

Is an Onset Vortex Important for Monsoon Onset over Kerala?

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Abstract

Inter-annual variability in the formation of the mini-warm pool (sea surface temperature > 30⁰ C) over the south eastern Arabian Sea and its role in the formation of the monsoon onset vortex has been examined using two independent sea surface temperature data sets. The role of sea surface temperature, convection, integrated columnar water vapour and the low level jet in the setting up of the monsoon onset over Kerala (MOK) is examined. It is found that the monsoon onset vortex which forms over the south eastern Arabian Sea region upsets the delicate balance between convection, build up of moisture, and strengthening and deepening of the westerlies over the south eastern Arabian Sea that is needed for the setting up of the MOK. Thus, the formation over the south eastern Arabian Sea of a monsoon onset vortex is not necessarily conducive for MOK. Furthermore, it is shown that a mini-warm pool over the southeastern Arabian Sea is not a sufficient condition for the formation of a monsoon onset vortex because such a warm pool is present over this region during most of the years, but an monsoon onset vortex does not necessarily form over there. A more detailed study is needed to understand the role of the mini-warm pool region in the setting up of the MOK as it is much more complex phenomenon involving several ocean-atmospheric processes at both regional and global level.

1. Introduction

In the Arabian Sea, the annual cycle of sea surface temperature (SST) is characterized by two cooling regimes during the winter and summer monsoons, and two heating regimes during the transitions between the monsoons (Rao and Sivakumar, 1999). The heating regime during the pre-monsoon season, resulting in the formation of a mini-warm pool, has received little attention. Studies (Ananthkrishnan 1964; De and Joshi, 1995) have shown that during most of the years, a monsoon onset vortex forms over the warm Arabian Sea waters and helps in the progress of monsoon over the Indian subcontinent.

Using MONEX – 79 data, Seetaramayya and Master (1984) showed the presence of a mini- warm pool (SST > 30.5⁰ C) in the south eastern Arabian Sea (SEAS) prior to the onset of the summer monsoon, and coinciding with the genesis of the onset vortex. The importance of this mini-warm pool over the Arabian Sea was amply demonstrated by Kershaw (1985, 1988) in the prediction of the monsoon onset. Joseph (1990) reported the presence of this mini-warm pool a week prior to the monsoon onset over Kerala (MOK) in analysis of the period 1961-1972. Rao et al. (1994) described the synoptic scale evolution of the mini-warm pool at selected locations during the pre-monsoon onset of MONEX-79 and evaluated the role of the local air-sea fluxes and entrainment for its formation.

The date the monsoon starts over Kerala is variable and can be categorised as early, normal or delayed. Similarly, advance of the monsoon over the Indian subcontinent is slow, rapid or normal depending upon the synoptic situation over the Arabian Sea and Bay of Bengal. Monsoon lows/depressions act as onset vortices or help further the advance of the monsoon over the country. These synoptic systems which form in the monsoon flow and the semi- permanent systems which establish as seasonal features contribute significantly to the onset and advance of the monsoon over India and the associated rainfall (Desai and Kulkarni, 2001).

Synoptic systems which form in the northern part of the hiatus region help in terminating this hiatus and allow the northern limit of the monsoon to progress further. Since the mean monsoon current is strongest at 850 hPa, the low level wind circulation is examined herein at this level to study the role of this current in the formation of the monsoon onset vortex (MOV). The presence of such a vortex over the Arabian Sea helps in the systematic northward progression of the MOK whereas its absence may delay the northward movement of the northern limit of the monsoon

A few years ago, a major field experiment, called the Arabian Sea Monsoon Experiment (ARMEX), was conducted under the Indian Climate Research Programme (ICRP) to investigate the role of warm SSTs in the SEAS on the onset process of the Indian summer monsoon. These field experiments, together with modeling studies, have generated new ideas regarding the role of the warm SSTs in the SEAS.

More details of some the ARMEX results can be found in the review by Vinayachandran et al., (2007). Hareesh Kumar et al., (2005) looked at the characteristics of the Arabian Sea mini-warm pool during May 2003 as part of the ARMEX. Their study showed that the mini-warm pool attained its maximum size about 8 days prior to the MOK. Both the satellite and in situ data from the INS *Sagardhwani* research vessel showed the presence of anomalous warm waters in excess of 31°C over the eastern Arabian Sea.

Sanilkumar et al., (2004) studied the presence of anomalous water in the SEAS and its potential role in the formation of the monsoon onset vortex by conducting an experiment onboard INS *Sagardhwani* during the middle of May, 2000. Their study revealed the presence of a mini-warm pool with temperature in excess of 30.25°C along 9°N between 68° and 75.5° E during the pre-onset phase of the southwest monsoon. They also reported that this mini-warm pool region coincided with a region of relatively low surface salinity (35.2 PSU).

Inter-annual variability in the mini-warm pool has been studied by Deepa et al., (2010) by analysing the NCEP fortnightly SST data over the east central Arabian Sea for the months of May and June (monsoon onset period) during 1992 to 2003. They found that strong inter-annual variability exists in the formation and intensification of the mini-warm pool. For example, out of the twelve years, only 1994, 1998 and 2001 showed that a monsoon onset vortex (MOV) formed on the northern flank of the low level wind jet and the northern region of the mini-warm pool region. In an earlier study of the monsoon during the 2000-2005 period, Deepa et al., (2007) suggested that the MOV only forms when the wind jet at 850 hPa is on the northern flank of the mini-warm pool. They further stated that an onset vortex may not form if this jet is weak, or the shear line of the jet is absent over the mini-warm pool, or if the warm pool itself is absent. Their study further showed that a mini-warm pool was essential for the formation of an MOV during the six seasons they analysed.

Using the 5th generation PSU/NCAR Mesoscale Model (MM5) version 3 (Dudhia et al., 2004), Deepa et al., (2011) modelled the influence of the Arabian Sea mini-warm pool on MOV formation. Their study showed that the mini-warm pool plays a key role in the development of the onset vortex. If the SST was too cold, the model failed to simulate the onset vortex thereby underlining the importance of the mini-warm pool for vortex formation. Their study further found that the mini-warm pool in the east central Arabian Sea favoured the formation of the onset vortex by increasing the horizontal shear and decreasing the vertical wind shear.

There have been several studies related to the synoptic features present during the onset phase of the summer monsoon over India. Ananthkrishnan et al., (1968) summarized many of these studies in a Forecasting Manual of the India Meteorological Department (IMD). Krishnamurti et al., (1981) observed that a MOV develops in the region of highest SST coinciding with the MOK. Using 120 years (1877-

1996) of data, Rao and Sivakumar (1999) showed that most of these onset vortices form in the SEAS during May, or in the eastern Arabian Sea during June.

Seetaramayya and Master (1986) suggested that fluxes of latent and sensible heat, and momentum at the ocean atmosphere interface, may play an important role in the initial establishment of large-scale low-level convergence and convection over the cyclogenesis region. Rao and Sivakumar (1999) analysed the geographical correspondence between the mini-warm pool and the MOV for the 30-year period (1961-1990). Their study revealed that even though the mini-warm pool forms during most of the time over the Arabian Sea, the MOV does not occur every year. Their study did not comprehensively address the issue of non-formation of this vortex over the Arabian Sea.

In the present study we use the criteria of Ananthkrishnan et al (1968) for the definition of Onset Vortex. They defined Onset Vortex as a synoptic disturbance in a trough of low pressure forming in the SEAS. This Onset Vortex has been studied in more detail by Krishnamurti et al (1981) who coined the term Monsoon Onset Vortex (MOV) to denote a cyclonic storm formed in the SEAS after an event which occurred on 11 June 1979 during summer Monsoon Experiment (MONEX) year. In the present study we use the term MOV for any synoptic disturbance which forms in the SEAS region.

The motivation for the present study stems from the fact even though there are several theories and hypotheses about the MOK, very little is known about the role of the mini-warm pool or the MOV over the SEAS on the MOK. Here the evolution of the mini-warm pool is examined using two different independent SST datasets, namely, a) pentad HOAPS SST data (Andersson et al., 2010) and b) daily TMI SST (Wentz et al., 2000) for the study period and its impact on MOV formation and the MOK considered..

3. Data

The study area extends from 48° E to 80° E and from 6° N to 24° N. In order to assess the relationship between the mini-warm pool and the MOV on the MOK, this study examines the Hamburg Ocean Atmosphere Parameters and Fluxes from Satellite (HOAPS 3) dataset for the study period (1989-2005). Important changes in HOAPS-3 from the previous versions 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 wind speed at a resolution of 0.25° x 0.25° for the period 1987 – 2005. More details of this dataset can be found in Andersson et al., (2010).

SST from the TRMM Microwave Imager (TMI) can be used for the study of the monsoon onset period as the Arabian Sea remains quite cloudy during May and June, hindering SST studies using infra-red based satellite data. Further, TMI SST compares well with in situ SST over the Arabia Sea (Hareesh Kumar et al., 2005). Studies by Wentz et al., (2000) have shown that TMI SST is not affected by the clouds, aerosols and atmospheric water vapour. SST data obtained during cloudy conditions is useful for the study of convection (especially for the formation of convective systems such as the monsoon onset vortex). Bhat et al., (2004) showed that the TMI SST has a cold bias in areas of deep convection or when surface wind speeds are more than 10 ms^{-1} . In the present study, 8 years (1998-2005) of daily TMI SST data are analysed for the months of May and June prior to consider any associations with the MOV and the MOK.

The outgoing long-wave radiation (OLR) used is the interpolated OLR data set. More details of the data set can be had from Liebmann and Smith, (1996). The MOK dates used in the present study were obtained from the India Meteorological Department. Data on the convective systems over the SEAS for the particular years (1998, 1999 and 2001) that are studied in detail, are taken from Mausam (1999, 2000 and 2002)

Daily wind data at 850 hPa were obtained from the NCEP/NCAR Reanalysis data (Kalnay et al. 1996) 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, the most reliable ones.

The position of the MOV along with its location and intensity and track details have been extracted from the IMD journal, Mausam for the study period. Further we have also extracted more details of the formation of the synoptic disturbances (MOV) and its intensification and these details are presented in section 4.1 for the MOV years (1998, 1999 and 2001).

