which is used for computing the El Nino and La Nina is also shown in Figure 1.

SST data are based on the extended reconstructed SST, which was constructed using the most recently available International Comprehensive Ocean Atmosphere Data Set data and improved statistical methods (Smith and Reynolds, 2004). We use monthly averages of the Interpolated outgoing long wave Radiation (OLR) data provided by NOAA/OAR/ESRL PSD, Boulder, Colorado,

USA, for the period June 1974 to December 2009 with the exception of the year 1978 from their Web site at <http://www.cdc.noaa.gov>. This is a satellite- derived product available on a  $2.5^{\circ} \times 2.5^{\circ}$  grid. Details of the interpolation technique are described in Liebmann and Smith (1996.). Ananthkrishnan and Soman (1988) have provided the MOK dates for the period 1901-1980 and data for recent years has been extracted from Joseph et al., (2006).

### **3. Convective systems in Arabian Sea and Bay of Bengal :**

According to the India Meteorological Department, convective systems over the North Indian Ocean can be classified as follows:

- a) A low pressure system (with sustained maximum surface wind speed (SMSWS) less than 17 knots)
- b) Depression (SMSWS between 17-27 knots)
- c) Deep Depression (SMSWS between 28-33 knots)
- d) Cyclonic Storm (SMSWS between 34-47 knots)
- e) Severe Cyclonic Storms (SMSWS between 48-63 knots)
- f) Very Severe Cyclonic Storms (SMSWS between 64-119 knots) and
- g) Super Cyclonic Storm (SMSWS equal to or greater than 120 knots).

Table 3 gives the convective systems formed over Arabian Sea and Bay of Bengal for the recent years from 1988 to 2007 as deduced by IMD together with the MOK date for that year. From the table it can be seen that the formation of severe cyclonic storm (SCS) or very severe cyclonic storms (VSCS) either in the Arabian Sea or the Bay of Bengal is quite conducive for an early MOK, as this helps in building up moisture over the peninsular India region much more rapidly and promotes instability in the troposphere. Even a deep depression (DD) formed over the Arabian Sea can lead to substantially increased integrated water vapour over the peninsular India region. On the other hand, convective systems formed over the Bay of Bengal irrespective of whether they are DD, SCS or even VSCS do not create much of a moisture build up over the peninsular region and hence they do not induce an early MOK (Figure 2).

### **4. Role of the tropical Indian Ocean, El Nino, La Nina, Positive and Negative Indian Ocean Dipoles on the tropical convective maximum**

Table 1 shows years with an early, normal or delayed MOK during 1974-2009. Table 2 further classifies these three categories of years using the method of Meyers et al (2007) into pure El Nino, La Nina, positive IOD and negative IOD events in order to see how these climate modes might impact

on MOK. Meyer et al (2007) used a new statistical method based on ocean physical mechanisms that identifies when positive and negative phases of the El Nino Southern Oscillation and IOD occur, thus classifying the various events for the period 1876 to 1999.

In the present study, we have used only those years which could be classified to a high degree of certainty as El Nino, La Nina, positive or negative IOD in making the various composites used in the present study and we have considered the period from 25 May to 7 June as normal MOK. From the table it can be seen that during the period (1901-1998), there were only three early MOK of which two were associated with La Nina (1933, 1949) and one was with a positive IOD (1961). In contrast, out of the 21 delayed MOK years, one third (7) occurred during positive IOD years and 6 occurred during El Nino years, with 3 associated with La Nina conditions (Table 2).

There have been several studies on the role of the tropical Indian Ocean (TIO), Indian Ocean Dipole and El Nino and La Nina on the monsoon activity over the Indian subcontinent with contradicting results. While some studies using general circulation models suggest that the Pacific Ocean SSTs only generate the monsoon anomalies similar, there other studies ( Zhu and Houghton, 1996, Terray et al, 2003, 2005) which show that the TIO SST causes significant changes in the Indian monsoon. The strongest interannual relationship between TIO SST and the monsoon has been found on the biennial time scale, as shown the tropospheric biennial oscillation (TBO) (Meehl, 1987, 1997, Meehl and Arblaster, 2002).

In the recent years, IOD has generated considerable interest in TIO studies. In some studies, IOD is considered as local ocean atmosphere coupled phenomena, whose evolution is usually independent from Pacific Influence (Behera et al., 1999, Rao et al., 2002). However several others (Allan et al., 2001, Xie et al., 2002, Krishnamurty and Kirtman, 2003) have shown that there is a strong relationship between IOD and ENSO.

Several studies have also explored the climate impact of southern Indian Ocean SST. Observational and modeling studies (Reason, 1998, 2001, 2002; Behera and Yamagata, 2001) have revealed a positive relationship between extratropical Indian Ocean SST and African rainfall. Nicholls (1989) has showed that southern Indian Ocean SST influences Australian rainfall. Zhu and Houghton (1996) found that the variability of Asian summer monsoon is sensitive to the conditions of SST in the tropical southern Indian Ocean. Terray et al., (2003) found that SST in the southeast Indian Ocean during boreal winter, when linked to the IOD pattern described Behera and Yamagata (2001) and to ENSO, is an important predictor for the Indian summer monsoon.

Following on from their earlier work, Terray et al., (2005) showed that the southern Indian Ocean plays an important role in the ENSO - Monsoon relationship. They emphasized the role played by

southeastern Indian Ocean SST in maintaining the overlying atmospheric circulation pattern, which interacts with ENSO and convection over the maritime continent region and in turn maintains the existing SST anomalies.

In the present study we have looked at the role of maritime continent region on the monsoon onset over Kerala. This area is bounded  $6^{\circ}$  S –  $6^{\circ}$  N ;  $111^{\circ}$  E –  $141^{\circ}$  E (please see figure 1). In order to assess the importance of tropical convection over this maritime region, we have looked into the role of SST, precipitation and outgoing long wave radiation over this region on MOK. Figure 2a gives the SST and rainfall over this region and figure 2b gives the SST and OLR over this area including the maritime continent region for the study period. An analysis of the SST, rainfall and OLR over the maritime continent region revealed that the both the OLR (rainfall) over this region is positively (negatively) significantly correlated with MOK.

### **5. Moisture build up over the peninsular region**

The integrated columnar water vapour (IWV) has been found to be a useful parameter for identifying the MOK by several authors (PM84; 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 region bounded by  $0^{\circ}$  –  $15^{\circ}$  N;  $70^{\circ}$  E –  $90^{\circ}$  E. 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 3 (bold line), after superposing the onset dates of all the years for the study period. From the figure (bold line) 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 (PM84; Simon et al., 2006). In order to consider the role that the different types of convective systems formed over the Arabian Sea and the Bay of Bengal might play in the moisture build up over peninsular India, Figure 3 also plots the IWV for some selected years. The most interesting feature is the build up of moisture over peninsular India during the formation of these systems over the Arabian Sea and the Bay of Bengal.

In order to consider possible relationships with ENSO and IOD events on the moisture build up, the IWV has been plotted for some individual events and for some cases where both ENSO and IOD occurred together. From Figure 4, it can be seen that the moisture build up over peninsular India increased more during a La Nina year as compared to other years. The minimum build up in moisture took place during the concurrent El Nino and positive IOD year.

## 6. Cross equatorial flow:

The warm pool in the Indian Ocean attains temperatures of more than 30°C around the time of MOK. A region of high SST such as this Indian Ocean warm pool (Seetharamayya and Master, 1984; Joseph, 1990) can create large scale moisture convergence, deep convective clouds and lowering of the surface pressure, all of which are favourable for MOK (Joseph et al., 1994). Ramesh Kumar and Schluessel (1998) have shown that an early peaking of SST in the Arabian Sea will help in the development of low pressure over this area and thus help create a stronger than average inter-hemispheric pressure gradient and strong cross equatorial flow (CEF), and thus conditions conducive for an early onset over the Indian subcontinent.

To see how this parameter can vary, Figure 5a gives the daily CEF derived from the 850 hPa meridional wind averaged over 5°S-5°N; 45°E-55°E from 1<sup>st</sup> April to 30<sup>th</sup> June for the composite years with early MOK, normal MOK, delayed MOK (see Table 1 for the years used to form the composite in each case). From the figure it can be clearly seen that the CEF is much stronger during an early MOK as compared to normal and delayed MOK, with the delayed MOK being the weakest. A delayed peaking of SST over the Arabian Sea results in a weaker inter-hemispheric pressure gradient, which in turn will cause a weaker CEF, hence leading to a delayed MOK.

