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Sea Surface Temperature (SST) and the Indian Summer Monsoon

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1. Introduction

Every year during the summer months (June-September), the southern part of Asia, in particular the Indian subcontinent receives continuous and widespread rains due to the monsoon (meaning seasonal change of wind direction) more specifically known as the summer or South-West (SW) monsoon. The phenomena in summer takes place due to the cross hemispheric reversal of winds bringing in considerable amount of water vapour from the high pressure regions over the relatively colder Indian and Pacific oceans and the Arabian sea to the low pressure system over heated land mass areas. Due to large geographical coverage and high inter annual variability in terms of associated rainfall it constitutes one of the important elements of the global climate system (Mooley & Parthasarathy, 1984). Also the overall mean monsoon precipitation distribution significantly depends on the intra-seasonal oscillations of dry and wet spells (Waliser et al., 2003). The sudden onset of monsoon is characterised by a highly energised pattern of lightning, thunderstorm, cloud burst and incessant rainfall over a large area of southwest coastal region of the Indian Kerala state (Soman & Kumar, 1993). Normally the first episodic rain of the monsoon occurs over Burma and Thailand in the middle of May and then extends to the northwest over most of India within a month. The northward progression of monsoon is symptomatic of a large-scale transition of deep convection system (called the tropical convection zone) from the oceanic-equatorial to tropical-continental regions (Sikka & Gadgil 1980).

While the SW monsoon period (June-September), accounting for about 80% of the total rainfall is vital to meet the Indian agricultural and hydrological requirements, the winter monsoon flowing from North East direction during October-November contributes only marginally albeit meeting the ground water requirement of some areas falling in the shadow region of the summer monsoon cover. Many oceanic and atmospheric parameters like the El Nino and Southern Oscillation (ENSO), Eurasian snow cover in winter/spring, northern hemispheric temperature in winter etc. influence the year-to-year variability of the monsoon rainfall over India (Rajeevan et al., 2004). Hence the inter annual variations severely affect the ground water resources of not only India and neighbouring countries like Sri Lanka, Bangladesh and Pakistan but also on small scales, the equatorial Africa, northern Australia, and south-western United States.

The monsoon rainfall intensity has intra- and inter- annual variation at different spatial scales impacting on the availability of water for agriculture and other uses. As a result almost half of the world's population living in monsoon region suffer from food and water insecurity. The detailed scientific reasons of such variation in monsoon rainfall conditions are not clearly understood. Effort directed to make accurate prediction of the overall monsoon rainfall of the season averaged over the whole country as such is quite useful for farming activity. More desirable objective of such forecasts is to predict the prospects of seasonal rainfall with finer details of its spatial distribution so that the peasants may decide about the sowing activity at district or even village levels for better crop yields.

There are three major monsoon variables: (i) the yearly onset date of monsoon over India (it first enters the coastal Kerala state by 1st June \pm 8 days and later progresses to cover the whole country), (ii) total seasonal rainfall during June-September (the area weighted summer monsoon long term average rainfall for the whole country as estimated by India Meteorological Department (IMD) is about 88 cm with a coefficient of variation of 10% which in real terms may lead to widespread drought/flood) and (iii) seasonal rainfall distribution over different Indian meteorological sub-divisions (prediction of this is the most difficult). To gain an early knowledge of the amount of seasonal monsoon rainfall or determination of its trend has been a challenging scientific problem for long. A number of empirical, statistical and dynamical/general circulation models have been developed for the purpose by various groups the world over (Munot & Kumar, 2007). For the Indian region mainly the statistical models have been used on an operational basis with partial success. For example the statistical model could not forecast the recent rain deficient years of 2002, 2004 and 2009. Moreover the variations of the 2 monsoon indices namely the time of onset and the total amount of monsoon rains are not directly correlated to the rainfall distribution in different parts of the country which would follow the dynamics of meteorological parameters at local or micro levels.

The Asian-Australian monsoon (another name of the same Indian summer monsoon in a regional context) is a coupled geophysical phenomenon the intensity of which is regulated through negative feedbacks between the land, ocean, and atmosphere. Indian Ocean heat transport calculations using 41-yr (1958–98) data revealed that the Indian Ocean heat transport possesses strong variability at all time scales from intra seasonal (10–90 days) to inter annual (a biennial signal is significant). The amplitude of the intra seasonal variability is similar to the seasonal cycle, and the amplitude of the inter- annual variability is about one-tenth of the seasonal cycle (Chirokova & Webster, 2006).

According to IMD's definition of monsoon transition, at the surface the onset is recognized as a rapid, substantial, and sustained increase in rainfall over a large spatial scale while the withdrawal marks the return to dry, quiescent conditions. The criterion is that the rainfall amounts over Kerala district increase from below 5 to over 15 mm/day during the onset (Anathakrishnan and Soman, 1988). A different condition that assesses the onset and withdrawal dates of the Indian monsoon has also been derived from variability in the large-scale hydrologic cycle. The hydrologic cycle is chosen as a key physical basis for monitoring the monsoon due to the essential roles played by zonal and meridional gradients in water vapour, clouds, and rainfall in driving the large-scale monsoon circulation. Lateral transports of water vapour are required for the sustenance of monsoon rains. To diagnose onset and withdrawal, vertically integrated moisture transport (VIMT) is considered more representative by some authors instead of rainfall, which over the large scale is often poorly

measured and modelled. An index, named the hydrologic onset and withdrawal index (HOWI), is thus formed from those regions where VIMT variability is pronounced at the beginning and end of the monsoon season respectively. Analysis of inter annual variability in monsoon onset and withdrawal dates based on the HOWI reveals robust associations that are weak and insignificant when assessed using other onset criteria. The HOWI criterion shows strong correlations between total rainfall and both onset and withdrawal of monsoon (Fasullo & Webster, 2006). But these indices have a drawback of being determined retrospectively and hence their less predictive potentials.

While the tropical day-to-day weather conditions have a restricted predictability of 2–3 days, the seasonal (June–September) mean monsoon circulation in the tropics is potentially more predictable (Rajeevan, 2001). This is understandable as the low frequency or longer period oscillatory features of the tropical variability is caused by slowly varying boundary conditions and forcings due to sea surface temperature (SST), land surface temperature, soil moisture, snow cover, etc. (Charney & Shukla, 1981). But a considerable fraction of monsoon variability results from internal dynamics at higher frequencies (intra seasonal) often due to local/regional effects of environmental factors including aerosol distribution, atmospheric pollution, orography, forest dynamics etc. This intra seasonal variation is the main limiting factor of the monsoon predictability at subdivision level. Still, overall it makes sense in estimating and forecasting the likely onset date of the summer monsoon as well as the total seasonal rainfall in three categories of normal (~area weighted average value of ~88 cm, excess (~97 cm) and deficient (~79 cm). This information is very important for macro level planning of 'Kharif' crop cultivation with paddy as the main crop. The 'Kharif' crops such as paddy, sugarcane, groundnut, maize, pulses etc., need timely and adequate water either through rains or through artificial irrigation system. Indian agriculture still depends heavily on monsoon rains and sowing times differ with locations and with crop-type during April–July months. It would therefore be ideal to get early alerts at micro level, a difficult proposition at present but may be realized in future. In absence of this, the accurate predictions of the monsoon onset dates (date over Kerala governs onsets over other regions following a climatological pattern of monsoon progress as shown in Fig-1 for the south Asian region and over India) and the integrated seasonal rainfall, help in managing the agricultural output to a large extent.

Efforts for accurately predicting the onset date and the overall strength of seasonal precipitation have been continuing for a long time using synoptic data analysis, empirical, statistical and dynamical modelling by the IMD (Hastenrath & Greischar, 1993; Raghu Kant & Iyengar, 2003). Out of a number of parameters SST anomalies of the Pacific/Indian ocean related to the strong El Nino and La-Nina events and associated circulation like ENSO have been correlated with delayed/weak and early/strong monsoon rainfall over India (Joseph et al, 1994; Nakazawa, 1988; Philander, 1990).

Due to the availability of all-weather and homogenized SST data sets since 2002–03 from microwave sensor (AMSRE) of AQUA satellite, it has been possible to carry out a quantitative assessment of SST anomalies with 3-day temporal and $0.25^\circ \times 0.25^\circ$ lat-long grid (pixel unit) resolutions. Hence a more detailed investigation of the effect of SST on the monsoon can be tested both for variations in the onset dates and also the total seasonal rainfall over monsoon fed regions. As a demonstration to utilizing the satellite data for monitoring the SST vis-à-vis the monsoon system over India, a study has been carried out to develop a real time model and the preliminary results published (Chakravarty, 2009).

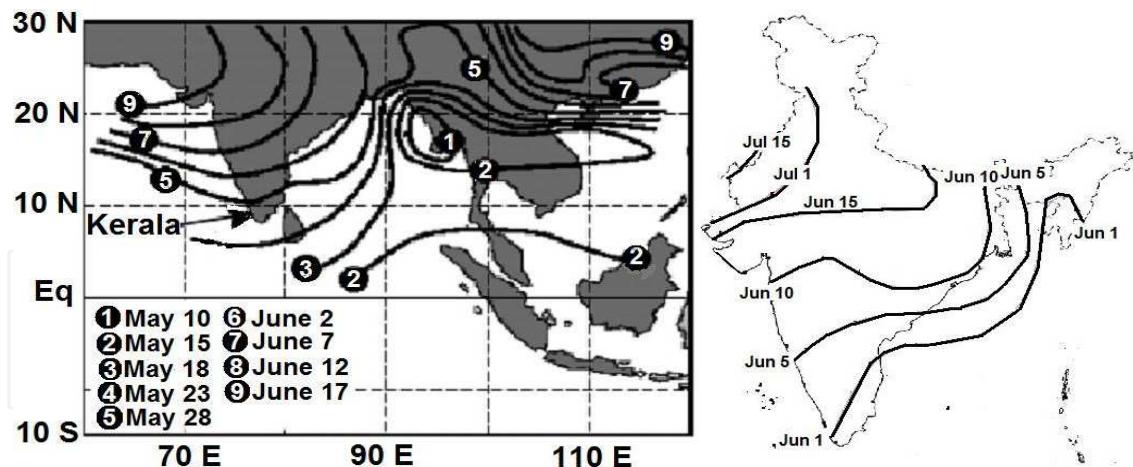


Fig. 1. Climatological dates of the onset of the south Asian summer monsoon (adapted from Fasullo and Webster, 2002). The monsoon onset date contours are also shown over India.