4. Results and Discussion

Table 1 gives the MOK dates for the period 1988 – 2005, according to the India Meteorological Department, along with the position and intensity of convective systems over the Arabian Sea on that date. The mean MOK, according to the IMD, is the 1st of June, with a standard deviation of 8 days (Syam et al., 2011). In the present study, the earliest MOK was on 18 May 2004 and the most delayed MOK was on 9 June 1997. An analysis of the MOV and the mini-warm pool over the Arabian Sea revealed that a vortex formed in only 3 years (1998, 1999 and 2001) during the study period. On the other hand, a mini-warm pool was observed during most of the years (70% of the cases).

4.1 Convective systems over the Arabian Sea

The India Meteorological Department has classified convective systems over the North Indian Ocean as follows:

- a) Low Pressure System (wind speed less than 17 knots)
- b) Depression (wind speed between 17 and 27 knots)
- c) Deep Depression (wind speed between 28 and 33 knots)
- d) Cyclonic Storm (wind speed between 34 and 47 knots)
- e) Severe Cyclonic Storm (wind speed between 48 and 63 knots)
- f) Very Severe Cyclonic Storm (wind speed between 64 and 119 knots)
- g) Super Cyclonic Storms (wind speed equal to or more than 120 knots)

Table 1 gives the convective systems formed over the Arabian Sea during the study period just prior to MOK. Only for 5 years out of 18 were convective systems present over the Arabian Sea at the time of MOK. In two cases, they formed well in advance whereas for the other three years, namely, 1998, 1999 and 2001, vortex formation was quite close to the MOK. For these three years, a brief life history of the various convective systems formed over the south eastern Arabian Sea is given. More details of these convective systems can be had from the official journal of the India Meteorological Department (Mausam, 1999, 2000 and 2002). Figures 1a-c give the position and intensity of the various convective systems formed over the Arabian Sea during the MOV years, 1998, 1999 and 2001 respectively.

4.1.1 MOV during 1998 (28 May, 1998)

A well marked low pressure system formed over 14° N; 60° E over central Arabian Sea on the evening of 27th May, 1998. It rapidly developed into a deep depression and lay centred around 13.5° N; 60° E. Over the next day, this deep depression moved in a westward direction to be centred near 13.5° N; 59° E. After further westward movement, it weakened into a low pressure system over western part of the central Arabian Sea by the morning of 29th May morning (Fig. 1a).

4.1.2 MOV during 1999 (16-22 May, 1999)

A well marked low pressure system formed over the Laccadive area and nearby Kerala coast on 15th May, 1999 (Fig. 1b). It intensified into a depression around 1200 GMT on 16th May near 12.5° N ; 72° E about 300 kms west southwest of Mangalore. Subsequently, it rapidly intensified into a cyclonic storm (estimated central pressure of 996 hPa) and lay centred around 14.5° N; 70.5° E, or about 350 kms west-southwest of Panjim, Goa. It then moved north-westwards and intensified into a severe cyclonic

storm at 0900 UTC of 17th May, 1999 and centred near 15^oN; 69.5^oE, or about 670 kms south-south-west of Veraval. By 0300 UTC on 18th May, it had intensified into a very severe cyclonic storm (VSCS, estimated central pressure of 976 hPa) and was centred near 17^oN; 67.5^oE, or about 500 kms southwest of Veraval. Between 1000 UTC and 1130 UTC of 20th May, it crossed the Pakistan coast about 80 kms west of Naliya. Thereafter, it moved north-north-eastwards and weakened into a cyclonic storm over northwest Pakistan and the adjoining parts of Rajasthan and Kutch, with its central region near 25^oN; 69^oE at 0300 hrs UTC of 21st May. It continued to move in this direction and weakened into a deep depression by 0300 hrs UTC of 22nd May, and centred near 27^oN; 71^oE, or about 50 kms southwest of Jaisalmer, Rajasthan. Further weakening into a depression occurred by 1200 hrs UTC of 22nd May when it was centred near 27.5^oN; 72^oE. Ongoing weakening over northwest Rajasthan occurred during the rest of 22nd May and 23rd May.

4.1.3 MOV during 2001 (21-28 May, 2001)

A low pressure area formed over southern parts of the central Arabian Sea on 21st May 2001 and became a well marked low pressure system in the same evening over the east central Arabian Sea (Fig. 1c). It evolved into a depression by 1200 UTC of 21st May near 13.5^oN; 69^oE and then into a deep depression in the early morning of 22nd May. Moving in a north-eastward direction, it intensified into a cyclonic storm by 0300 hrs UTC of 22nd May and lay centred near 14^oN; 71.5^oE. It then remained stationary, intensifying into a severe cyclonic storm by 1500 hrs UTC 22nd May. Further intensification into a very severe cyclonic storm occurred by 2100 hrs UTC of 22nd May when it was centred near 14.5^oE; 71.5^oE. Over the next few days, it weakened into a severe cyclonic storm while moving north-westwards. It then weakened into a cyclonic storm while moving in north-eastwards and then further into a deep depression by 1200 hrs UTC of 28th May when it was centred near 21^o N; 68.5^oE. Figure 1c gives the track and position of the convective system from 21-28 May, 2001.

4.2. Mini Warm pool

Sadler et al., (1987) showed that the North Indian Ocean warms rapidly from March onwards. By May, a large area in the North Indian Ocean attains SSTs above 29.5^o C, and this area can be called the Indian Ocean warm pool (Joseph et al., 1994). By April, the warmest area north of the equator is located in the North Indian Ocean and the SSTs continue to rise till the MOK in May-June. This region of warm SSTs in the Arabian Sea can create large-scale moisture convergence, deep convective clouds, and a lowering of surface pressure, which can create conditions conducive for the formation of a monsoon onset vortex over this area. Furthermore, the Indian Ocean warm pool attains temperatures higher than 30^o C around the time of the MOK (Seetaramayya and Master 1984; Joseph 1990).

In their study on the inter-annual variability of the mini-warm pool and the monsoon onset vortex formation over the Arabian Sea for the period 1961-1990, Rao and Sivakumar (1999), found that there is a remarkable coincidence between the SST maxima (two weeks preceding the formation of an onset vortex). They also found significant differences in the intensity of the mini-warm pool. Their study did not, however, identify the reasons why the monsoon onset vortex was formed only in certain years and absent in the other years.

One of the questions addressed in this manuscript is whether a mini-warm pool is essential for the formation of a monsoon onset vortex over the south eastern Arabian Sea area. An analysis of the HOAPS SST data for the three case study years was performed. In 1998, the mini-warm pool formed over an extensive area of the Arabian Sea several pentads prior to the formation of a monsoon onset vortex there, but the convective system which formed over the Arabian Sea was only a deep depression. In 1999, the mini-warm pool was not as intense as that for the year 1998 but the convective system which formed over the Arabian Sea became a very severe cyclonic storm, indicating little or no influence of the mini-warm pool in this case. This result is in agreement with Ramesh Kumar and Syam Sankar (2010) who showed that it is not the SST alone but the environmental parameters such as low level vorticity, vertical shear of the horizontal wind between the lower and upper troposphere, and the mid-tropospheric relative humidity which play an important role in the formation of convective systems.

To address the issue of whether the mini-warm pool is important or not, SST conditions prevalent over the Arabian Sea during the months of May and June when the MOK takes place have been investigated. Figures 2-5 depict the mini-warm pool conditions over the Arabian Sea for 4 years, namely, three MOV years (1998, 1999 and 2001) and a year with no MOV and close to average MOK date (i.e. 2000 when MOK was on 1st June). The areal extent as well as the intensity of the mini-warm pool for about 12 days prior to MOK as well as prior to any formation of a monsoon onset vortex has been considered.

In the case of the a MOV year 1998, the mini-warm pool (figure 2) covered the entire study region with the warmest waters over the Somalia region as well as close to the west coast of India ($>31.5^{\circ}\text{C}$) (figure 2a) by 21st May. These conditions more or less remained similar on 22nd May (figure 2b). The intensity and areal extent increased substantially during 23rd and 24th May (figures 2c and 2d). On 25th May (figure 2e), the band of warmest waters off Somalia moved eastwards and merged with those off the west coast of India. A similar situation prevailed during 26th May (figure 2f) with the warmest waters off the west coast of India spreading northwards. The areal extent of the core of the mini-warm pool SST ($\text{SST} > 31^{\circ}\text{C}$) was maximum off the west coast of India, one day prior to the formation of a monsoon onset vortex (i.e. on 27th May; figure 2g) On 28th May, (the day the vortex formed; figure 2h), the

spread of the warm waters of the mini-warm pool was quite substantial. A deep depression formed over the south eastern Arabian Sea during this season.

In the case of 1999, when a very severe cyclonic storm formed over the south eastern Arabian Sea, the areal extent of the mini-warm pool was much reduced and only occurred on the peripheral regions of the study area (figure 3). It remained more or less the same throughout the next three days up to 13th May. On 14th May, the SSTs off the west coast of India slowly started increasing along a very narrow band with further small increases during 16th and 17th May. This scenario is in sharp contrast to the 1998 case, when the mini-warm pool occurred over the entire study area. Further, in 1998 only a deep depression formed over the study region, whereas in 1999, a very severe cyclonic storm occurred over the study area.

During the 2001 case (figure 4), the core of the mini-warm pool occurred mainly in the southern parts of the Arabian Sea, with the maximum intensity (SST > 32^oC) observed at two locations. These core mini-warm pool regions gained in intensity as well as areal extent during 16th and 17th May (figures 4b and 4c) . During 18th May (figure 4d), the core mini-warm pool was more off the west coast of India near Karnataka. During 19th and 20th May (figures 4e and 4f) , the SSTs off the entire west coast was more than 31^oC. On the day of the formation of the monsoon onset vortex (i.e 21st May; figure 1c), the largest mini-warm pool was off the central west coast of peninsular India near Goa.

There have been different definitions for the Mini warm pool region over the north Indian Ocean. Different authors (Seetaramayya and Master 1984; Joseph 1990; Rao and Sivakumar (1999); Sanil Kumar et al.,(2004) ; Hareesh Kumar et al., (2005); Deepa et al., (2010)) have used different thresholds of SST for the definition of mini warm pool and different regions (Arabian Sea, East Central Arabian Sea, SEAS .. etc). We are planning another study for objectively identifying Mini warm pool threshold, its location, its evolution, dissipation etc in more detail.