Figure 5b plots the same information as Figure 5a except that the influence of ENSO and the IOD are considered by plotting the CEF for a year with a pure positive IOD (1983), a year with a pure negative IOD (1985), a pure El Nino year (1987), a pure La Nina year (1973), a year with a concurrent positive IOD and El Nino (1991), and a year with a concurrent negative IOD and La Nina (1975). From the figure, it can be clearly seen that the CEF is stronger during the negative IOD year (1985) than either the El Nino or the La Nina year. This pattern of CEF matches well with the pattern for the early MOK composite (see Figure 5a). The combined impact of a positive IOD and El Nino results in much weaker inter-hemispheric pressure gradient, which in turn will cause a weaker CEF, which in turn will result in a delayed MOK as happened in the case of 1997, where MOK was on 9<sup>th</sup> June, this CEF pattern matches reasonably well with the delayed MOK composite as shown in figure 5a.

## 7. Strength of the Monsoon Hadley Cell Circulation:

The strengths of the monsoon Hadley Cell (MHC) for different conditions are presented in figure 6. The convection in the east and south east Arabian sea gives rise to a local Hadley circulation with an 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 to 55° E and 10° S to 10° N (we denote this by  $V_{850}$ ) shown in figure 1 (as box a). The upper



branch of the MHC is taken as the average of the meridional wind speed at 200 hPa over the region  $45^{\circ}$  E to  $75^{\circ}$  E and  $20^{\circ}$  S to equator (we denote this by V200) shown in Figure 1 (as box b). The intensity of the MHC is then determined by the difference between the lower and upper branches of the MHC ( $V_{850} - V_{200}$ ).

It is clearly seen that the MHC begins to strengthen about 5 pentads prior to MOK during a La Nina year (figure 6) and hence it might be possible to use this as a potential predictor for MOK. The MHC remained strong even two pentads after the MOK in the case of the La Nina year (1973). The strength of MHC was weak during the concurrent El Nino and positive IOD year (1991), which suggests that El Nino and the positive IOD may play an important role in modulating the strength of the MHC, thus resulting in a delayed MOK.

### **8. Strength and Depth of the Westerlies**

Rao (1976) has shown that the monsoonal westerlies increase in depth and strength with the MOK. We have used NCEP/NCAR reanalysis zonal wind data to monitor the vertical structure of the horizontal wind in the box ( $5^{\circ}$  N –  $10^{\circ}$  N;  $70^{\circ}$  E –  $85^{\circ}$  E) to check for the strength and depth of the westerlies following Joseph et al., (2006). We have also used the criteria of Joseph et al., (2006) that the 6 m/s wind in the above box should occur to at least the 600 hPa level in order for the date to be considered as MOK. Figures 7 and 8 show vertical sections of the zonal wind for various years from which it is apparent that easterly winds occur longer prior to MOK during years that are El Nino, a concurrent positive IOD and El Nino, or a positive IOD as compared to years that are La Nina, a concurrent negative IOD and La Nina, or a negative IOD. For the latter three groups of years, weak westerlies are present in the lower levels several days prior to MOK. For example, for the positive IOD year of 1983 (Figure 7), the IMD declared that MOK occurred on 13<sup>th</sup> June whereas for the negative IOD year of 1985 (Figure 8), the IMD declared MOK was on 28<sup>th</sup> May and the westerlies persisted in strength and height for a fortnight after the onset date. In the case of the La Nina year (1973), similar strong and deep westerlies persisted for two weeks. These results are in agreement with study of Ananthakrishnan et al., (1968) who indicated that in years of normal or delayed MOK, there was a sudden weakening of the upper tropospheric westerlies over north India at the time of the onset. In case of early MOK, they found that the westerlies persisted in strength for a fortnight after onset. In the case of El Nino, positive IOD and concurrent El Nino and positive IOD years, easterlies or weak westerlies prevailed prior to MOK (figures 7 and 8). Thus, it is apparent that the combined impact of the El Nino and positive IOD is to delay the MOK, by decreasing the strength and depth of the monsoonal westerlies.

### **9. Composite SST anomalies for different composites:**

Using the composite dates in Table 1, the SST mean of the pre-monsoon season (March to May) for the early and delayed MOK were determined. The SST anomaly pattern for the delayed minus early MOK composite (figure 9a) shows some similarities to the SST anomaly pattern for the El Nino minus La Nina composite for this season (figure 9b), consistent with the earlier results of Joseph et al., (1994). The difference in SST anomalies between the positive IOD minus the negative IOD composite (figure 10a) also shows a similar pattern to that of the El Nino minus La Nina, except that larger positive anomalies are observed over the central and eastern equatorial Pacific ocean. In case of the difference in concurrent El Nino and PIOD minus the concurrent La Nina and NIOD there are significant differences, the most important being in the central and northern Arabian Sea (figure 10b), an area thought to be important for the Indian monsoon. These large positive SST differences in the Arabian Sea, together with the negative SST differences here between the delayed and early MOK SST differences (figure 9a) highlight the important role that the Arabian sea SST anomalies play on the MOK. If the SST is high in the North Indian Ocean and Arabian Sea in particular during the pre-monsoon season, then these conditions are conducive for developing low pressure over the area, thus creating a greater inter-hemispheric pressure gradient and strong cross equatorial flow, all of which are conducive for early MOK (Ramesh Kumar and Schluessel, 1998).

On the other hand, relatively large negative SST differences occur over the western tropical Pacific in the delayed minus early MOK composite (figure 9a). Using a 'cold only' AGCM experiment for the west Pacific ocean region, Soman and Slingo (1997) showed that even small amplitude warm SST anomalies can play a major role in delaying MOK. These results are consistent with that of Joseph et al., (1994) who obtained the strongest correlations between MOK and SST over the west Pacific, just north of equator. The slightly warmer and larger area of positive SST anomalies near and south of the equator in the tropical southeast Indian Ocean (figure 9a), suggests that convection stays over the southeast Indian Ocean longer than normal and thus delays the tropical convergence zone from advancing into the Indian subcontinent and establishing MOK. This result agrees with Joseph et al (1994) who suggested that if the equatorial convective maximum is near and south of the equator in the Indian Ocean, then the MOK is delayed by several days.

### **10. Composite OLR anomalies for different composites:**

With the exception of the year 1978, the mean monthly OLR data for June 1974 to December 2009 has been used to consider the pre-monsoon convective activity over the Indo-Pacific Oceanic region from 30° E to 60° W and 30° S to 30° N. The difference in OLR anomalies for the delayed minus early MOK composites (figure 11a) for the pre-monsoon season show a similar pattern to the

difference composite between El Nino and La Nina (figure 11b) except that the magnitudes of the latter differences are larger everywhere. Consistent with Ju and Slingo (1995) and Soman and Slingo (1997), these results suggest that the tropical convective maxima occurs over the eastern equatorial Indian Ocean region near Indonesia region for both the early MOK and La Nina composites (figures not presented). A large positive convective anomaly is observed in the El Nino minus La Nina composite (figure 11b) over the region of the tropical convective maximum in the southern Bay of Bengal and equatorial west Pacific region, thus indicating its significant influence on MOK.

The large positive convective anomalies in these regions imply a suppression of convection in these regions which results in a delayed MOK. In the case of the positive IOD minus the negative IOD composite (figure 12a), the large positive anomalies shift to the central Pacific Ocean. In the concurrent El Nino and positive IOD minus the La Nina and NIOD case (figure 12b), the positive anomalies shift to the Maritime Continent region. The tropical convective maximum (negative anomalies) which is usually observed in the Indonesian region is now observed over the central equatorial Pacific Ocean. The convective maximum is usually observed over the southern Bay of Bengal and the Indonesian region in an early MOK composite, whereas convection there is weak during the normal MOK composite and the maximum shifts to the central or eastern Pacific Ocean in a delayed MOK composite (figures not presented), indicating their significant influence on MOK. Further, the intensity of the tropical convective maxima during the early MOK is more than that for the normal MOK composite (figure not presented)

## 11. Correlation between MOK and SST

In order to look into the role of the pre-monsoon SST on MOK, we calculated the correlation coefficient between them for different study periods such as for the entire period of 109 years (1901-2009), the first epoch (1901-1950), the second epoch (1951-2009) and recent decades (1974-2009). Table 4 gives the MOK for the different time frames. From the table it can be seen that mean MOK date for the 109 years (1901-2009) is 1<sup>st</sup> June, with a standard deviation of 7.35 days. In the case of the first epoch (1901-1950), the mean MOK is 3<sup>rd</sup> June and the standard deviation is 7.08 days whereas for the second epoch (1951-2009), the mean MOK is 31<sup>st</sup> May and the standard deviation is 7.27 days. For the recent decades (1974-2009), the mean MOK is again 31<sup>st</sup> May but the standard deviation is quite low at only 6.05 days.