In addition to SST data from satellites, upper air balloon and rocket experiments have been regularly conducted from Thiruvananthapuram, the capital of the Kerala State to detect any changes in the temperature and wind fields up to ~70 km owing to monsoon circulation. A special campaign called ROMEX (Rocket Monsoon Experiment), involving balloon and rocket borne wind measurements was carried out during April-June, 2007 for real-time monitoring of middle atmospheric zonal/meridional winds to study the prognostic potential of early reversal of upper winds for the possible date of setting in of summer monsoon over the Kerala coastal region (Chakravarty & Namboodiri, 2007). The essential statistics for such prediction was built up using voluminous data already collected between 1971-90 using balloon/rocket flights from Thumba Equatorial Rocket Launching Station (TERLS) of the Indian Space Research Organisation (ISRO), Thiruvananthapuram. The results showed distinct potential of upper tropospheric and stratospheric wind reversal parameters (circulation indices) being used for predicting the monsoon onset day from the climatological trends of these circulation indices and 2007 campaign data used as a test case. In the background of the above summary providing the present status of the various observational and modelling aspects and their applications to predict the prospects of seasonal monsoon rainfall, the main purpose of this chapter is to (a) review and carry out further studies on the development of a real time model using SST as the main parameter over a region covering central/western Pacific ocean and the Indian ocean to predict at regular intervals the prospects of possible onset date and total rainfall over India (b) as a collateral and supporting information to (a) above, demonstrate possible use of upper air parameters like the troposphere/stratosphere circulation indices for predicting the monsoon onset and strength for the ensuing season, (c) possible operationalisation of the MATLAB programme with features to provide periodic updates on the monsoon rainfall during April-September with built in graphics for various plots to show the monsoon trends. This assumes that the AQUA/AMSRE satellite type SST and other data would continue to be available.

2. Data and method of analysis

The Southern Oscillation Index (SOI) is calculated from the monthly or seasonal fluctuations in the air pressure difference between Tahiti and Darwin. Sustained negative values of the

SOI often indicate El Niño episodes. These negative values are usually accompanied by sustained warming of the central and eastern tropical Pacific Ocean, a decrease in the strength of the Pacific Trade Winds, and a reduction in rainfall over eastern and northern Australia. Though there are departures as the strong El Niño event of 1997/98 had only marginal effect on Australia. But severe droughts resulted from the weak to moderate El Niño events of 2002/03 and 2006/07. Positive values of the SOI are associated with stronger Pacific trade winds and warmer sea temperatures to the north of Australia, popularly known as a La Niña episode. Waters in the central and eastern tropical Pacific Ocean become cooler during this time. Together these give an increased probability that eastern and northern Australia will be wetter than normal. The strong and preceding El Niño/La Niña episodes are also used mainly to parameterise a statistical correlation coefficient. This aspect is further dealt in this chapter. The method used by the Australian Bureau of Meteorology is based on the Mean Sea Level Pressure (MSLP) difference between Tahiti and Darwin. It is calculated as follows:

$$SOI = 10 \frac{[P_{diff} - P_{diffav}]}{SD(P_{diff})}$$

where P_{diff} = (average Tahiti MSLP for the month) - (average Darwin MSLP for the month), P_{diffav} = long term average of P_{diff} for the month in question, and $SD(P_{diff})$ = long term standard deviation of P_{diff} for the month in question. The multiplication by 10 is a convention. Using this convention, the SOI ranges from about -35 to about +35, and the value of the SOI can be quoted as a whole number. The SOI is usually computed on a monthly basis, with values over longer periods such as year being sometimes used. Daily or weekly values of the SOI do not convey much in the way of useful information about the current state of the climate and can fluctuate markedly because of daily weather patterns, and should not be used for climate purposes. The monthly average SOI data are used to calculate the annual and pre-monsoon period (Jan-April) mean SOI values for 1970-2010 period. The monthly average SOI contours are generated with respect to the different years to identify El Nino and La-Nina episodes. The official monsoon onset dates over Kerala for different years are taken from daily weather bulletins, Met. Center, Thiruvananthapuram, Kerala for correlation studies with ENSO, SST etc.

The global daily SST data from AQUA satellite's TMI/AMSRE sensors are produced by Remote Sensing Systems and sponsored by the NASA Earth Science REASoN DISCOVER Project and the AMSR-E Science Team. Data since 2002-03 are available at their official website (www.remss.com). The daily global SST values for the period 2003-11 are examined during the pre-monsoon as well as monsoon months. A MATLAB computer program is developed to read daily binary AMSRE files of global SST (3 days aggregate values at a fixed morning time every day) and generate global contour plots. After going through a large number of day's data of all these years a part of Pacific Ocean region bounded by -20° to 10° in latitude & 80° to 240° in longitude is selected as test site for further analysis. This oceanic region (ignoring a small part of land area) is termed Nino-Broad Pacific or Nino-BP to distinguish it from other existing Nino region definitions. Fig-2 shows the areas bounded by existing Nino regions and the new Nino-BP region used in the present analysis. The program then can focus on any Nino area and produce time series of SST pixel (25 km x 25km area) number values distributed in the selected 27-31 °C temperature bins with a

resolution of 1 °C separately for the years 2003-11. Total number of pixels within this test region is 65,000. Using MATLAB graphics, the SST contours and bar charts (at weekly intervals) are automatically plotted separately for each year covering Jan-May and June-September months. The programme with the regular input of TMI/ AMSRE data can thus be used to follow the trends for prospects of monsoon strength on real time basis.

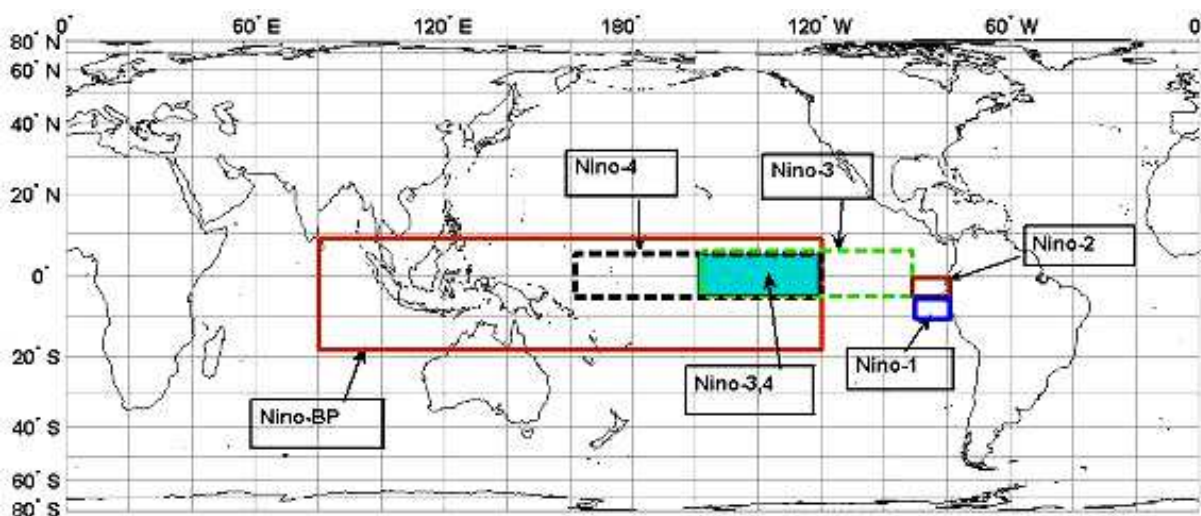


Fig. 2. Oceanic regions called Nino-1, Nino-2, Nino-3, Nino-4, Nino-3, 4 for carrying out different sensitivity analysis and the new Nino-BP region defined here for association with Indian monsoon sensitivity.

3. Results

The results obtained are categorised in the following sub sections: (a) variations of annual average, pre-monsoon and monthly averages of SOI and its correlation with onset and strength of monsoon rainfall, (b) global and Nino-BP region maps of SST, (c) variations of pixel-based structure of SST in the Nino-BP and Nino-4 regions and efficacy of a real time model for monitoring the monsoon system and (d) upper air indices of monsoon circulation.

3.1 SOI and onset of monsoon

Every 3 to 7 years, SST off the South American (SA) coast suddenly warms up compared to the temperatures of the western Pacific region. This phenomenon is known as an El Nino, or 'warm event'. It is initiated by a decrease in easterly trade winds reducing the upwelling near SA coast with consequent warming. This lowers atmospheric pressure over the eastern Pacific, causing the trade winds to be further reduced. Gradually, if this process continues, an El Nino develops. In strong El Nino situations, warmer than normal waters cover nearly the entire eastern and central tropical Pacific. The area of strong convection (large rain clouds) usually shifts eastward as waters in those areas warm up. In the western Pacific, easterly trade winds often reverse and blow from the west, reducing ocean temperatures and increase in atmospheric pressure and decrease in cloud formation. The whole process of El Nino or La Nina (reverse of El Nino) is found to have some influence on SW monsoon variability though not clearly quantified.