In order to better understand the role of the mini-warm pool on the MOK, TMI SST was examined from about 12 days prior to MOK for a normal year (MOK on 1st June in 2000). The areal extent of the mini-warm pool in this season was very less (figure 5) occurring only over and was only over small regions in the northern parts and in a small band off the Cochin coast during 25th of May. The areal extent of the mini-warm pool over the northern parts of the Arabian Sea increased during the next two to three days (i.e up to 28th May). However, off the west coast of India the mini-warm pool decreased in intensity on 29th May. On 30th May, the intensity of the mini-warm pool further decreased, especially over the northern parts. One day prior to the MOK date (i.e 31st May), the scenario remained more or less the same.

Thus, figures 2,3 and 4 indicate that the areal extent of the mini-warm pool was maximum during 1998, when only a deep depression formed over the study area. On the other hand, during the 1999 and 2001 seasons when the mini-warm pool areal extent and intensity were much less, stronger convective systems (severe cyclonic storm and a very severe cyclonic storm respectively) formed over the study area. These results are in agreement with Ramesh Kumar and Syam Sankar (2010) who found that there is no preferred range for the formation of cyclonic systems or severe cyclonic systems over the North Indian Ocean. They further found that warm SSTs alone are not sufficient for the formation of convective systems over the Bay of Bengal, atmospheric parameters such as low level vorticity, mid-tropospheric humidity and vertical wind shear all play an important role in the initiation and genesis of convective systems. This work suggests that a similar argument holds good for the south eastern Arabian Sea also.

Figure 6 depicts the mini-warm pool characteristics on the MOK date for all the above mentioned years, namely, three years (1998, 1999 and 2001) when a monsoon onset vortex formed and one year (2000) without an onset vortex. From the figure it can be seen that there is hardly any presence of a mini-warm pool during 1999 (an onset vortex year) and 2000 (a normal MOK year).

4.3 Outgoing Long-wave Radiation

Since the monsoon onset vortex usually forms in region of intense convective activity, another way to assess it is by means of OLR data. Rao et al., (1989) suggested that areas marked by persistent well below average values of OLR should be carefully watched as potential cyclo-genesis zones. In order to identify regions of intense convection, low values of OLR over the Arabian Sea (i.e. $OLR < 220 \text{ W/m}^2$) were identified. An example is Figure 7 which plots such low OLR values for 1st May upto 25th June, 1998 (this was a monsoon onset vortex season). It can be seen that intense convection developed over the south eastern Arabian Sea in the pentad when an onset vortex formed there (figure 7g). The convection remained more or less same during the next pentad (when the MOK occurred; figure 7h). Incidentally, the MOK during this year was on 2nd June or about 5 days after the occurrence of the onset vortex. However, the convective system was relatively weak and only a deep depression formed over the south eastern Arabian Sea.

In the case of 2001 (figure 8), strong convection occurred over the study region in the pentad centred on the onset vortex date (21 May, figure 8e). The convection further intensified as a very severe cyclonic system formed during this period. Another interesting aspect during this season was that there was only two days difference between the date of onset vortex formation and MOK date. This two day value is the smallest difference between the occurrence of the onset vortex and the MOK during 1989-2005. By comparison, the largest difference was 23 days which occurred in 2002.

During 1999 (another season with a monsoon onset vortex, figure not presented) the convection over the south eastern Arabian Sea started about 2 pentads prior to the onset vortex and further intensified during the pentad when this vortex formed. The convection was sustained until the MOK date which was earlier than average. During this season, the convection lasted for about two pentads after MOK. The convection over the south eastern Arabian Sea increased from 10th June and was sustained up to 20th June. By contrast in the normal MOK year (2000), the convection over the south eastern Arabian Sea was maximum about one pentad prior to MOK, agreeing with the Joseph et al., (2006) and Ramesh Kumar et al., (2009). The south eastern Arabian Sea region remained convectively active for about two pentads after the MOK pentad (figure 9).

4.4 Integrated columnar water vapour

Integrated columnar water vapour obtained from satellite data can also be used for identifying the monsoon onset vortex since mid-tropospheric humidity plays an important role in tropical cyclo-genesis (Gray, 1979). Pearce and Mohanty (1984) showed that prior to MOK, moisture build up takes place over the Arabian Sea region, helping synoptic systems and transient meso-scale systems to develop. Simon et al. (2003) found that the MOK occurs about 2.5 weeks after the peaking of the integrated columnar water vapour over the western Arabian Sea, except for the years when there was already a convective system over the Arabian Sea. They suggested that if a convective system forms in the Arabian Sea, it may upset the delicate balance of the moisture build up needed for the pre-conditioning needed for the MOK.

Using integrated columnar water vapour from the HOAPS III dataset, Ramesh Kumar et al (2009) found that there are three water vapour peaks prior to MOK; one at 14 pentads, the second one at 7-8 pentads, and the third one at 3-4 pentads. They further found that it is the Pre-Monsoon Water Vapour peak over peninsular India about 8 pentads prior to MOK which supplies the moisture needed for the pre-monsoon rainfall over peninsular India.

Figure 10 depicts the pentad mean values of the integrated water vapour over the south eastern Arabian Sea region from 1st May to 25th June of 1998 (an onset vortex season). Water vapour values above 50 mm are contoured in the figure. A sudden build up of moisture occurred during the 21 May and 26 May pentads (figures 10e and 10f respectively), especially over the southern parts of the south eastern Arabian Sea where the humidity values reached more than 80 mm. This type of situation is quite conducive for the formation of an onset vortex. Ramesh Kumar and Byju (2010) obtained similar results while studying the cyclonic system over this region for the 2004 season, where they found that the integrated water vapour increased by about 32% from the pre-disturbance condition to the depression stage.

The pentad mean values of integrated columnar water vapour for the period 1st May to 25th June of 2001 (an onset vortex season with a very severe cyclonic storm) is shown in figure 11. In this case, the water vapour values increased dramatically from one pentad prior to formation of the onset vortex to the formation date itself (figure 11d to 11e). A further increase occurred during the next pentad (figure 11f) followed by a decrease. Over the next two pentads, there was another strong increase in columnar water vapour values off the west coast of India (figures 11h and 11i).

In the case of a normal MOK year (2000, figure 12), the integrated columnar water vapour showed a substantial increase values off the west coast of India about two pentads prior to MOK (figure 12e). A further increase occurred during the pentad after the MOK (figure 11h), which may be related to the active monsoon conditions over peninsular India then. Thereafter, a decreasing trend occurred for the next few pentads (figures 12i-l).

These results therefore suggest that formation of a MOV either in the Arabian Sea or the Bay of Bengal prior to MOK is not conducive for MOK since this formation can upset the building up of moisture needed. There are then competing interests between the moisture needed for the convective system which forms either over the Arabian Sea or the Bay of Bengal, and the moisture build up over peninsular India needed for the MOK. On the other hand, if the MOV forms after MOK, it can help in the progress of the northern limit of the monsoon over India (Ananthakrishnan et al., 1968).

4.5. Low Level wind circulation at 850 hPa

Several authors (Fein and Kuettner, 1980; Krishnamurti et al 1981, 1985; Hui, 1980; Chen-Rui Rong, 1980) have examined the low-level circulation features prevailing at the time of the MOK, and the formation of the onset vortex over the Arabian Sea, using MONEX-79 meteorological observations. A common conclusion reached is that the incipient formation and development of an onset vortex is closely related to the characteristics of a low level wind jet. The onset vortex tended to form in the cyclonic shear over northern flank of the jet, followed by strengthening of the monsoon westerlies on its equator-ward side. Typically, the monsoon current or low level jet is strongest at 850 hPa.

Joseph and Sijikumar (2004) used a threshold of 7.5 ms^{-1} for the low level wind jet whereas a threshold of 8 ms^{-1} is used here with values above that plotted in figures 12-14. The winds were not at all organised in the pentads prior to the onset vortex formation or during MOK in the 1998 season (figures 13f and 13g respectively). However, the winds became much organised after MOK and the low level jet was present near the southern tip of India (figure 13h). Figures 13-15 indicate that there is large inter-annual variability both in the intensity and direction of the jet over the Arabian Sea from year to year. It is this intensity and orientation of the jet over the mini-warm pool area which helps determine whether an onset vortex will form or not as suggested by Deepa et al., (2007).

An analysis of the low level wind circulation at 850 hPa for the seasons with an onset vortex (figure 13 and 14) shows the significant role of the low level wind circulation, its intensity and orientation in the formation of the vortex as compared to the non-vortex year (figure 15). A cyclonic circulation on the northern flank of the jet is present in the 1998 and 2001 but not in the normal MOK year (2000). Consistent with Deepa et al., (2010), this result suggests that the strength and the direction of the low level wind circulation at 850 hPa plays a significant role in the formation of the onset vortex.

In the 2000 normal MOK season (figure 15), the low level jet was much better organised almost two to three pentads prior to MOK. This result agrees with Ramesh Kumar et al (2009) who found that there was strengthening and deepening of the westerly winds from three pentads prior to MOK date until MOK itself. For the other seasons (1998 and 2001), the presence of convective systems over the Arabian Sea (a deep depression in 1998 and a very severe cyclonic storm in 2001) leads to a change in the wind pattern prior to onset vortex formation as well as in the MOK. In both 1998 and 2001, the low level jets were much better organised over the south eastern Arabian Sea after the MOK (figures 13i-13l, 14f-14j respectively). Thus, it may be suggested that any convective system which forms over the south eastern Arabian Sea prior to MOK does not help in the strengthening and deepening of the monsoon westerlies, one of the necessary conditions for the setting up of an MOK

5. Conclusions:

Inter-annual variability in the formation of the mini-warm pool (sea surface temperature $> 30^{\circ}$ C) over the SEAS, and its role in the formation of the MOV, has been examined using two independent sea surface temperature data sets. The present study examined the role of sea surface temperature, convection, integrated columnar water vapour and the 850 hPa low level wind jet in the setting up of the MOK. The results suggest that an onset vortex which forms over the SEAS upsets the delicate balance between convection, build up of moisture, and strengthening and deepening of the westerlies over the south eastern Arabian Sea that is needed for the setting up of the MOK. Thus, our present study suggests that formation of an MOV over the SEAS is not necessarily conducive for MOK. The study further shows that a mini-warm pool over the SEAS is not a sufficient condition for the formation of an MOV, as a mini-warm pool is present over this region during most of the years, but an MOV does not necessarily form over there. The exact role of the mini-warm pool in the MOK needs to be studied further as it appears to be a highly complex phenomenon which involves several ocean-atmospheric processes at both regional and global scales.