Figure 13 indicates large and spatially coherent relationships between MOK and SST for both the Indian and the Pacific Oceans for the pre-monsoon season for each epoch. In fact, these correlation patterns exist almost one season in advance of MOK. However, it can be seen that the correlation coefficients have changed with time over certain regions such as north Arabian Sea, the north west

Pacific Ocean, south equatorial Pacific Ocean etc. Further it can be seen that the correlation coefficients have become much more statistically significant in recent decades (1974-2009) as compared to the entire period of 109 years (1901-2009).

Large positive correlations between MOK and SST were found over the eastern equatorial Indian Ocean during the 1901-1950 epoch. This correlation decreased substantially during the next epoch, i.e. 1951-2009 indicating the significant role played by IOD events. Several studies have shown that the frequency of positive IOD events has been increasing in recent decades (1974-2009). The correlation between SST and MOK has also increased substantially over the southwest Indian Ocean during the epochs 1951-2009 and 1974-2009. This result agrees well with the study of Annamalai et al., (2005) who has shown the importance of this region for the MOK. Their study showed that when warm SST anomalies persist near and south of equator in the Indian Ocean during boreal spring, there is a delay in the northward migration of the deep moist layer and in the formation of the low level jet. Furthermore, they showed that this southwest Indian Ocean warming effect lingers into early summer and significantly delays MOK by a week.

Yuan and Chong Yin (2008) have shown that during the 1948-1969 period, the IOD and ENSO events were independent of each other, but that after the 1970's they tended to occur together. They attributed this to the fact that the warmer SST's around the Maritime Continent give rise to anomalous low level convergence and that this intensified convergence apparently increases the SST linkage between the eastern equatorial Indian Ocean and western Pacific Ocean, thereby encouraging an IOD and ENSO event to occur together.

## **12. Conclusions:**

The inter-annual variations of MOK for the study period revealed that El Nino, La Nina, positive IOD, negative IOD and concurrent years play a significant role in altering the MOK. Based on the analyses of in situ, satellite and reanalysis products, an attempt has been made to assess their influence. The present findings point to the role of enhanced (suppressed) convection in the maritime continent region being conducive for early (delayed) MOK. Warm SST anomalies near or south of the equatorial Indian Ocean may delay the advancement of the tropical convergence zone into the subcontinent and thus may delay the MOK. Another remarkable feature is that the easterlies persist longer several days prior to MOK during an El Nino, a positive IOD or a concurrent El Nino and positive IOD year than for other years. In the case of La Nina, negative IOD and concurrent La Nina and NIOD years, weak monsoonal westerlies were prevalent in the lower levels several days prior to MOK.

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**Table 1**

Monsoon Onset dates (MOK) used for making different composites, namely, early, normal and delayed

| Early |                | Normal |                | Delayed |                |
|-------|----------------|--------|----------------|---------|----------------|
| Year  | MOK date (IMD) | Year   | MOK date (IMD) | Year    | MOK date (IMD) |
| 1990  | 19 May         | 1975   | 31 May         | 1979    | 13 June        |
| 2001  | 23 May         | 1976   | 31 May         | 1983    | 13 June        |
| 2004  | 18 May         | 1977   | 30 May         | 1995    | 8 June         |
| 2009  | 23 May         | 1980   | 1 June         | 1997    | 9 June         |
|       |                | 1981   | 30 May         | 2003    | 8 June         |
|       |                | 1982   | 1 June         |         |                |
|       |                | 2000   | 1 June         |         |                |
|       |                | 2008   | 31 May         |         |                |



**Table 2**

Years of positive and negative IOD events, and El Niño and La Niña years based on DMI and Niño-3 indices are classified into early, normal and delayed MOK for the period 1901-1998. Normal MOK is considered as the period from 25 May to 7 June. Concurrent El Niño and PIOD events as well La Niña and NIOD are shown in bold faces.

| MOK     | El Niño  | La Niña   | Positive IOD  | Negative IOD   |
|---------|--|---|---|--|
| Early   | -  | 1933, 1949  | 1961  | -  |
| Normal  | <b>1902</b> ,<br>1911,1914,<br><b>1963</b> , 1965,<br><b>1982</b> , 1986,<br>1987, <b>1991</b> | <b>1909</b> ,<br><b>1910,1917</b> ,<br><b>1928</b> , 1938,<br><b>1950</b> , 1964,<br>1973, <b>1975</b> , 1988 | <b>1902</b> , 1919,<br>1926, 1944,<br>1945, 1946,<br><b>1963, 1982</b> ,<br><b>1991</b> | <b>1909</b> ,<br><b>1910,1917</b> ,<br><b>1928, 1950</b> ,<br>1974, <b>1975</b> ,<br>1980, 1985,<br>1989, 1992 |
| Delayed | <b>1905,1923</b> ,<br>1930,<br>1940, <b>1972</b> ,<br><b>1997</b>                              | 1903, <b>1906</b> ,<br><b>1942</b> ,  | <b>1905, 1923</b> ,<br>1935,<br>1967, <b>1972</b> ,<br>1983,<br><b>1997</b>             | <b>1906</b> , 1930,<br><b>1942</b> , 1958,<br>1968   |
| Total   | 15   | 15  | 17  | 16   |

**Table 3**

Years with systems in Arabian Sea, Bay of Bengal according to Mausam. M and J stands for the months of May and June respectively. DD stands for Deep Depression; CS stands for Cyclonic Storm and SCS stands for Severe Cyclonic Storm and VSCS stands for Very Severe Cyclonic Storm.

| Year | AS                                | BB  | MOK  |
|------|-----------------------------------|---|------|
| 1989 | ---                               | 23-27M Balasore <b>SCS</b> (17 N 90 E)        | 03 J |
| 1990 | ---                               | 05-11M Machilipatnam <b>SCS</b> (10 N 85.5 E) | 19 M |
| 1991 | ---                               | 31 M – 2J Bangladesh coast (14 E 90 E)        | 02 J |
| 1992 | ---                               | 16-19 M Myanmar coast                         | 05 J |
| 1993 | ---                               | ---   | 28 M |
| 1994 | ---                               | 29 A – 03 M <b>VSCS</b> (8 N 94 E)            | 28 M |
| 1995 | ---                               | 5-7 M <b>DD</b> 8-10 M <b>DD</b> 14-17 M      | 05 J |
| 1996 | ---                               | 7-8 M <b>DD</b> Bangladesh -Myanmar coast     | 03 J |
| 1997 | ---                               | 15-20 M <b>SCS</b> Bangladesh coast           | 09 J |
| 1998 | 28 M <b>DD</b> (14 N 60 E)        | 17-20 M <b>SCS</b>                            | 02 J |
| 1999 | 16-22 M <b>VSCS</b> (12.5 N 72 E) | ---   | 25 M |
| 2000 | ---                               | ---   | 01 J |
| 2001 | 21-28 M <b>VSCS</b> (13.5 N 69 E) | ---   | 23 M |
| 2002 | 6-10 M <b>CS</b> (11 N 67 E)      | 11-12 M <b>DD</b> (13.5 N)                    | 29 M |
| 2003 | ---                               | 10-19 M <b>VSCS</b> Myanmar coast             | 08 J |
| 2004 | 5-10 M <b>SCS</b> (11.5 N 73 E)   | 16-19 M <b>VSCS</b> Myanmar coast             | 18 M |
| 2005 | ---                               | ---   | 05 J |