The annual means and the means of pre-monsoon months (Mar-May) of SOI data (or ENSO index) for the period 1970-2010 are plotted in Fig-3. The figure also shows the variability of

SOI smoothened by taking 12 months running means of the monthly average SOI data for the same period. A high value of correlation coefficient (~ 0.84) is found between the annual average and pre monsoon months average values indicating that the effect of these events during pre monsoon months normally continue in a similar manner of warming or cooling for a longer period of the year. Fig-4 shows the contour plot of the monthly mean ENSO index values for the period. It is seen that the El Nino and La Nina events take place in an alternating manner both having periodicities of ~ 5 -6 years. The darkest (black) shades indicate occurrence of El Nino and lightest (white) shades La Nina episodes. Other grey shades indicate different intermediate states of these events including the normal condition of neither being present. There are higher frequency seasonal structures within the episodic year that can be seen in the contours.

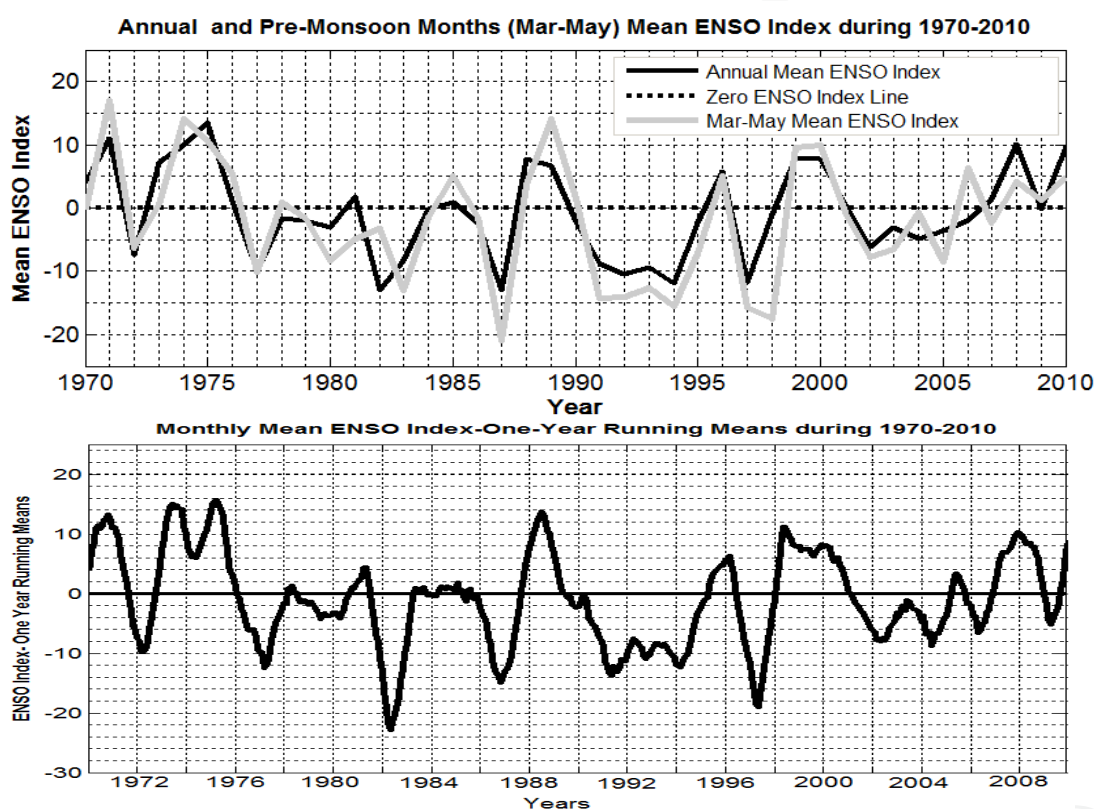


Fig. 3. Variation of ENSO index during the period 1970-2010. Top panel shows the annual and pre monsoon months (Mar-May) average values and the bottom panel 12 months running means.

The determination of the monsoon onset date over Kerala is normally announced and later slightly modified based on the event definition by IMD. Since there is another criterion of the hydrologic onset and withdrawal index (HOWI) mentioned earlier, a comparison is made by plotting these two sets of dates in Fig-5. The HOWI index data is available only during 1970-2000. The figure shows some major differences between the onset dates with a correlation coefficient of ~ 0.61 . Hence the studies related to the causes of variations of onset dates would have less meaningful results if there were a change in the definition itself. It is found that a burst of rainfall due to non-monsoon reasons may happen locally to mimic an early onset of monsoon applicable to both the data sets with differing degrees.

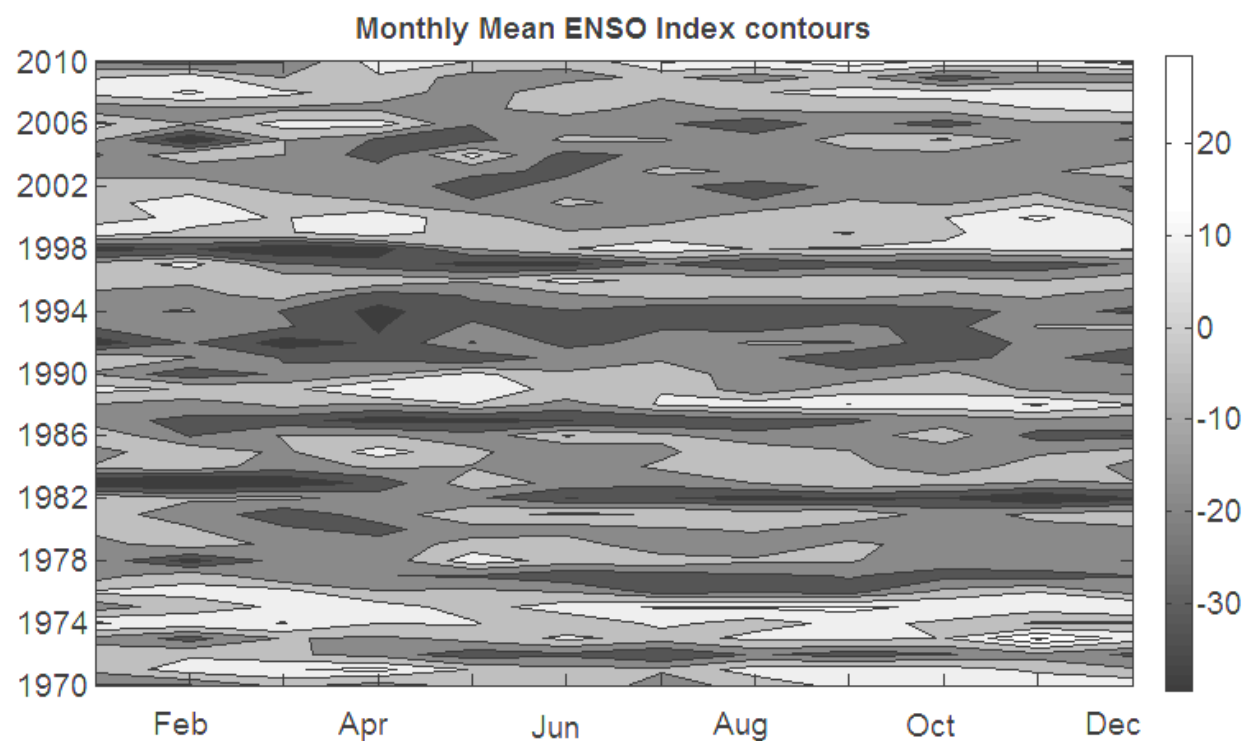


Fig. 4. Contour plot of monthly mean ENSO index during 1970-2010. The darker shades show El Nino and the lighter La Nina episodes.

Notwithstanding the imperfect way the monsoon onset is defined, it may still be helpful to examine any direct influence of the El Nino/La Nina events on the monsoon onset dates over Kerala coast. The annual and pre-monsoon period means of SOI are plotted with respect to the onset dates of each year during 1970-2010 in Fig-6. From the distribution it is

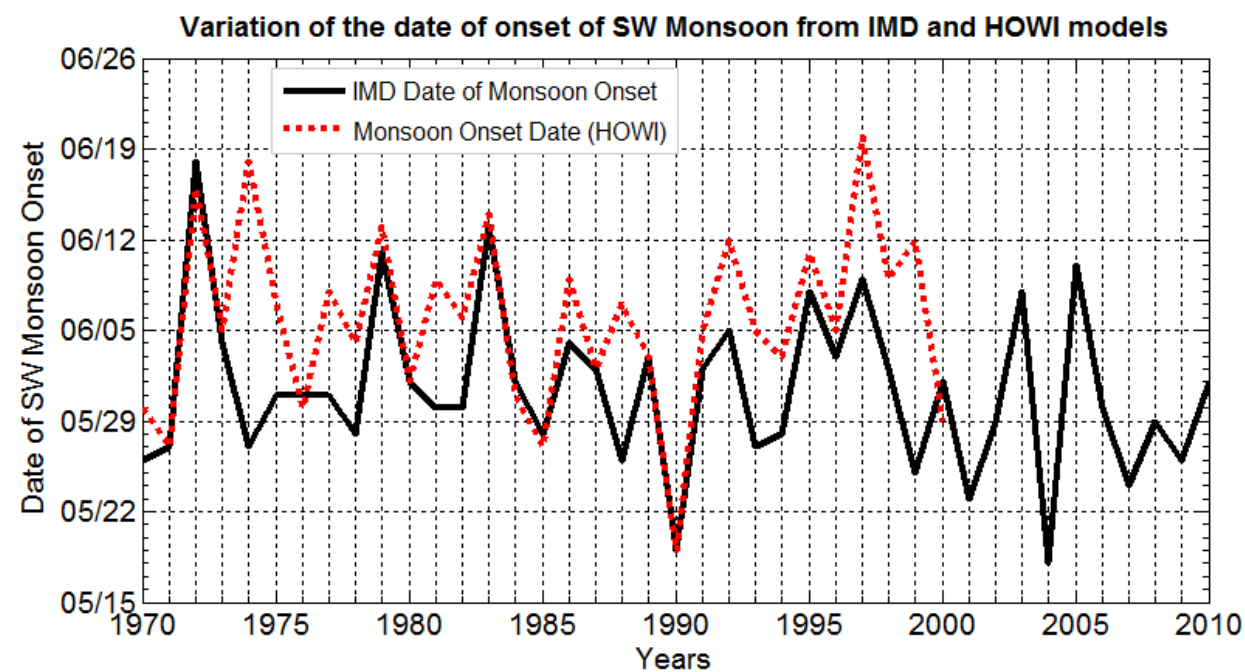


Fig. 5. Comparison of monsoon onset days using IMD and HOWI data sets.