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Figure Captions

Figure 1: Track of the convective systems over the Arabian Sea during the years a) 1998 b) 1999 and c) 2001 which formed prior to MOK. D stands for depression, 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. The thin line in the figure indicates the depression track and the thick or bold line indicates the storm track.

Figure 2: Daily mean SST over the Arabian Sea from the TMI data for the period a) 21 May b) 22 May c) 23 May d) 24 May e) 25 May f) 26 May g) 27 May h) 28 May i) 29 May j) 30 May k) 31 May l) 1 June for an MOV year and a DD is formed over SEAS for the year 1998. Mini warm pool with SST values greater than 30°C are shown

Figure 3: Daily mean SST over the Arabian Sea from the TMI data for the period a) 10 May b) 11 May c) 12 May d) 13 May e) 14 May f) 15 May g) 16 May h) 17 May i) 18 May j) 19 May k) 20 May l) 21 May for an MOV year and a VSCS is formed over SEAS for the year 1999. Mini warm pool with SST values greater than 30°C are shown.

Figure 4: Daily mean SST over the Arabian Sea from the TMI data for the period a) 15 May b) 16 May c) 17 May d) 18 May e) 19 May f) 20 May g) 21 May h) 22 May i) 23 May j) 24 May k) 25 May l) 26 May for an MOV year and a VSCS is formed over SEAS for the year 2001. Mini warm pool with SST values greater than 30°C are shown

Figure 5: Daily mean SST over the Arabian Sea from the TMI data for the period a) 20 May b) 21 May c) 22 May d) 23 May e) 24 May f) 25 May g) 26 May h) 27 May i) 28 May j) 29 May k) 30 May l) 31 May for an non MOV year and a normal MOK year (2000, MOK was 1st June). Mini warm pool with SST values greater than 30°C are shown

Figure 6: Daily mean SST over the Arabian Sea from the TMI data for the MOK date a) 2nd June, 1998 b) 25th May c) 1st June 2000 d) 23rd May 2001. Mini warm pool with SST values greater than 30°C are shown.

Figure 7: Pentad mean OLR over the Arabian Sea during the period a) 1 May b) 6 May c) 11 May d) 16 May e) 21 May f) 26 May g) 31 May h) 5 June i) 10 June j) 15 June k) 20 June l) 25 June for an MOV year and a normal MOK year (MOK was on 2nd June) with a DD formed over the SEAS region (1998). Only OLR values less than 240 Wm^{-2} are plotted. To differentiate active convection values than 200 Wm^{-2} are contoured and the contour interval is 20 Wm^{-2} .

Figure 8: Pentad mean OLR over the Arabian Sea during the period a) 1 May b) 6 May c) 11 May d) 16 May e) 21 May f) 26 May g) 31 May h) 5 June i) 10 June j) 15 June k) 20 June l) 25 June for an early MOK year (MOK was on 23rd May) and a MOV present. Only OLR values less than 240 Wm^{-2} are plotted. To differentiate active convection values than 200 Wm^{-2} are contoured, and the contour interval is 20 Wm^{-2} .

Figure 9: Pentad mean OLR over the Arabian Sea during the period a) 1 May b) 6 May c) 11 May d) 16 May e) 21 May f) 26 May g) 31 May h) 5 June i) 10 June j) 15 June k) 20 June l) 25 June for a normal MOK year (MOK was on 1^d June) and no MOV was present over SEAS. Only OLR values less than 240 Wm^{-2} are plotted. To differentiate active convection values than 200 Wm^{-2} are contoured and the contour interval is 20 Wm^{-2} .

Figure 10: Pentad mean PWAT over the Arabian Sea during the period a) 1 May b) 6 May c) 11 May d) 16 May e) 21 May f) 26 May g) 31 May h) 5 June i) 10 June j) 15 June k) 20 June l) 25 June for a normal MOK year (1998; MOK was on 2nd June) and an MOV (DD) was present. Only PWAT values more than 30 mm are plotted. To differentiate maximum PWAT regions values more than 50 mm are contoured, and the contour interval is 5 mm.

Figure 11: Pentad mean PWAT over the Arabian Sea during the period a) 1 May b) 6 May c) 11 May d) 16 May e) 21 May f) 26 May g) 31 May h) 5 June i) 10 June j) 15 June k) 20 June l) 25 June for an early MOK year (2001; MOK was on 23rd May) and an MOV (VSCS) was present. Only PWAT values more than 30 mm are plotted. To differentiate maximum PWAT regions values more than 50 mm are contoured, and the contour interval is 5 mm.

Figure 12: Pentad mean PWAT over the Arabian Sea during the period a) 1 May b) 6 May c) 11 May d) 16 May e) 21 May f) 26 May g) 31 May h) 5 June i) 10 June j) 15 June k) 20 June l) 25 June for a normal MOK year (2000; MOK on 1st June) and no MOV was present. Only PWAT values more than 30 mm are plotted. To differentiate maximum PWAT regions values more than 50 mm are contoured, and the contour interval is 5 mm

Figure 13: Pentad mean wind at 850 hPa over the Arabian Sea during the period a) 1 May b) 6 May c) 11 May d) 16 May e) 21 May f) 26 May g) 31 May h) 5 June i) 10 June j) 15 June k) 20 June l) 25 June for a normal MOK year (1998; MOK was on 2nd June) and an MOV (DD) was present. The colour bar is from 8 to 14 ms^{-1} with an interval of 1 ms^{-1} . The size of the standard vector is 10 ms^{-1} as shown in the figure

Figure 14: Pentad mean wind at 850 hPa over the Arabian Sea during the period a) 1 May b) 6 May c) 11 May d) 16 May e) 21 May f) 26 May g) 31 May h) 5 June i) 10 June j) 15 June k) 20 June l) 25 June for an early MOK year (2001; MOK was on 23rd May) and an MOV (VSCS) was present. The colour bar

is from 8 to 14 ms^{-1} with an interval of 1 ms^{-1} . The size of the standard vector is 10 ms^{-1} as shown in the figure

Figure 15: Pentad mean wind at 850 hPa over the Arabian Sea during the period a) 1 May b) 6 May c) 11 May d) 16 May e) 21 May f) 26 May g) 31 May h) 5 June i) 10 June j) 15 June k) 20 June l) 25 June for a normal MOK year (2000; MOK was on 1st June) and no MOV was present. The colour bar is from 8 to 14 ms^{-1} with an interval of 1 ms^{-1} . The size of the standard vector is 10 ms^{-1} as shown in the figure

Table 1: Position and intensity of the convective system over AS along with MOK date for the study period. The data on convective system and the MOK date are based on the information provided by the India Meteorological Department. DD means Deep Depression, CS means Cyclonic Storm, SCS means Severe Cyclonic Storm, VSCS means Very Severe Cyclonic Storm respectively.

Year	MOK	Position of the convective system over AS
1988		---
1989	03 June	---
1990	19 May	---
1991	02 June	---
1992	05 June	---
1993	28 May	---
1994	28 May	---
1995	05 June	---
1996	03 June	---
1997	09 June	---
1998	02 June	28 May DD (14°N ; 60°E)
1999	25 May	16-22 May VSCS (12.5°N ; 72°E)
2000	01 June	---
2001	23 May	21-28 May VSCS (13.5°N ; 69°E)
2002	29 May	06-10 May CS (11°N ; 67°E)
2003	08 June	---
2004	18 May	05-10 May SCS (11.5°N ; 73°E)
2005	05 June	---