**Table 4**

MOK Statistics for different epochs

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| Period    | Mean   | Standard Deviation | Earliest MOK<br>& year | Delayed MOK<br>& year |
|-----------|--------|--------------------|------------------------|-----------------------|
| 1901-2009 | 1 June | 7.35 days          | 11 May (1918)          | 18 June (1972)        |
| 1901-1950 | 3 June | 7.08 days          | 11 May (1918)          | 15 June (1915)        |
| 1951-2009 | 31 May | 7.27 days          | 14 May (1960)          | 18 June (1972)        |
| 1974-2009 | 31 May | 6.05 days          | 18 May (2004)          | 13 June (1979)        |

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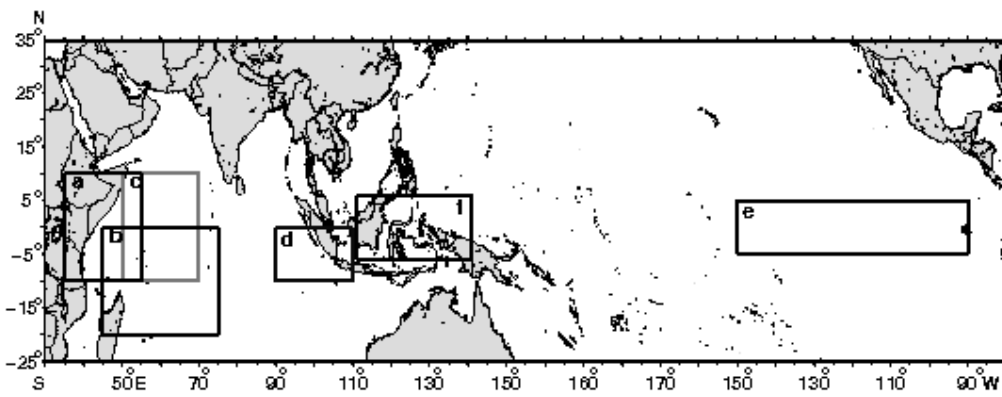
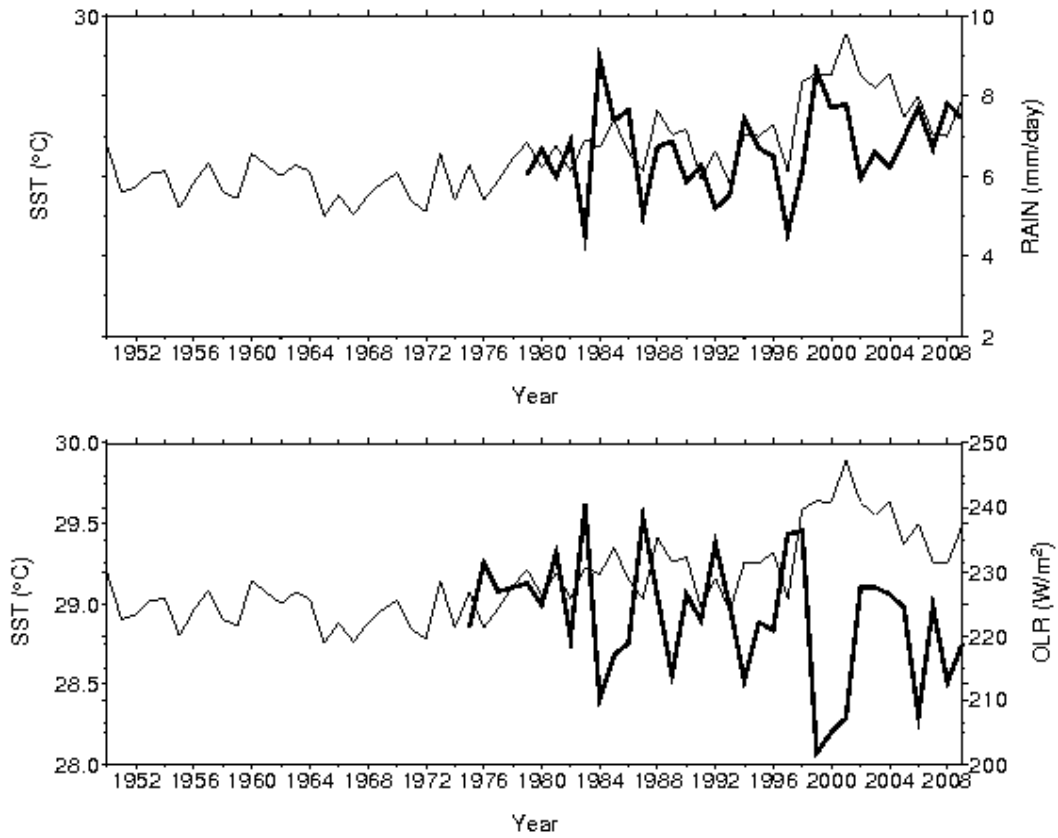
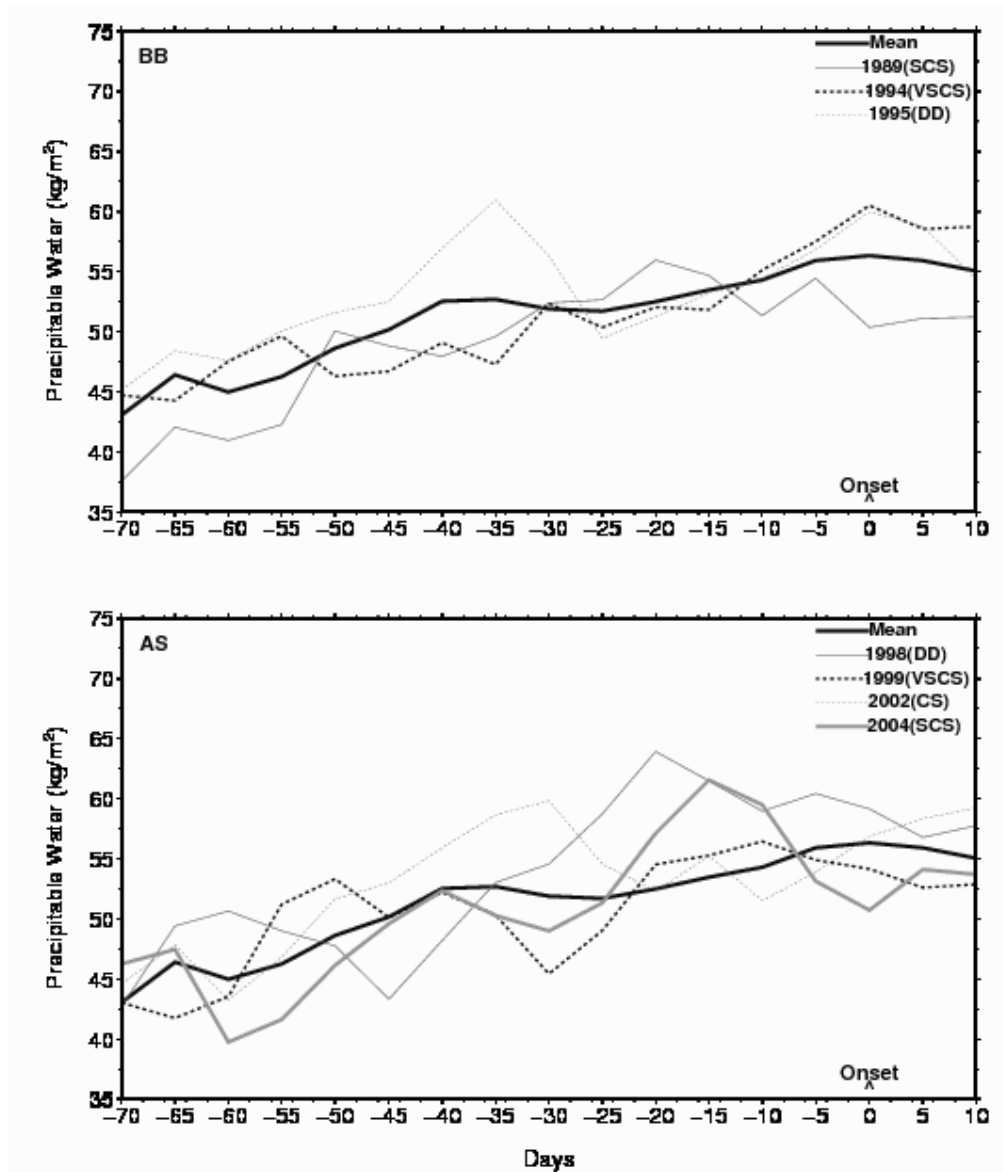


Figure 1: Study areas used for averaging various parameters. See text for more details. a) lower branch of monsoon Hadley cell b) upper branch monsoon Hadley cell c) western box used for computing SST for DMI d) eastern box used for computing SST for DMI and e) Nino 3 box used for computing El Nino and La Nina index f) Maritime Continent Region



**Figure 2:** a) SST and Rainfall over the Maritime Continent Region as described in the text. b) The SST and OLR distribution over the Maritime continent region for the study period.