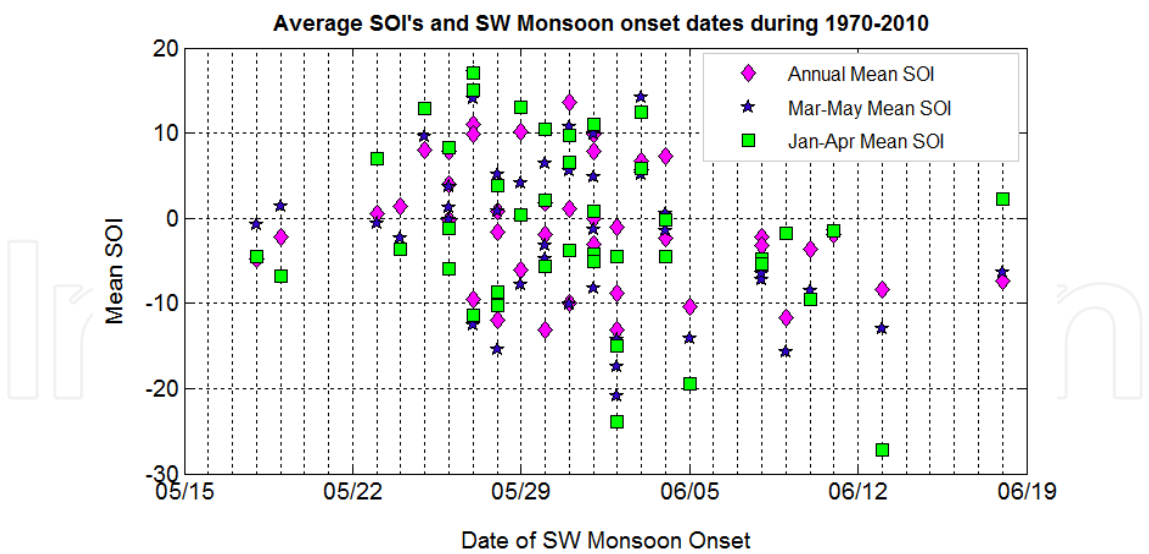


Fig. 6. Scatter plot of mean values of SOI and monsoon onset dates for the years 1970-2010.

clear that only in 4 cases out of 40 years of data, the SOI exceeded 15 in the negative scale (strong El-Nino event) and for all of these years the monsoon onset dates were delayed, i.e., beyond the normal onset date of 1 June. For all other values of SOI ranging between -14 and +15 the correlation is very poor. There have been much more delayed onset for smaller negative values of mean SOI. It may be noted that at least for positive values of SOI the onset has taken place within 4 June. So from normal conditions to La-Nina events provide a better prognosis that the monsoon would be timely compared to the El Nino events association with delayed monsoon. Apart from the onset date the other parameter is the % deviations of total area weighted seasonal (June-September) rainfall from long term mean value over India. Table-1 shows a few selected years of strong El Nino or La Nina events and associated SOI indices, onset dates and % deviations of rainfall. It is noted that there is a better correlation of negative and positive association to rainfall index with strong El Nino and La Nina events respectively.

Year	Annual Average SOI	Mar-May Average SOI	SW Monsoon Onset Date	% Deviation of Total seasonal rain
El Nino Years				
1982	-13.1	-3.2	30-May	-13.6
1987	-13.1	-20.9	02-Jun	-18.0
1991	-8.8	-14.3	02-Jun	-7.5
1992	-10.4	-14.1	05-Jun	-7.6
La Nina Years				
1971	11.0	17.0	27-May	3.9
1975	13.6	10.7	31-May	13.1
1988	7.8	3.7	26-May	13.1
2010	9.8	4.9	01-Jun	2.0

Table 1. Selected years of strong El Nino and La Nina events, associated SOI values, Monsoon onset date and percentage deviations (from long term mean) of monsoon seasonal rainfall.

From the above analysis it is noted that the mere presence of El Nino/La Nina events does not in itself provide any definite clue to the prospects of the ensuing monsoon (onset date in particular). However the normal conditions of oceanic state and mild La Nina situations appear to be favourable for a better monsoon. It is not possible to quantify these effects on the basis of these events. Hence it is necessary to deal with the oceanic state in a more quantitative manner. The sea surface temperature variations can be studied in more details using regular satellite data at a high resolution. The main parameter which is responsible for rainfall under monsoon system is the evaporation from the ocean surface which is closely linked to cloud formation and rainfall while being transported away from the source region.

3.2 Global and regional SST maps from satellite data

NASA's AQUA satellite launched during 2002 to an orbit of about 700 km has been broadcasting all the data on X-Band. Remote Sensing Systems (RSS), Santa Rosa, California produces Level 3 TMI/AMSR-E Ocean Products, *i.e.*, SST, sea surface wind (SSW) speed, atmospheric water vapor, and cloud liquid water. Data is visualised as daily, 3-day, weekly and monthly aggregates. As against daily maps with gaps in total coverage, the 3-day aggregate data covers the entire globe and represents the values on the present and past two days taken together. The microwave sensors produce all weather data with a high spatial resolution or pixel dimensions of 25 km x 25 km. The products are optimally interpolated and corrected for diurnal variations finally providing data normalised to a daily minimum SST, defined to occur approximately at 8 AM local time. The core MATLAB code uses the daily binary files of global SST data available on near real-time basis and converts these SSTs into global/regional maps. An example of such a global SST map on 9 April 2007 is shown in Fig-7. There are overall 1440 x 720 temperature points in the map; each presenting the average temperature value of pixel area 25 km x 25km. The map shows that the eastern/central Pacific Ocean temperatures are colder and there was no El Nino in progress. A sequence of such maps for following days would help monitoring appearance of any anomalous change in SST (allowing for the usual seasonal variation).

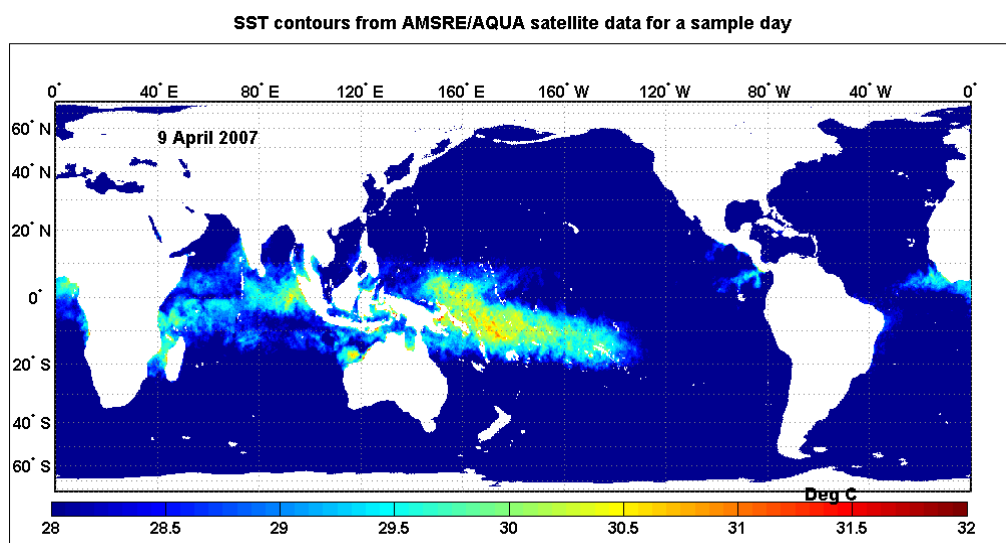


Fig. 7. Global SST contour map using AQUA data On 9 April 2007. Blue to red colour coding is to distinguish low and high temperature pixels. There are no measurements over the land areas and these are shown in white. Concentration of high temperature pixels in the Indian and western Pacific oceans is a nominal phenomena for April month.

The same programme can be employed to focus on the specific Nino regions of interest and map the SST values for different days. As an illustration for the Nino-BP region the SST maps are drawn on 3 days in the pre monsoon months (Mar-May) for two years of 2004 and 2008. Fig-8 shows these 2 sets of SST contours for comparison. The year 2004 had an early monsoon onset on 18 May and year 2008 a near normal onset on 29 May. The total seasonal rainfall over India for 2004 was 12% deficient and 2008 almost normal. It can be noted from the figure that the SSTs were generally higher during 2004 compared to 2008 for the same days of the year. The figure also shows that there is a larger region in the eastern Pacific Ocean which is colder during 2008 with a gradual decrease in the size of this area as the days progress compared to those during 2004. More quantification of these results is required and this has been attempted in terms of the distribution of SST values at pixel levels.