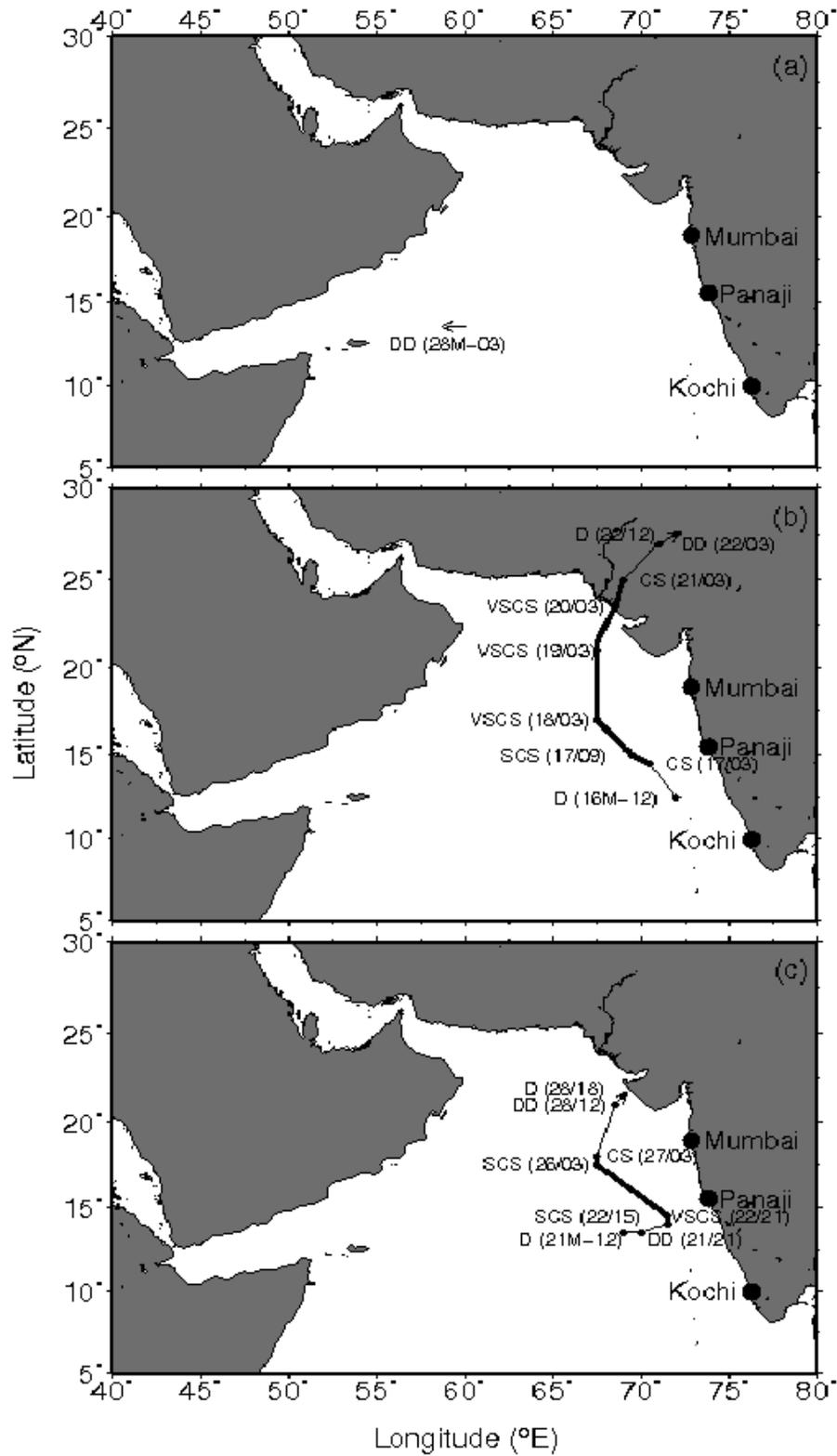


Figure 1

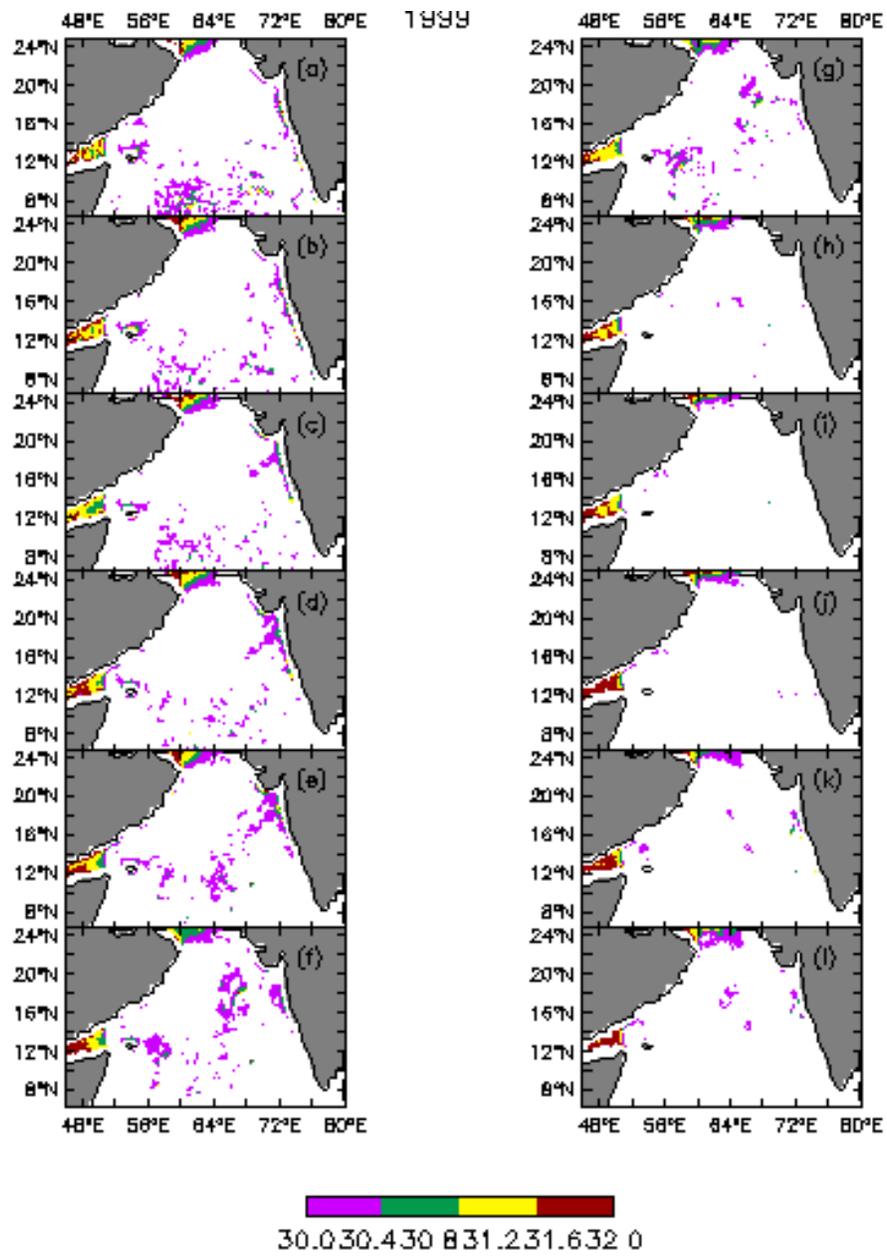


Figure 3

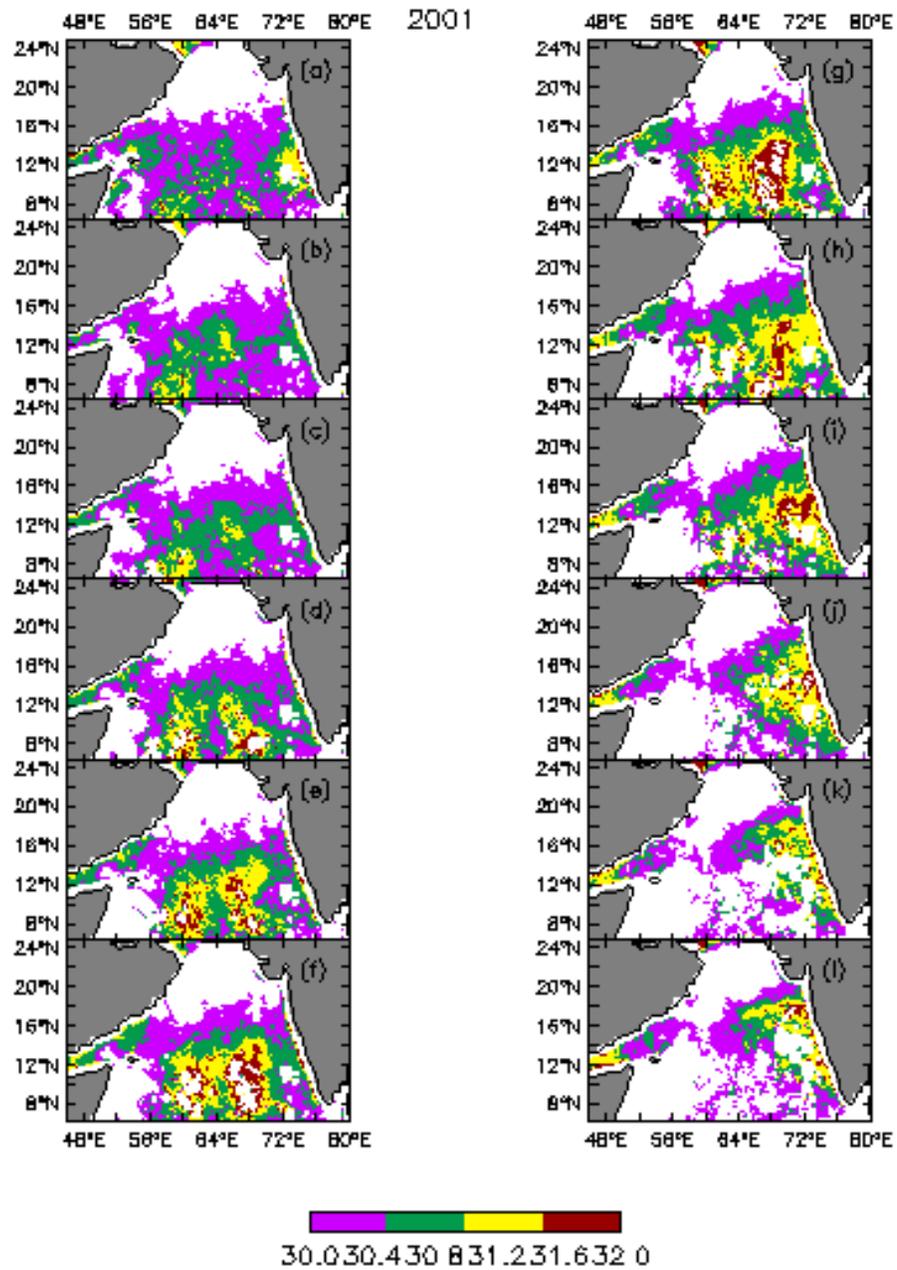


Figure 4