**Figure 3:** Moisture build up over peninsular India from -70 days upto 10 days after MOK, with MOK day as 0, during the formation of convective systems over Arabian Sea (AS) and Bay of Bengal (BB) for selected years. DD stands for Deep Depression; CS stands for Cyclonic Storm and SCS stands for Severe Cyclonic Storm and VSCS stands for Very Severe Cyclonic Storm.

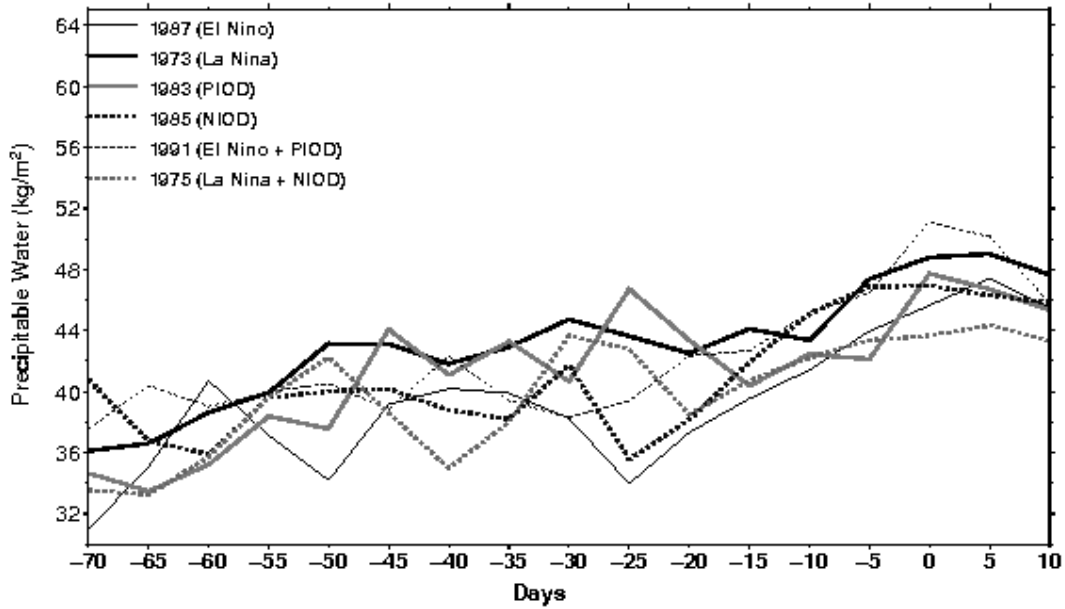


Figure 4: Moisture build up over peninsular India from -70 days upto 10 days after MOK, with MOK day as 0, during the pure EI Nino (1987), La Nina (1973), PIOD (1983), NIOD (1985), concurrent EI Nino and PIOD (1991) and concurrent La Nina and NIOD (1975).

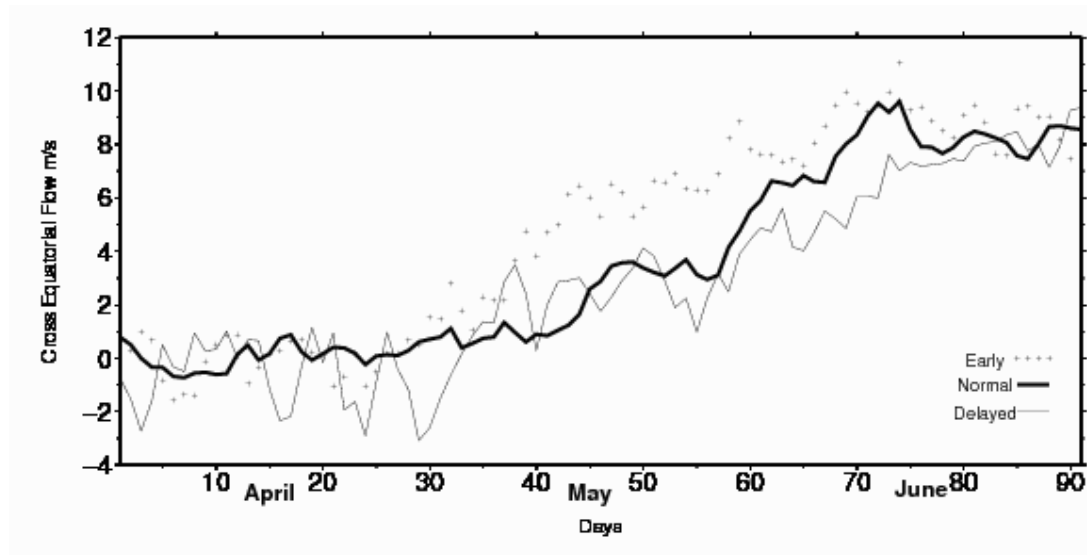


Figure 5a: Cross Equatorial Flow averaged over the region ( $5^{\circ}$  S -  $5^{\circ}$  N ;  $45^{\circ}$  E -  $55^{\circ}$  E) for three different MOK's composites based on Table 1 - 1) Early MOK 2) Normal MOK and 3) Delayed MOK