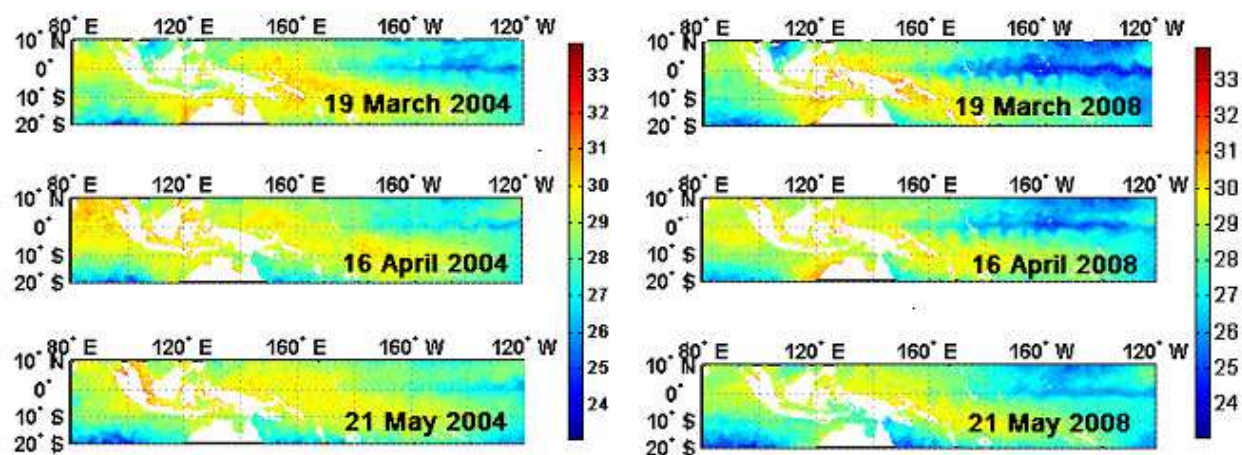


Fig. 8. SST contours of 3 selected days during pre-monsoon period for the years 2004 and 2008 over the Nino-BP region. Red/blue colours indicate cold/hot regions. White areas are landmasses.

3.3 Sensitivity analysis of SST at pixel level

The AQUA satellite data is available from 2003 and hence the detailed investigation at pixel levels is carried out for the period 2003-11. The data up to 30 April 2011 has been analysed to get an idea about the prospects of the monsoon of the coming season, i.e., June-September, 2011. The study shows that both the trend of the average temperature over the Nino-BP region and distribution of number of temperature bins between 25-31 °C with 1°C resolution point towards a near normal monsoon onset and rainfall distribution in 2011 similar to the year 2008.

Mean temperature values are calculated for each days SST data summed over the selected Nino regions and these are used in the time series for trend analysis. Similarly the distribution of number of pixels having temperatures between 25-31 °C is estimated for each day to compute the monthly averages. Fig-9 shows the time series of daily average SST values for pre monsoon months of different years over the Nino-BP region. The time series is built by analysing the daily data at weekly intervals. Fig-10 is a similar time series of mean SST values during the monsoon season (Jun-Sep). The years selected for this and subsequent plots include 2 anomalous years 2004 and 2009 with deficient rainfall and early monsoon onset and the other two, 2007 and 2008 as near normal monsoon years with 2008 being more

well behaved from the view point of overall monsoon seasonal rainfall distribution over India. From Fig-9 it is clear that the basic trend of the curves are similar but there is a large variation in absolute values of mean SST from year to year. The lowest temperatures were observed in 2008 (a near perfect monsoon year) and the values up to April for the current year (2011) also shows low SSTs indicating that the monsoon during 2011 could be like 2008 unless there are some drastic systemic deviations during the monsoon months.

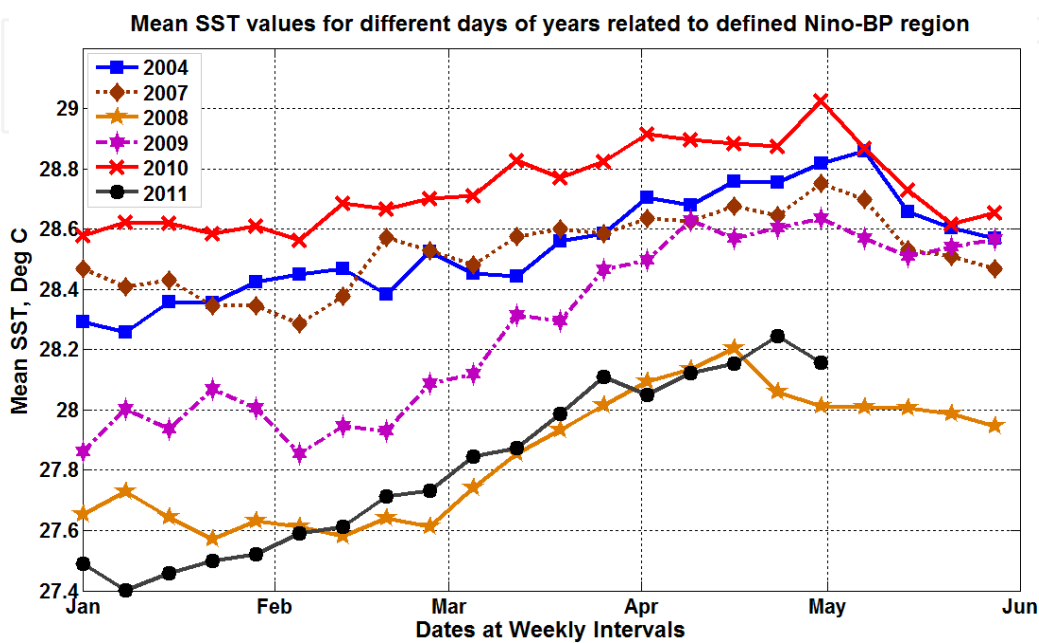


Fig. 9. Mean SST values over Nino-BP region for different days of pre-monsoon months at weekly interval for individual years (2004-11).

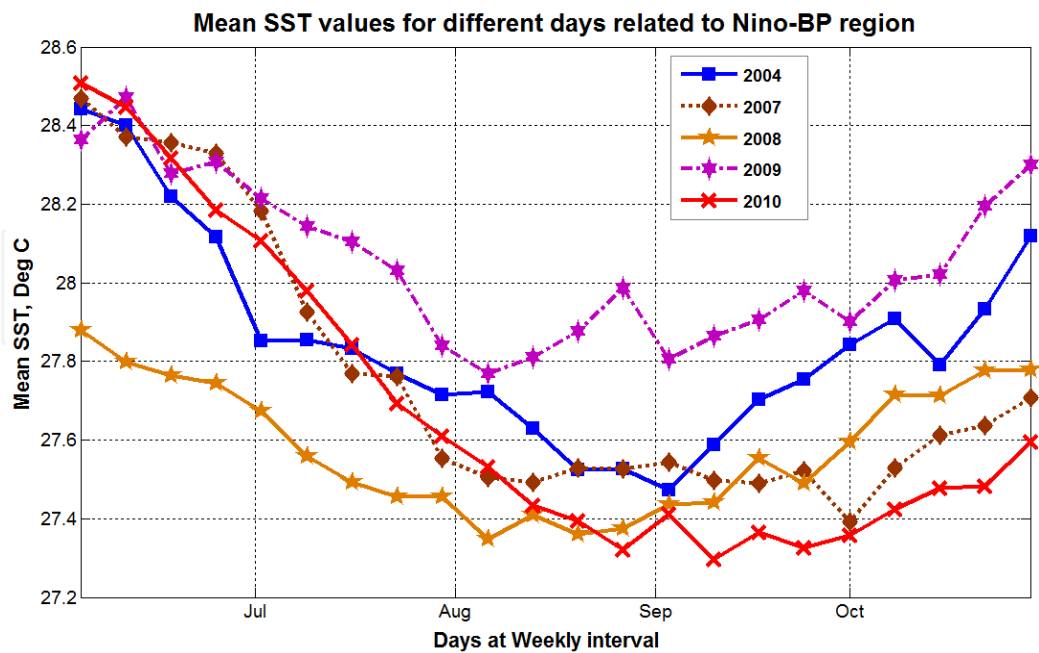


Fig. 10. Mean SST values over Nino-BP region for different days of monsoon months at weekly interval for individual years (2004-10).

For other 4 years which include 2 normal years (2007, 2010) and 2 abnormal years (2004, 2009) no definite conclusions can be drawn based on the trend and absolute values of mean SST. Fig-10 provides another clue that mean SSTs should come down to 2008 level for the monsoon to pick up. It is noted that while the mean SSTs showed gradual cooling up to end August for 2007 and 2010 the cooling trend was not enough for 2004 (12% deficient rainfall occurred compared to long period average, LPA) and 2009. In fact for 2009 mean SSTs remained high resulting in a major failure of monsoon rains (23 % deficient from LPA). Hence the mean SST over Nino-BP region can provide a better handle by monitoring it on a real time basis which may help in short-term (a week or so in advance) prediction. In order to check if the actual pixel level temperatures can provide additional information the contours of number of pixels distributed over the temperature bins 25-31 °C for the observation days (at weekly interval) for the pre monsoon period for 4 selected years (2004, 2007, 2008, 2009) are drawn and shown in Fig-11. The pattern of variation of number of low and high temperature pixels are similar in pairs for [2007, 2008] and for [2004, 2009]. Both 2004 and 2009 years show presence of high number of pixels ≥ 28 °C. This would have implications in losing the water vapour flux transport through oceanic and pre-monsoon rains before the onset of monsoon. Sometimes this may mimic arrival of monsoon at an early date. This appears to have happened during 2004.