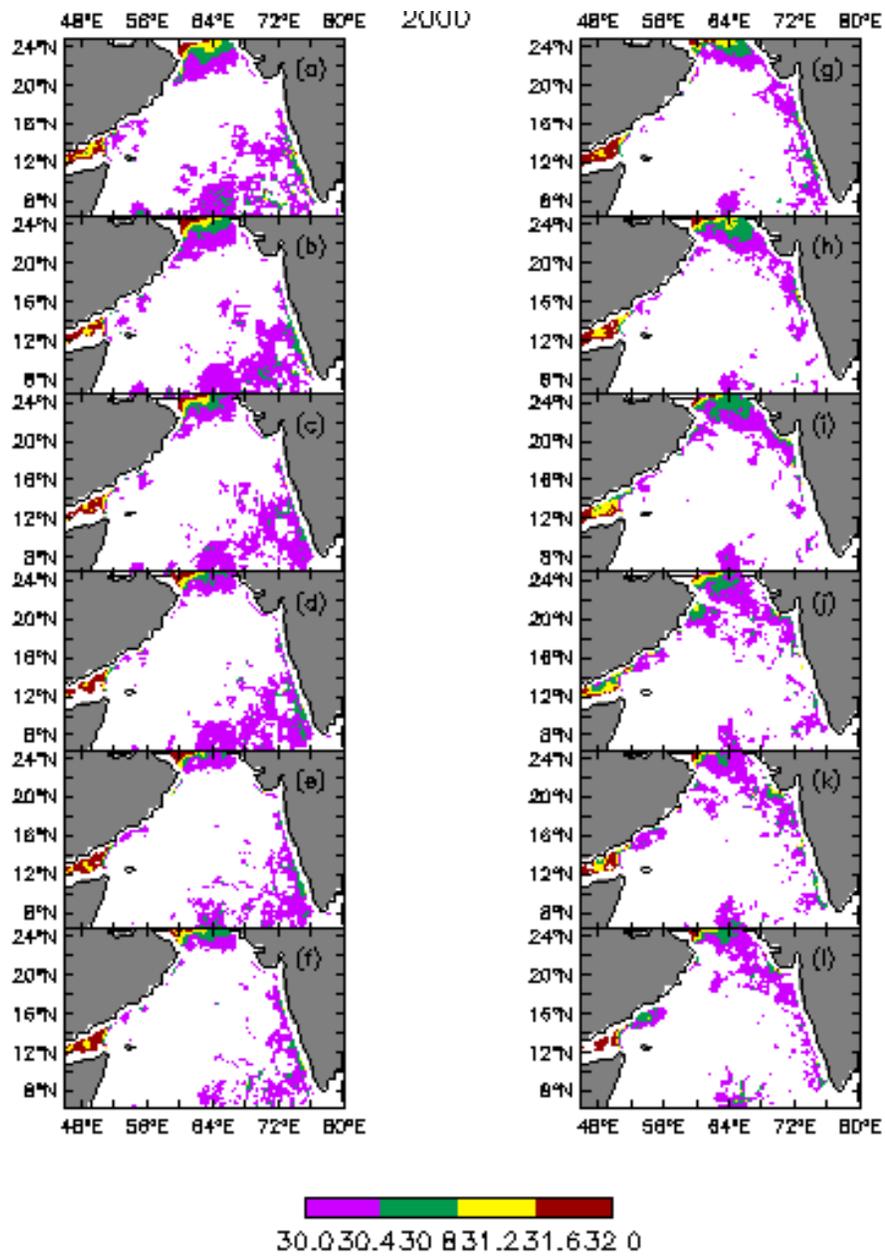


Figure 5

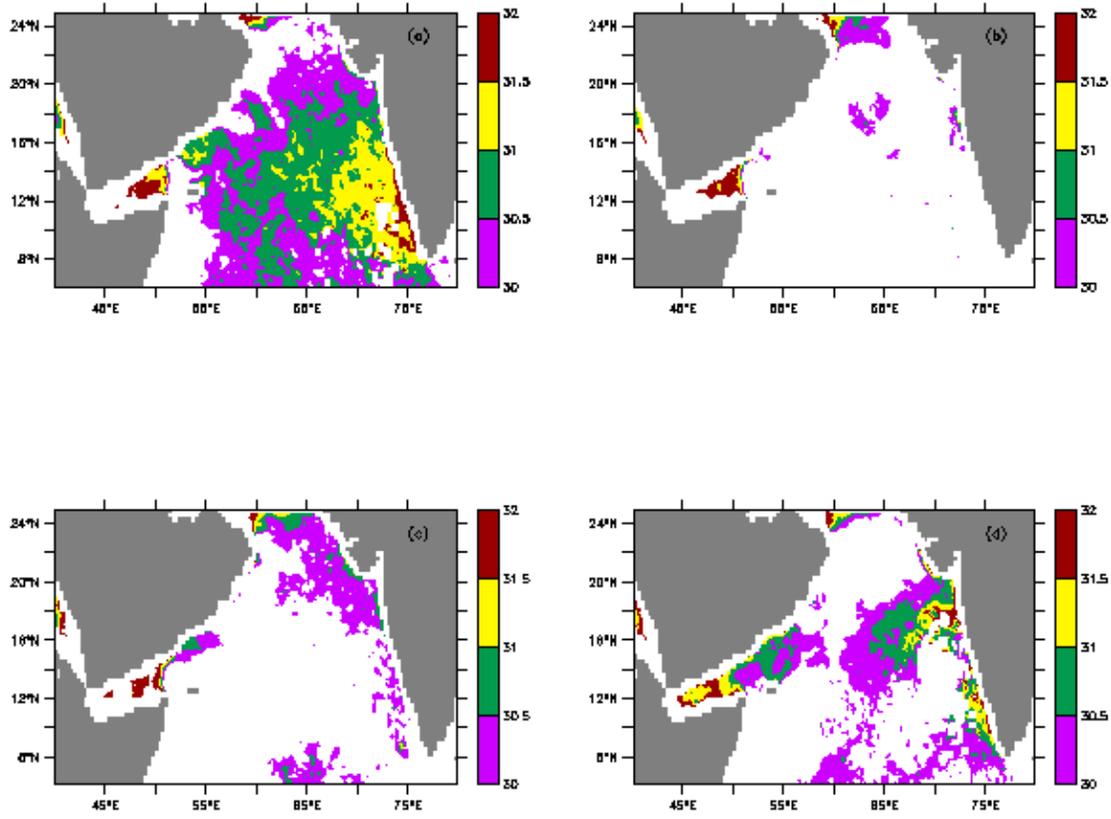


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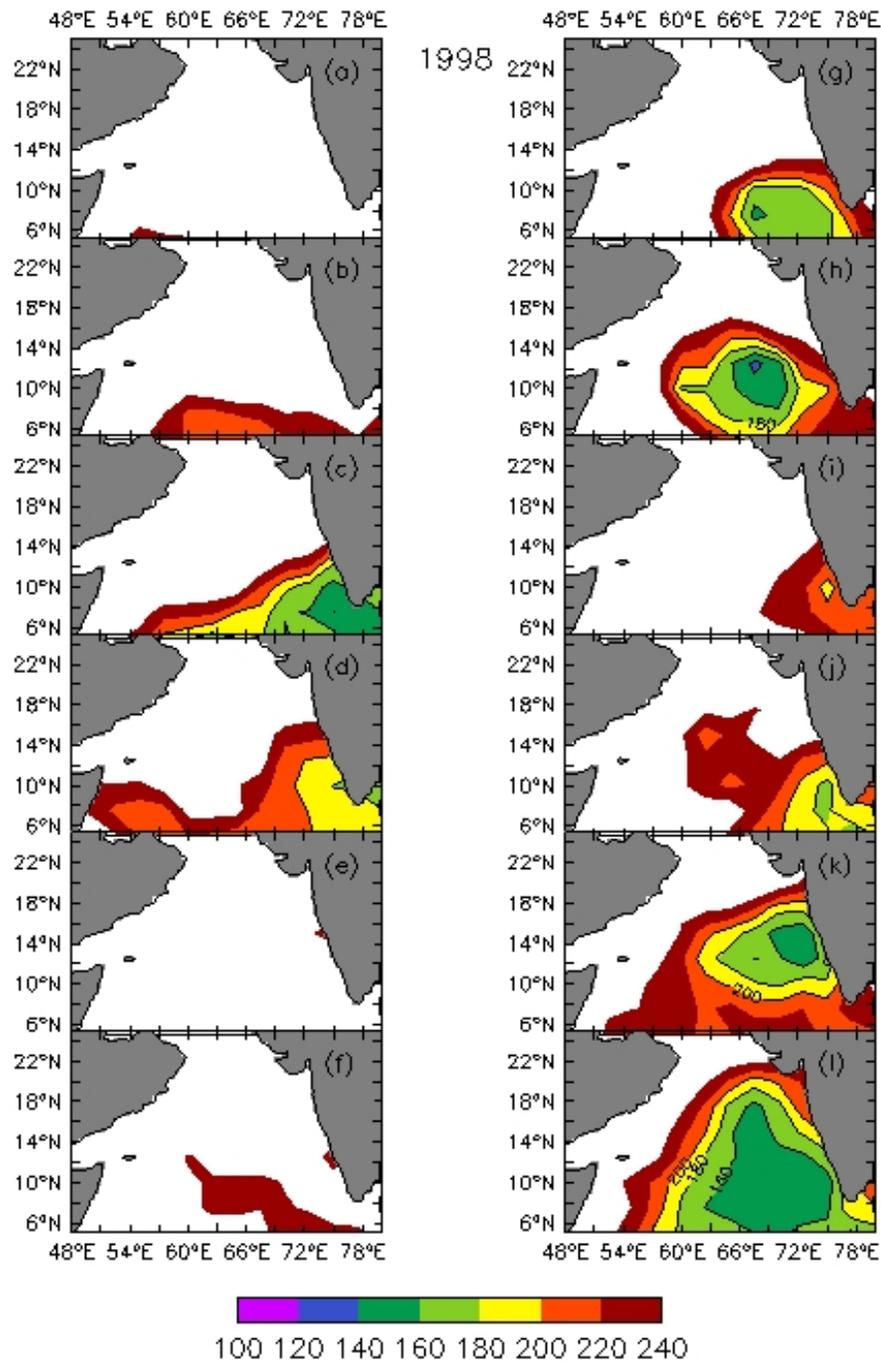