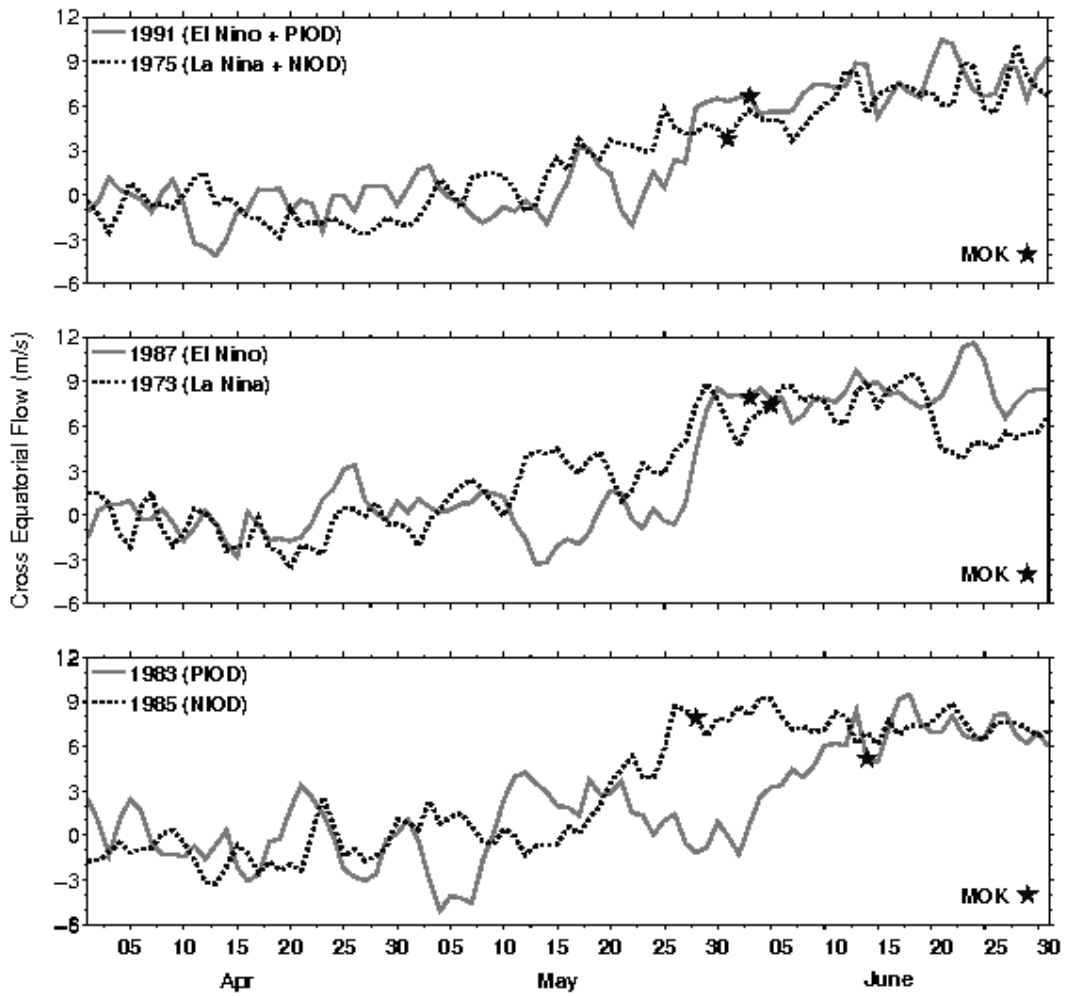


Figure 5b: Cross Equatorial Flow averaged over the region ( $5^{\circ}$  S -  $5^{\circ}$  N ;  $45^{\circ}$  E -  $55^{\circ}$  E) for different MOK's (MOK date is represented by star ) conditions 1) concurrent El Niño and PIOD (1991) and concurrent NIOD and La Niña conditions (1975) 2) pure El Niño (1987) and pure La Niña (1973) 3) PIOD(1983) and NIOD (1985)

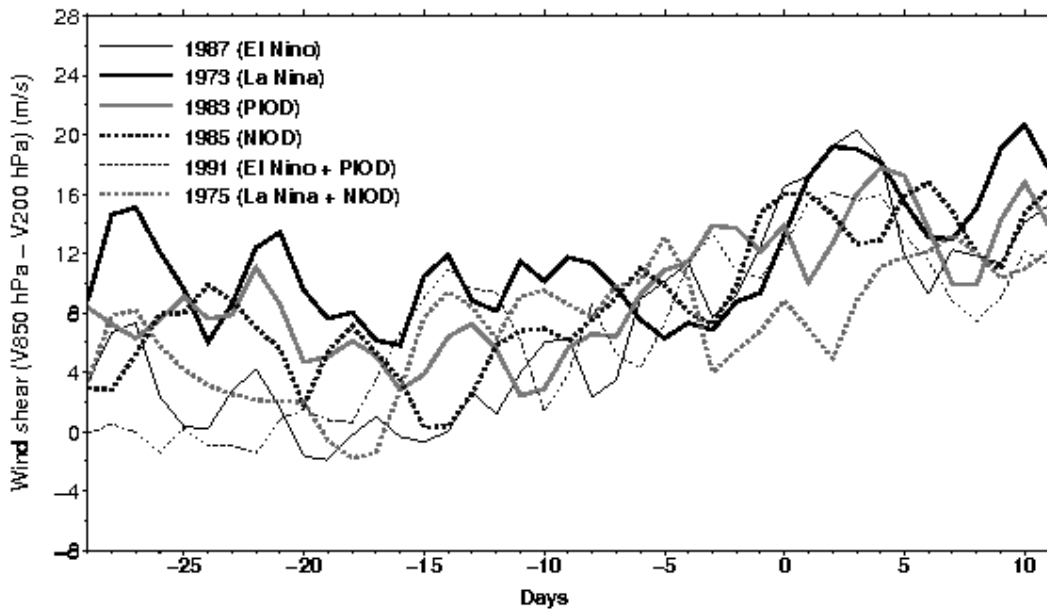


Figure 6. Daily strength of the MHC (V850 - V250) in m/s from -30 days to + 10 days for a PIOD (1983), NIOD (1985), pure El Nino year (1987), pure La Nina year (1973) , concurrent El Nino and PIOD (1991) and a concurrent La Nina and NIOD (1975)..

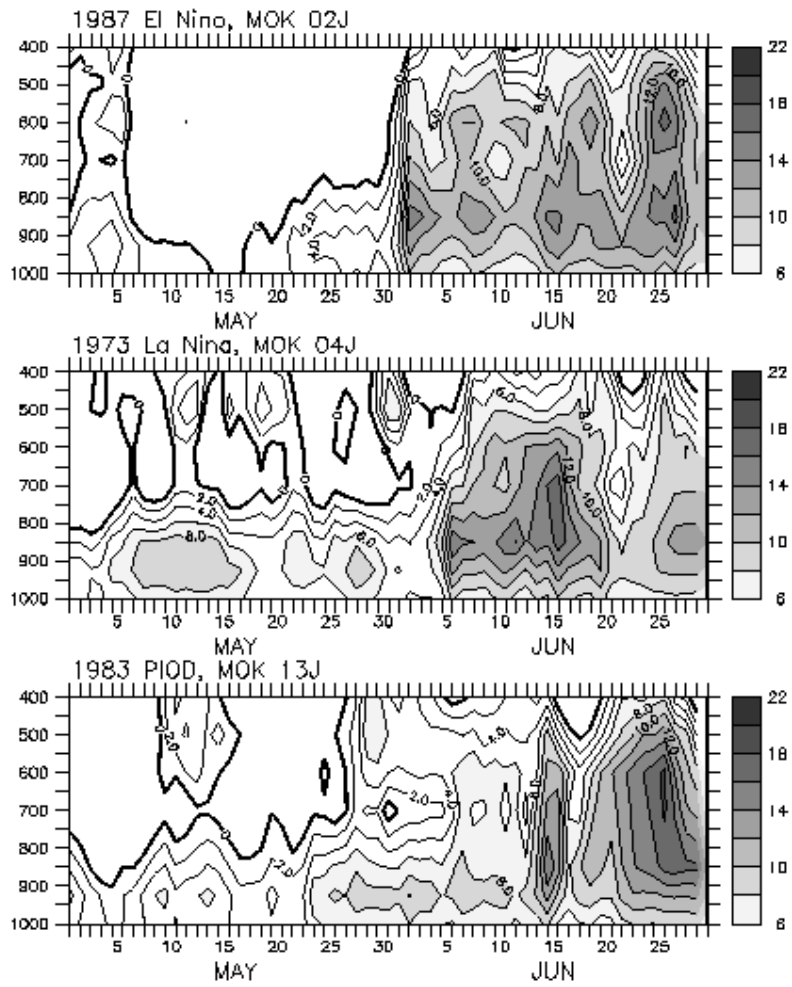


Figure 7: Vertical variation of the zonal (U) wind averaged over the box bounded by latitudes  $5^{\circ}$  N and  $10^{\circ}$  N and longitudes  $70^{\circ}$  E and  $85^{\circ}$  E for El Niño (1987), La Niña (1973) and PIOD (1983) years