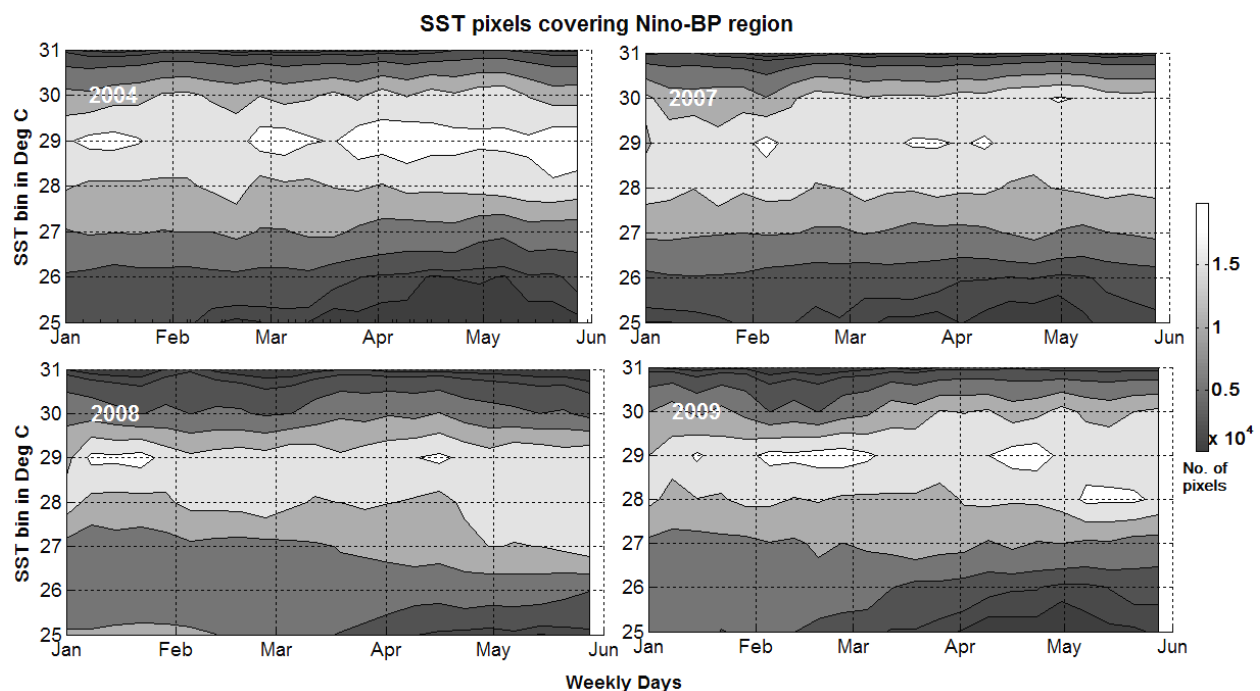


Fig. 11. Contour plots of number of pixels having different temperature values between 25-31 °C during pre-monsoon months for different years, 2004, 2007, 2008, and 2009 over Nino-BP region.

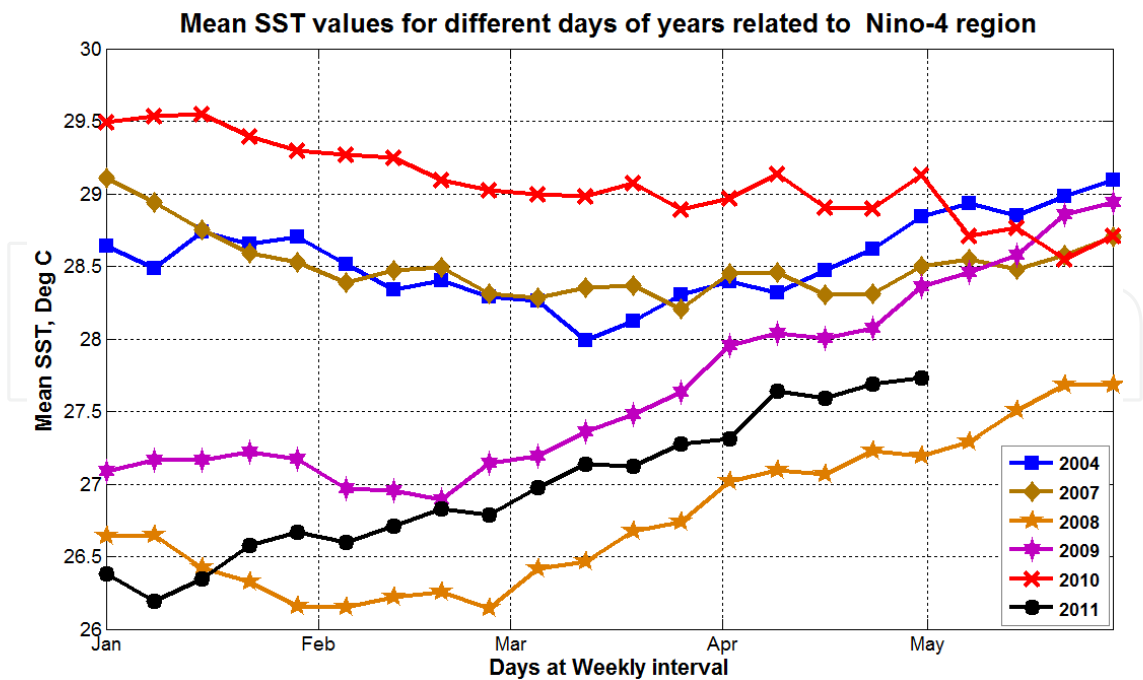


Fig. 12. Mean SST values over Nino-4 region for different days of pre-monsoon months at weekly interval for individual years (2004-11).

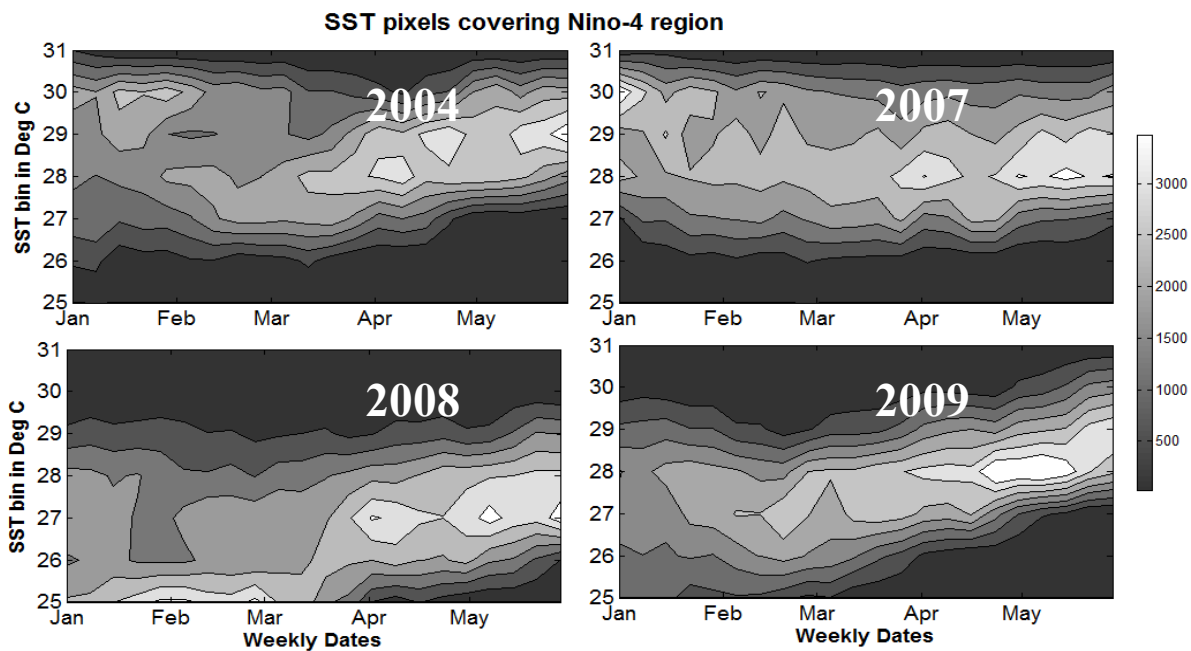


Fig. 13. Contour plots of number of pixels having different temperature values between 25-31 °C during pre-monsoon months for different years, 2004, 2007, 2008, and 2009 over Nino-4 region.

Similar analysis has been carried out for the Nino-4 region and the results presented in Fig-12 and Fig-13. The trends of mean SST over Nino-4 are similar but being a small region it could get influenced by local effects. From Fig-13 the similarities in paired years of [2007, 2008] and [2004, 2009] cannot be easily discerned as in the case of Nino-BP plots. However it

would help to conduct SST analysis for both Nino-BP and Nino-4 regions as part of the monsoon forecasting and real time modelling.

For determining the characteristics of SST pixel distribution during the build up phase of the monsoon system, monthly average values are computed and shown as bar charts over Nino-BP for the years 2004, 2007, 2008 and 2009 in Fig-14. While excess number of pixels with SST $\geq 28^{\circ}\text{C}$ is found for anomalous years 2004 and 2009 particularly in May, these were found to be only little lower during 2007. Similar analysis in Fig-15 for the Nino-4 area shows a clearer demarcation of pixel distribution comparison between the two pairs of years. During 2010 there was a strong El Nino effect from Jan-Mar and hence the prospects of monsoon looked bleak. But the situation improved subsequently with a La-Nina setting in. This change over took place at right time so that monsoon rains picked up from July onwards. A comparison of relevant parameters between 2008 and 2010 is shown in Fig-16. It can be noted that the pixel number distribution with SST in both the years are similar for the month of May which changed the prospects for a better monsoon during 2010.