Figure 7

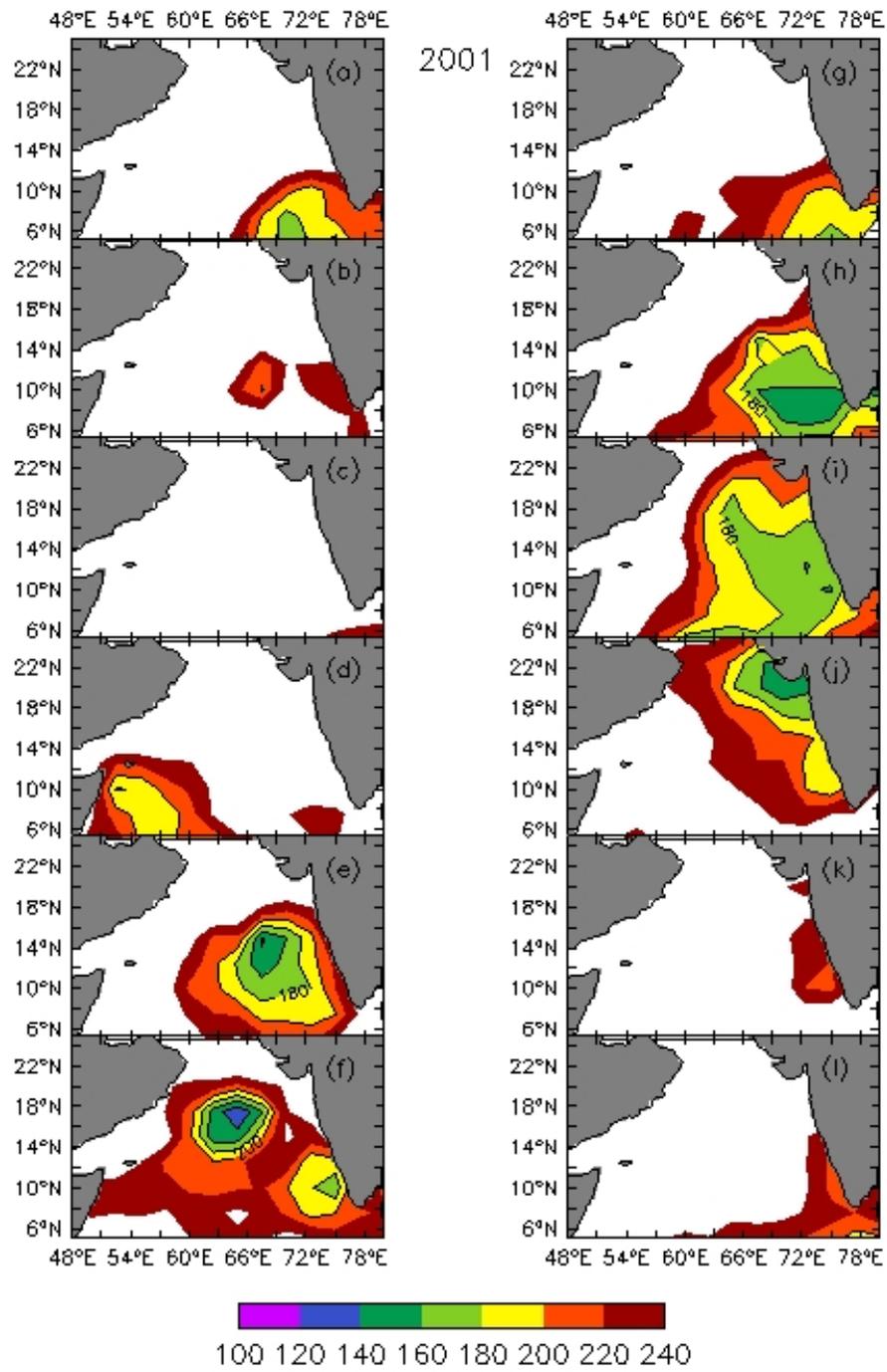


Figure 8

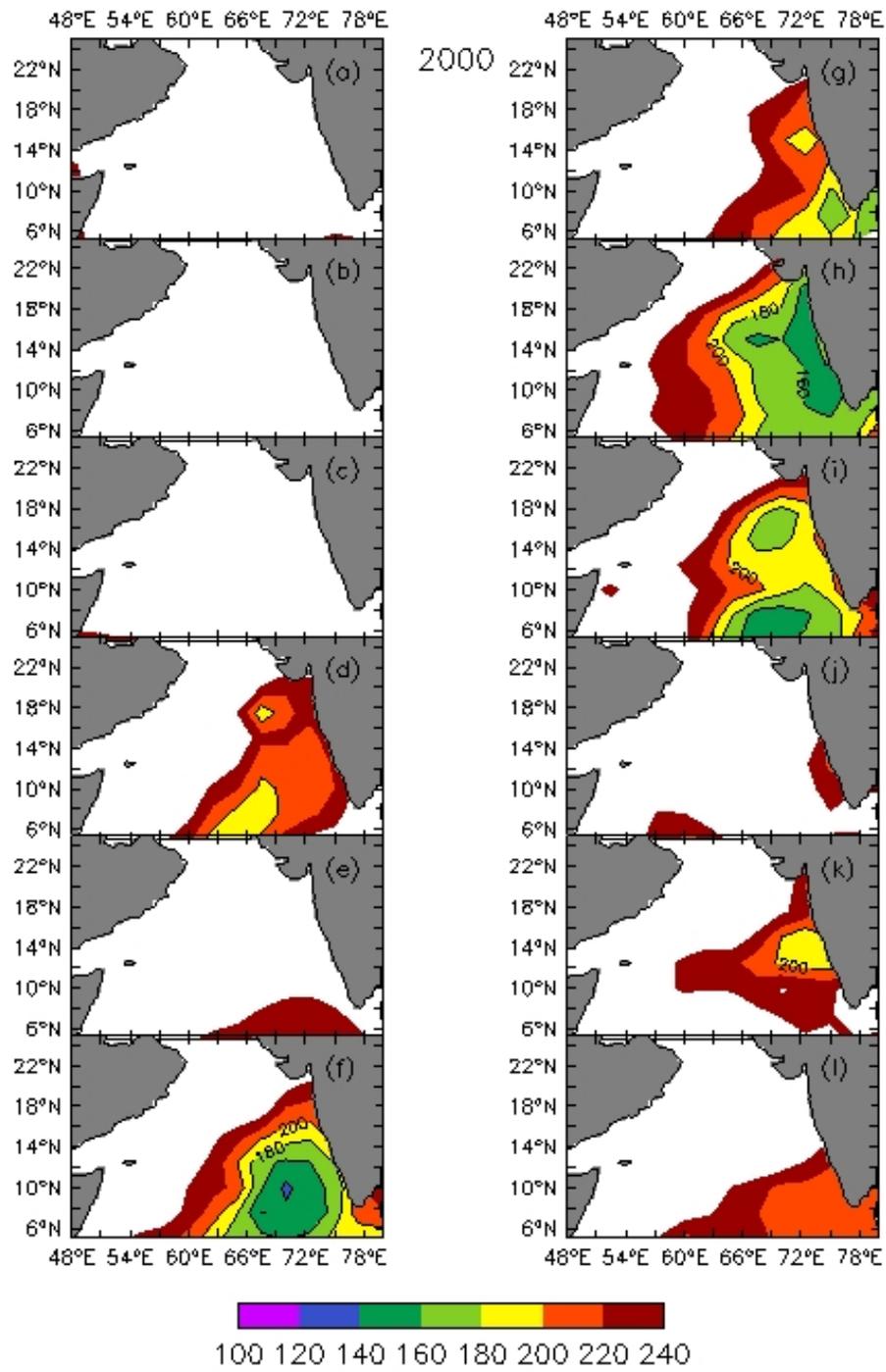


Figure 9

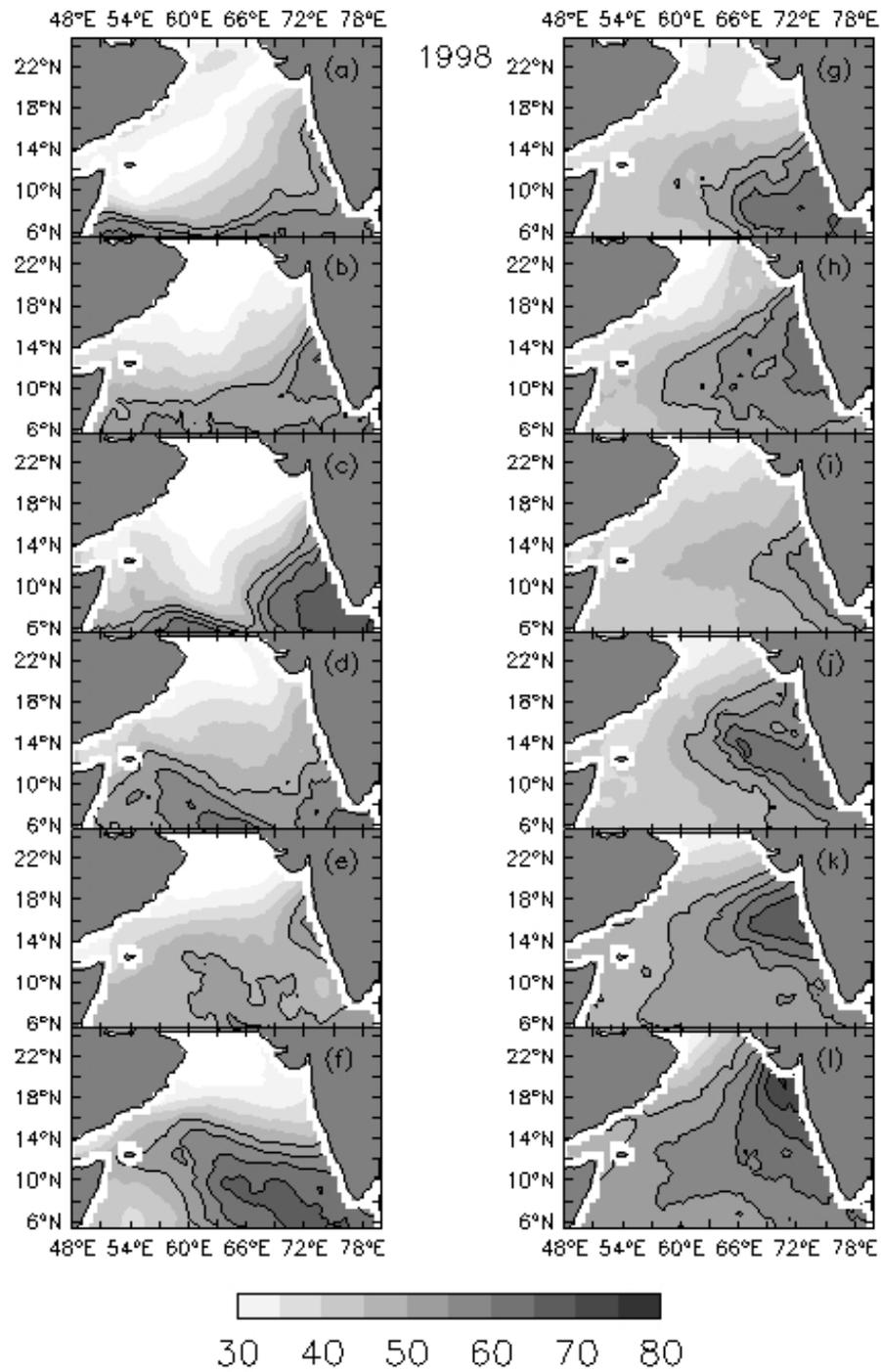


Figure 10