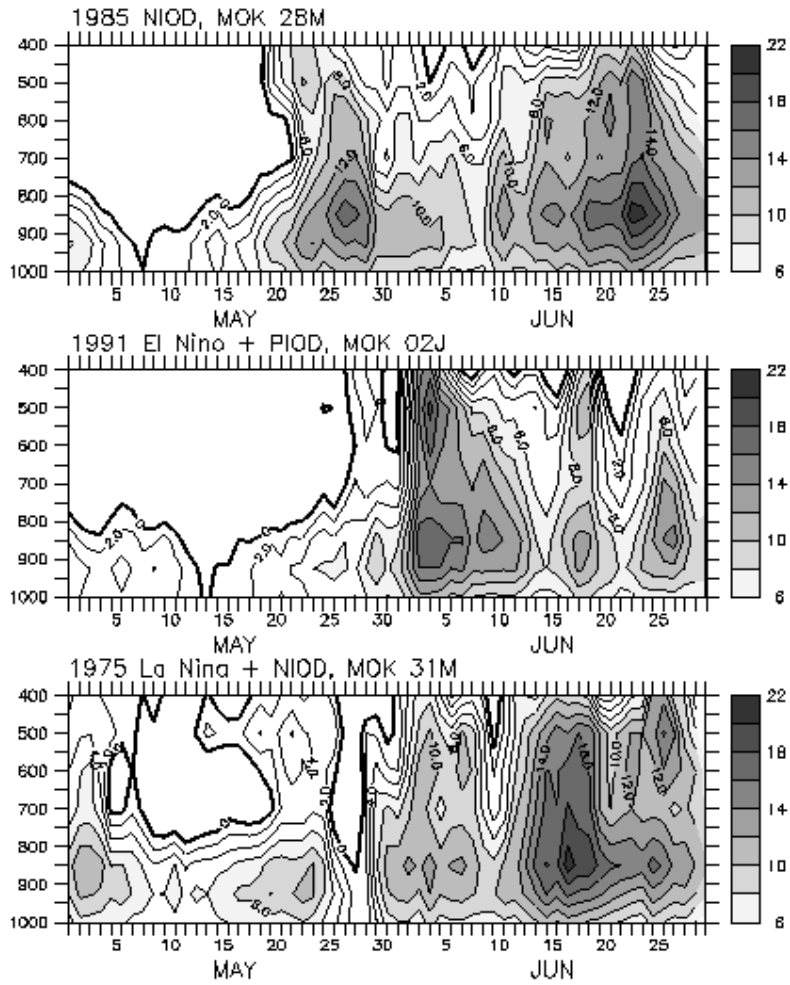


Figure 8: Vertical variation of the zonal(U) wind averaged over the box bounded by latitudes  $5^{\circ}$  N and  $10^{\circ}$  N and longitudes  $70^{\circ}$  E and  $85^{\circ}$  E for NIOD (1985), concurrent El Nino and PIOD (1991) and concurrent La Nina and NIOD (1975)

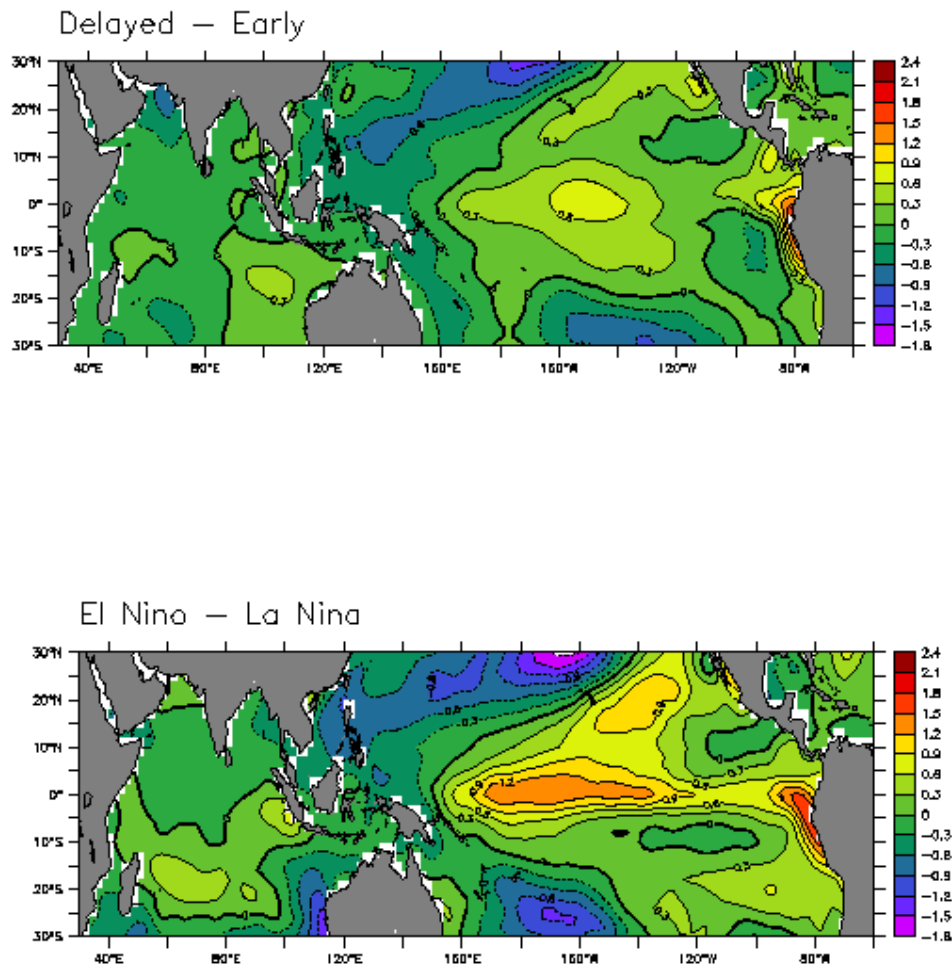


Figure 9. Difference in SST anomaly for the pre monsoon season (March to May) for the a) delayed minus early composite and b) El Niño minus La Niña Composite

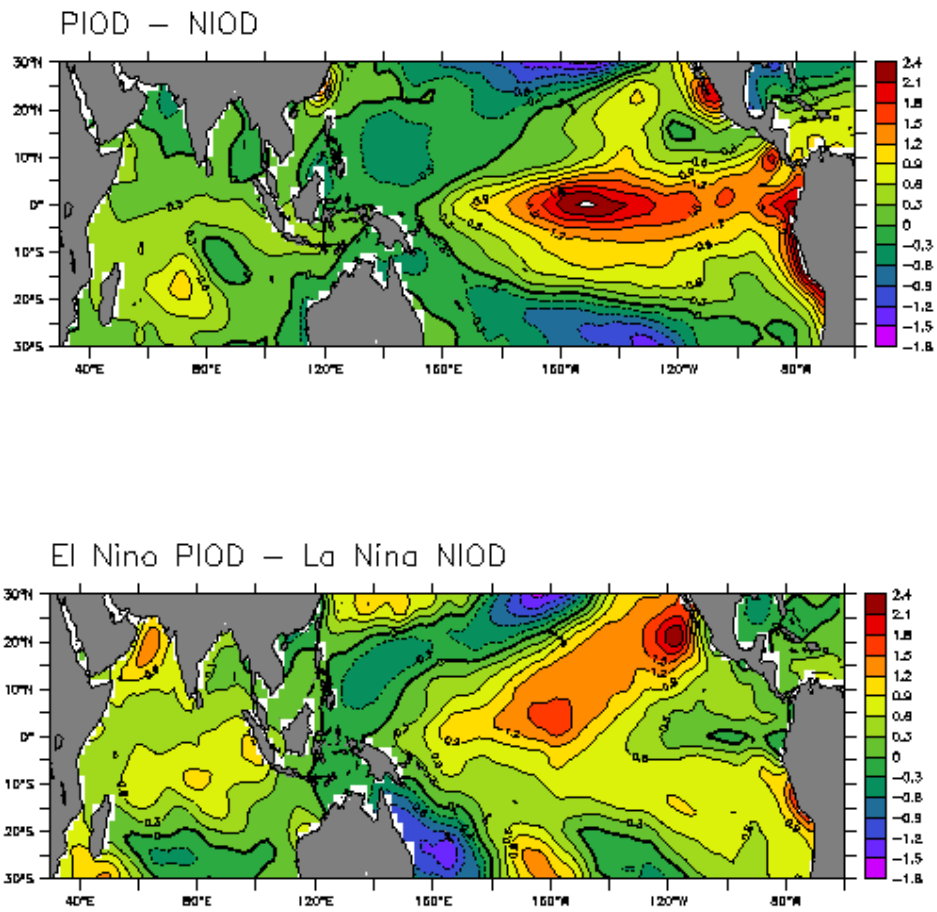


Figure 10. Difference in SST anomaly for the pre monsoon season (March to May) for the a) PIOD minus NIOD and b) Concurrent PIOD and El Niño minus concurrent NIOD and La Niña