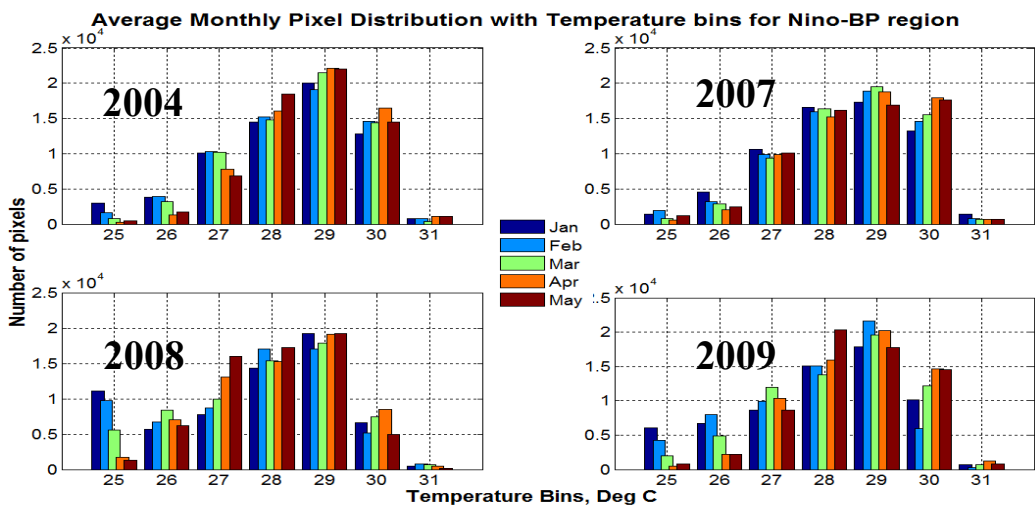


Fig. 14. Average monthly pixel (25-31 °C) number distribution for pre monsoon months of Jan-May for 2004, 2007, 2008 and 2009 over the Nino-BP region.

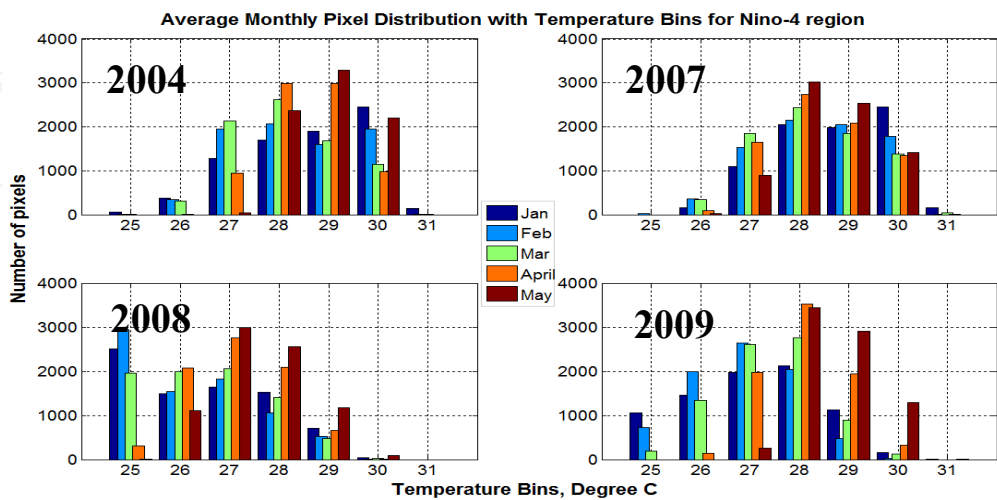


Fig. 15. Average monthly pixel (25-31 °C) distribution for pre monsoon months of Jan-May for 2004, 2007, 2008 and 2009 over the Nino-4 region.

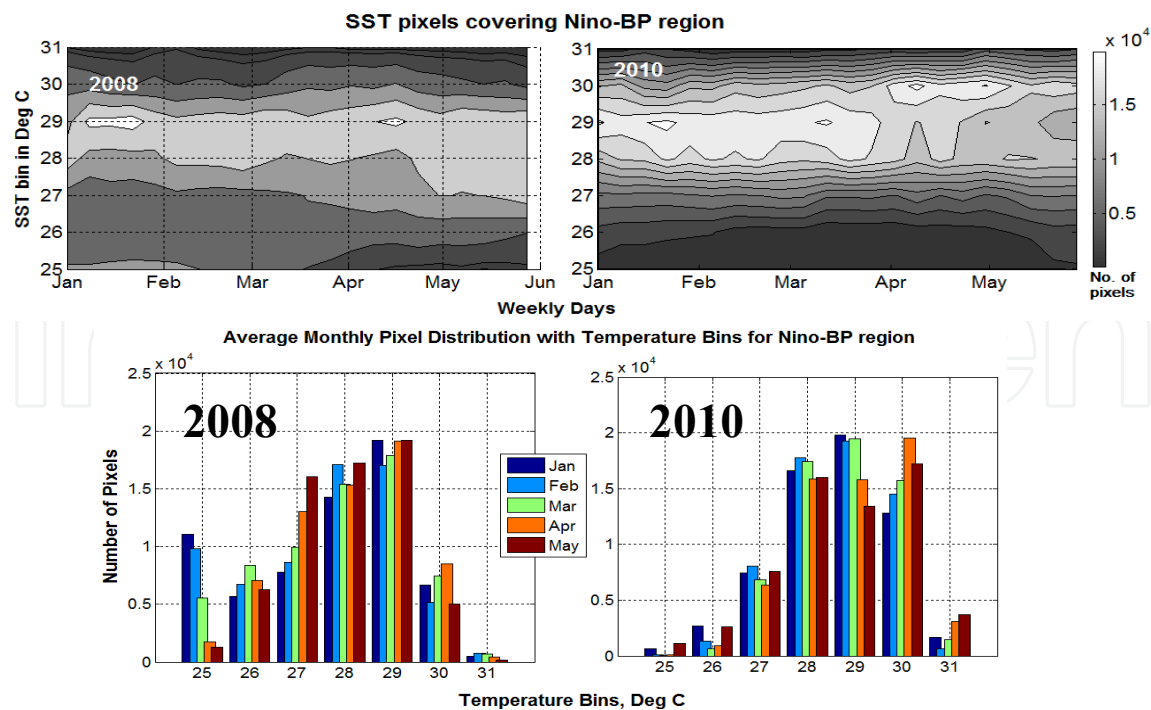


Fig. 16. Comparison of pixel number contour and monthly average pixel distribution over Nino-BP region during 2008 and 2010.

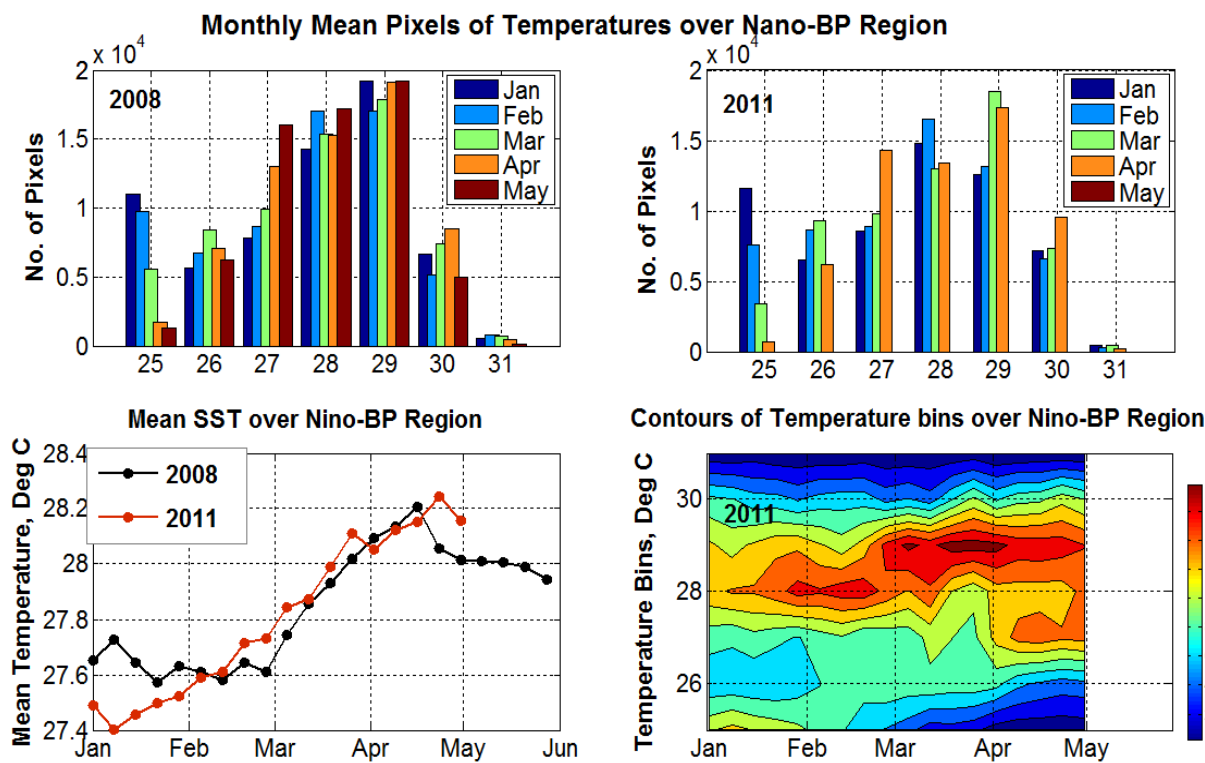


Fig. 17. (Clockwise) Comparison of monthly mean Nino-BP region pixel distribution for 2008 and up to April of 2011, time series of mean SST over Nino-BP region for 2008 and up to April, 2011 and contours of pixel numbers pertaining to temperature bins of 25-31 °C up to April of 2011.