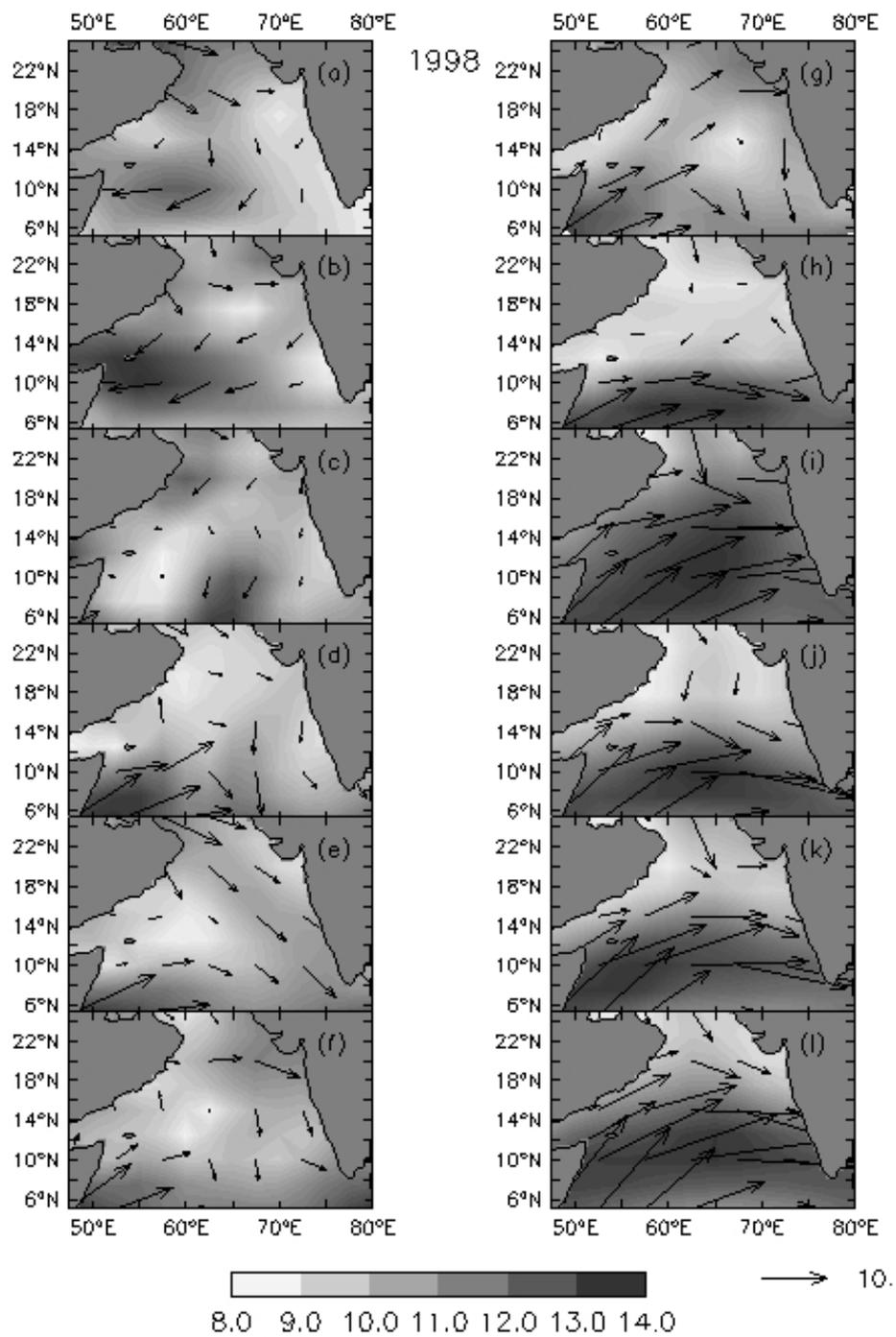


Figure 13

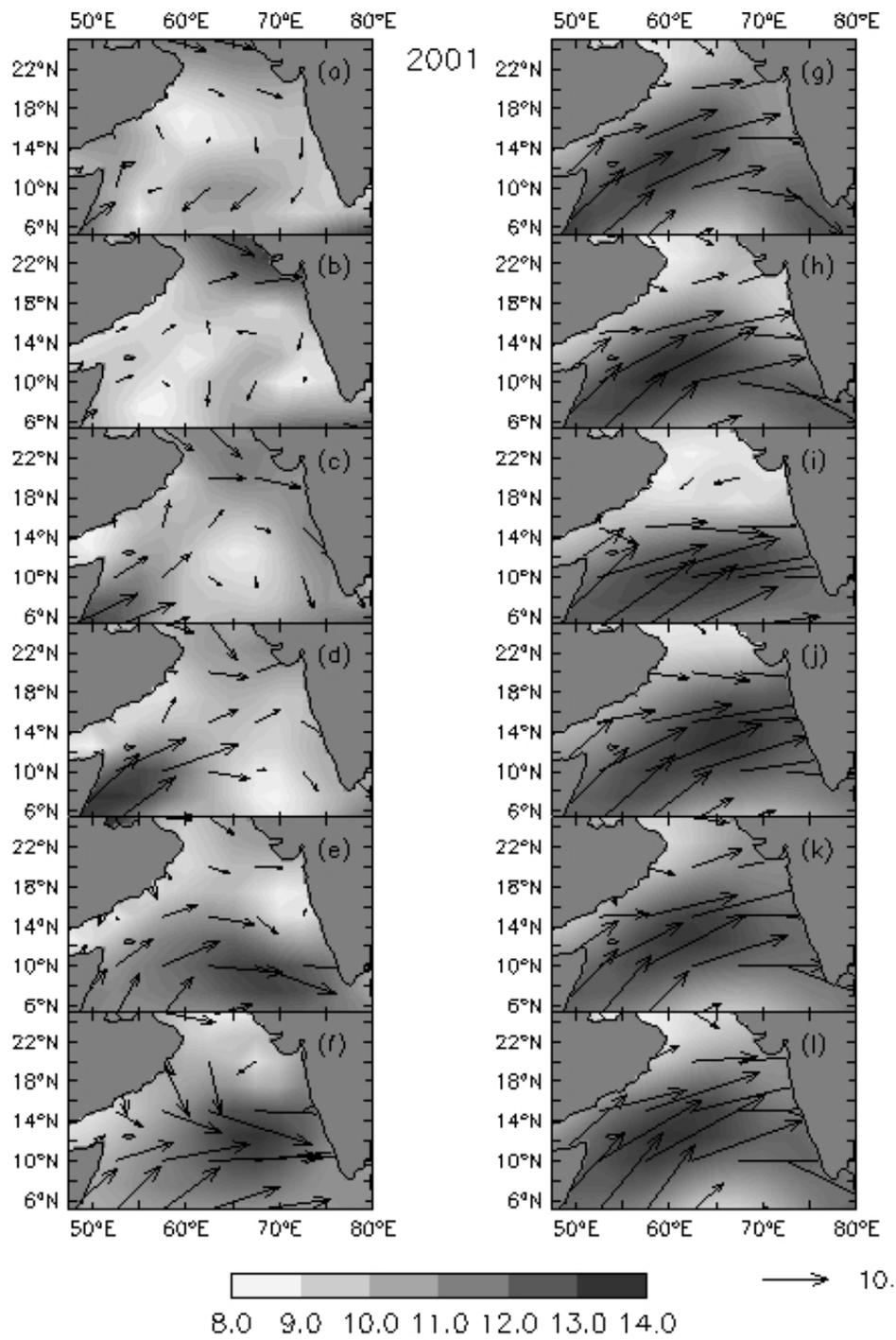


Figure 14

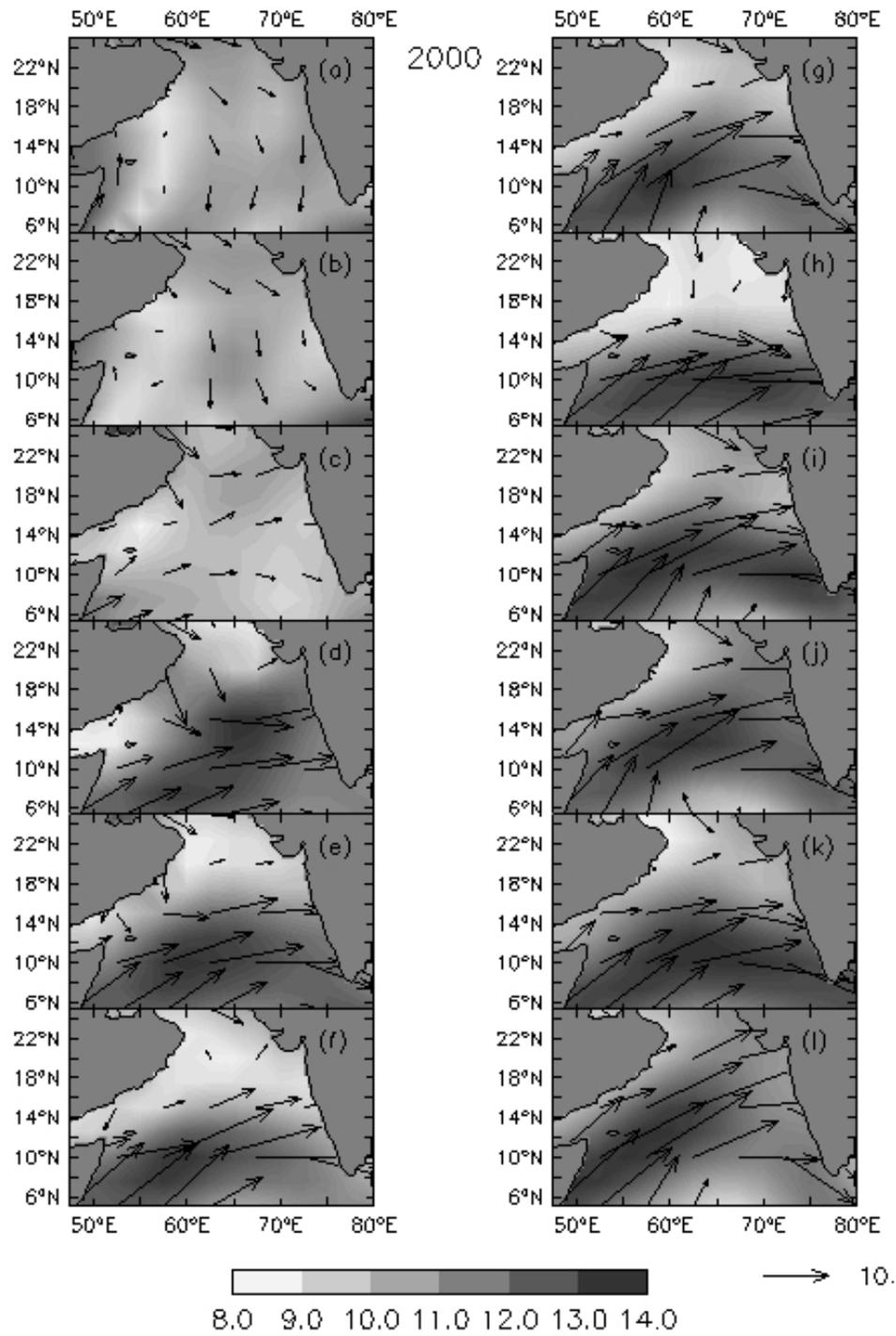


Figure 15