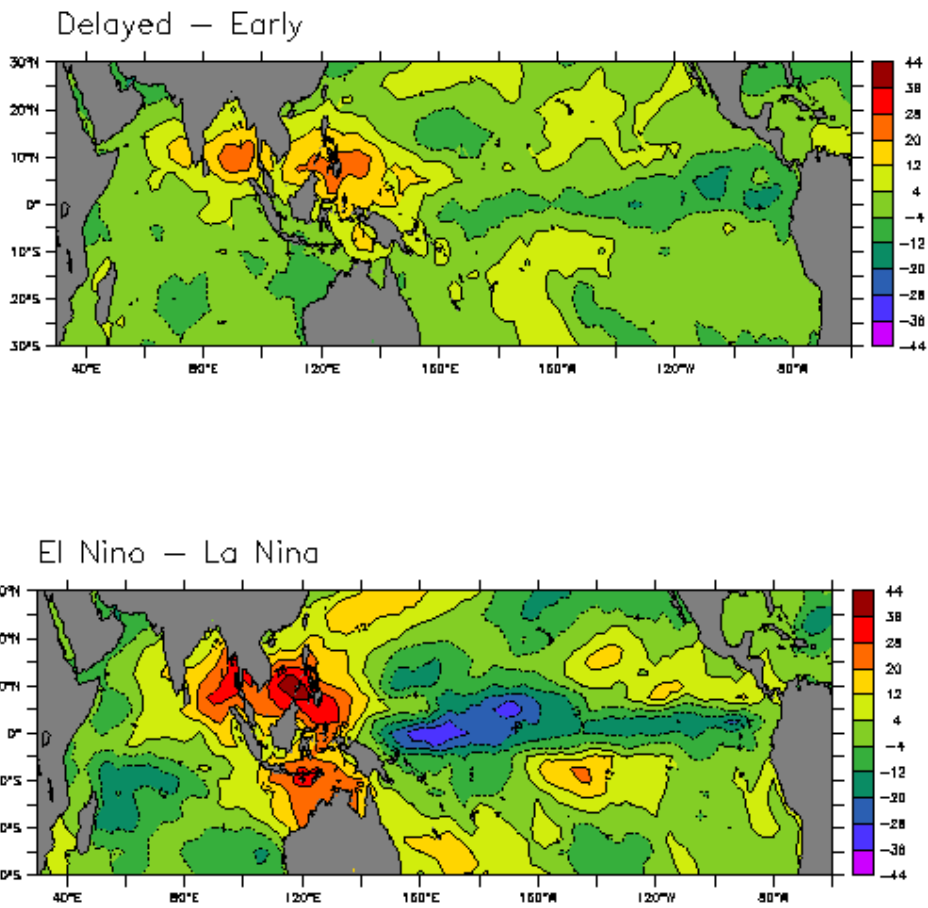


Figure 11. Difference in OLR anomaly ( $W/m^2$ ) the pre monsoon season (March to May) for the a) delayed minus early MOK composite and b) El Nino minus La Nina composite

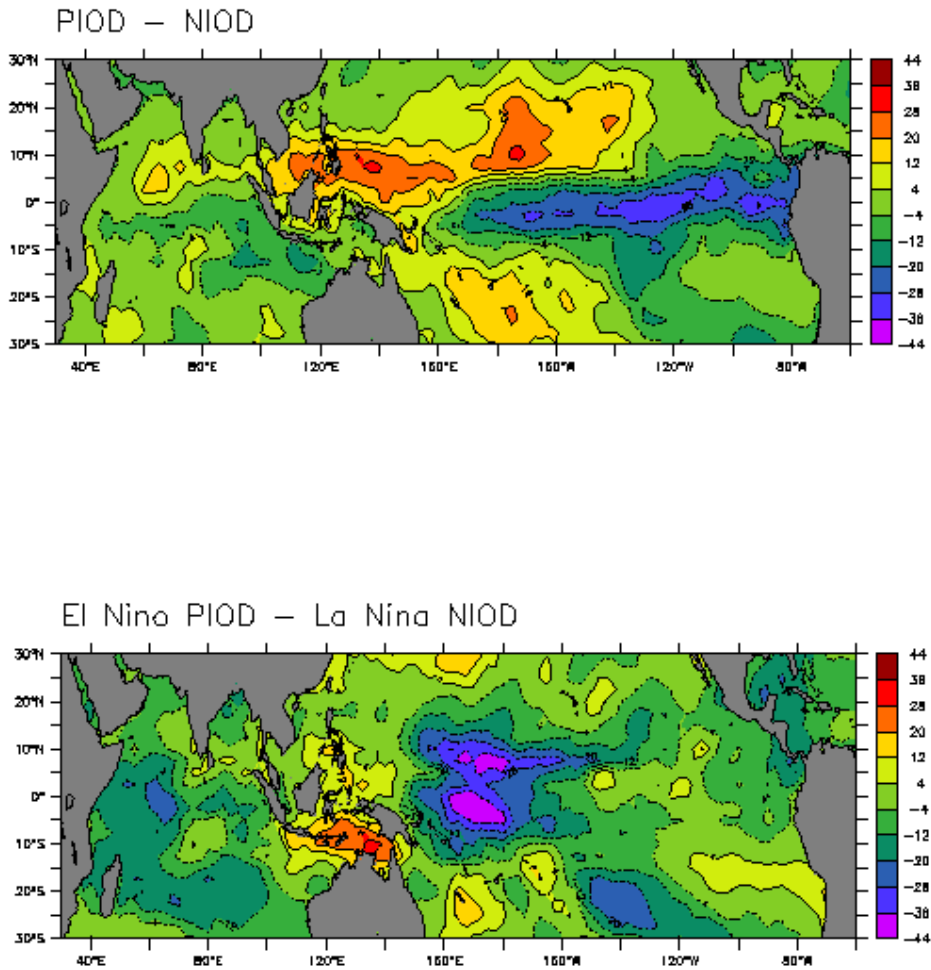


Figure 12. Difference in OLR anomaly ( $W/m^2$ ) for the pre monsoon season (March to May) for the a) PIOD minus NIOD composite and b) concurrent PIOD and El Niño minus concurrent NIOD and La Niña.



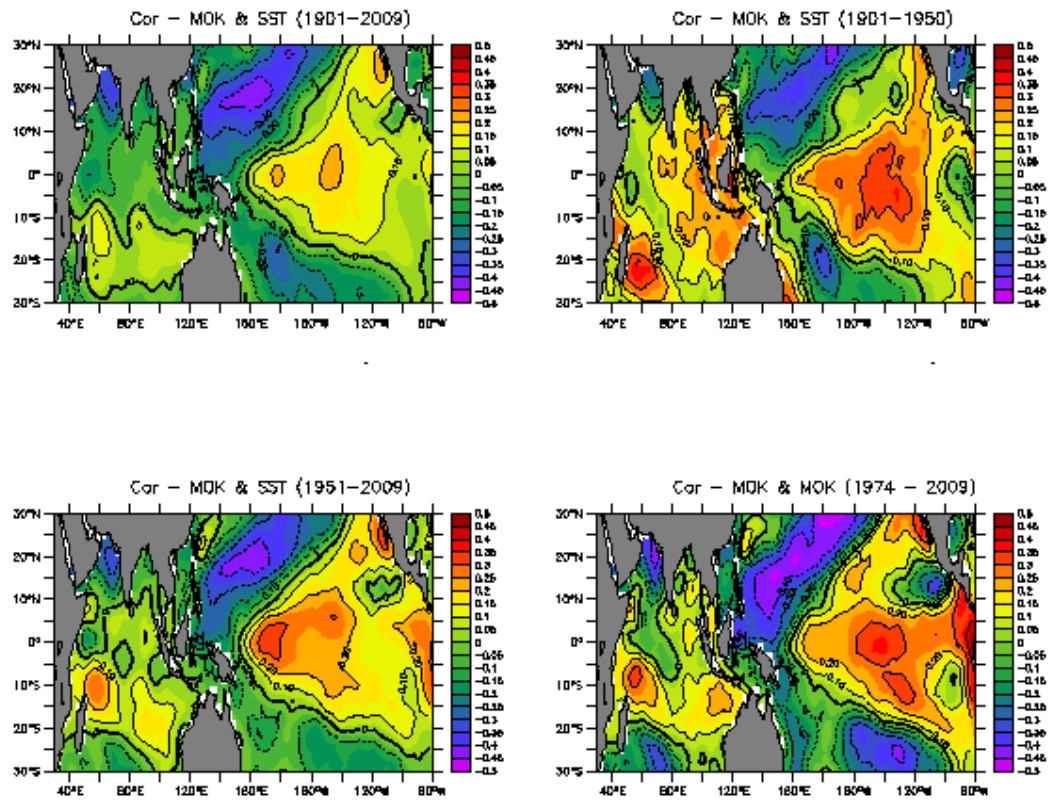


Figure 13: Correlation coefficient between the pre monsoon season (March-may) SST and the date of MOK of the same year as given by the India Meteorological Department for the periods a) 1901-2009 b) 1901-1950 c) 1951-2009 and d) 1974-2009.