Fig-17 shows a comparison of monsoon build up parameters of 2008 and 2011 (data used up to April 2011). It clearly shows a striking similarity in the variations of the mean monthly pixel distribution, the absolute values and the trend of mean SST over Nino-BP region between 2008 and 2011 so far (April, 2011). The contour of pixel numbers for SST bins also shows similarity to the 2008 plot up to end of April. Hence all conditions are favourable for 2011 monsoon to be a success and there are chances that it would be like the one during 2008 along with its near uniform spatial distribution.

3.4 Upper air indices of monsoon circulation

Wind and temperature data from ground to about 70 km have been collected over Thiruvananthapuram since 1971 using meteorological balloons and Russian made M-100 and Indian made RH-200 sounding rockets (Chakravarty & Datta, 1992). The rocket flights continued at regular weekly intervals up to 1990. The voluminous data has been archived and being used for various studies of troposphere-middle atmosphere coupling processes. Different types of waves like the QBO, SAO, Rossby-Gravity and Kelvin waves have been characterized using such global data sets (Fukao, 2006). Efforts have also been made to detect any upper level changes in wind pattern before the onset of the monsoon over Kerala. While there were some preliminary results on likely reversal of winds from westerlies to easterlies around 22-24 km altitudes about 4-5 days before the onset, these could not be confirmed. Taking into account that a long period data set exists and as a test year of data specifically to look for changes/reversals of upper winds in relation to monsoon activity, the Rocket Monsoon Experiment (ROMEX) was carried out during April-June, 2007 from Thiruvananthapuram under ISRO Headquarters, Bangalore. The main objective of the ROMEX campaign was to monitor the dynamical features of troposphere /stratosphere/ mesosphere from the Rocket and Balloon winds measured at frequent intervals to explore the key changes of wind patterns related to the onset features of SW monsoon over Karala coast.

The detailed results from the ROMEX campaign 2007 are available in an unpublished ISRO report. Salient campaign findings are only presented here. The long period data (1971-90) from the Thumba Equatorial Rocket Launching Station (TERLS) near Thiruvananthapuram is used to generate a statistical model of zonal winds averaged over different height ranges and then the ROMEX campaign data for 2007 is used as a test case in relation to onset date as well as seasonal rainfall. Fig-18 shows the vector wind profiles at 1 km height resolution of all the individual campaign days of balloon and rocket launches during April-June 2007. It can be noted that in particular there are 3 height ranges of interest, 11-20 km, 41-50 km and 51-60 km which show either strengthening of easterlies or reversal from westerlies to easterlies close to the onset date which was 28 May in 2007. Same data is used to get an interpolated time-height contour plot of zonal winds. The red coloured contours are for westerly winds and blue easterly. The three identified regions of interest are seen in the figure with gradual transitions of wind strength and directions.

The mean zonal winds for the identified height ranges are computed and plotted as a time series during ROMEX period. This is shown in Fig-20. It is noted that close to the onset day clear change over from westerly to easterly has taken place for the mean zonal wind in 41-50 km height range about 4-5 days in advance. The mesospheric zonal winds (mean of 51-60 km) reversed the direction just after the onset date. The easterlies in the height range (11-20 km) strengthened about 4-5 days before the onset but difficult to quantify in terms of a scale

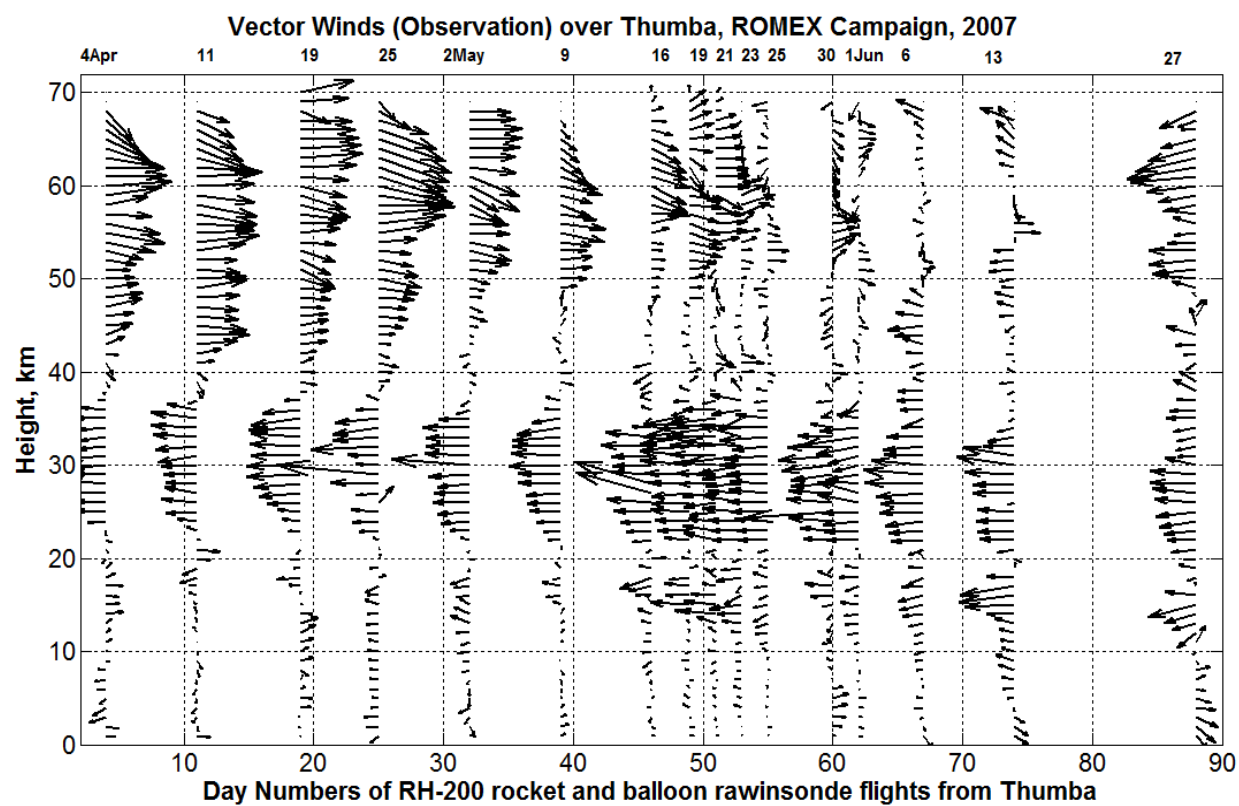


Fig. 18. Vector wind profiles of individual days of observation using RH-200 rocket and rawinsonde balloon launches from Thumba during April-June 2007 under ROMEX campaign.

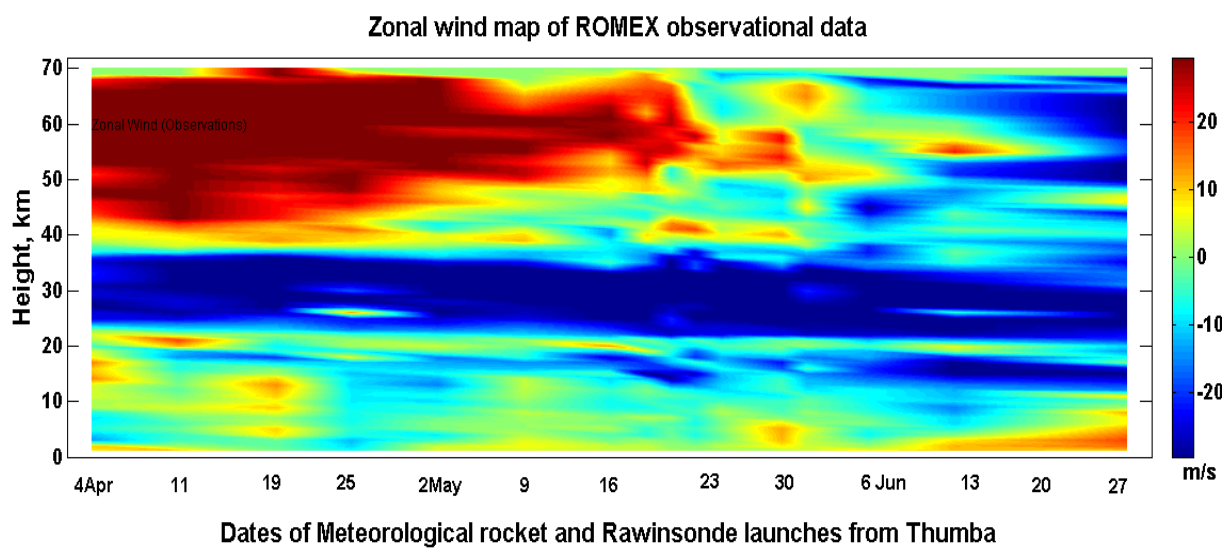


Fig. 19. Smoothed contour plot of zonal winds between 0-70 km height ranges over Thumba. Red contours show westerly winds and blue easterlies.

for such strengthening. Acquiring a value of mean zonal wind of 10 m/s in this troposphere/ lower stratosphere height range appears to be a rough figure to work with for linking with monsoon.

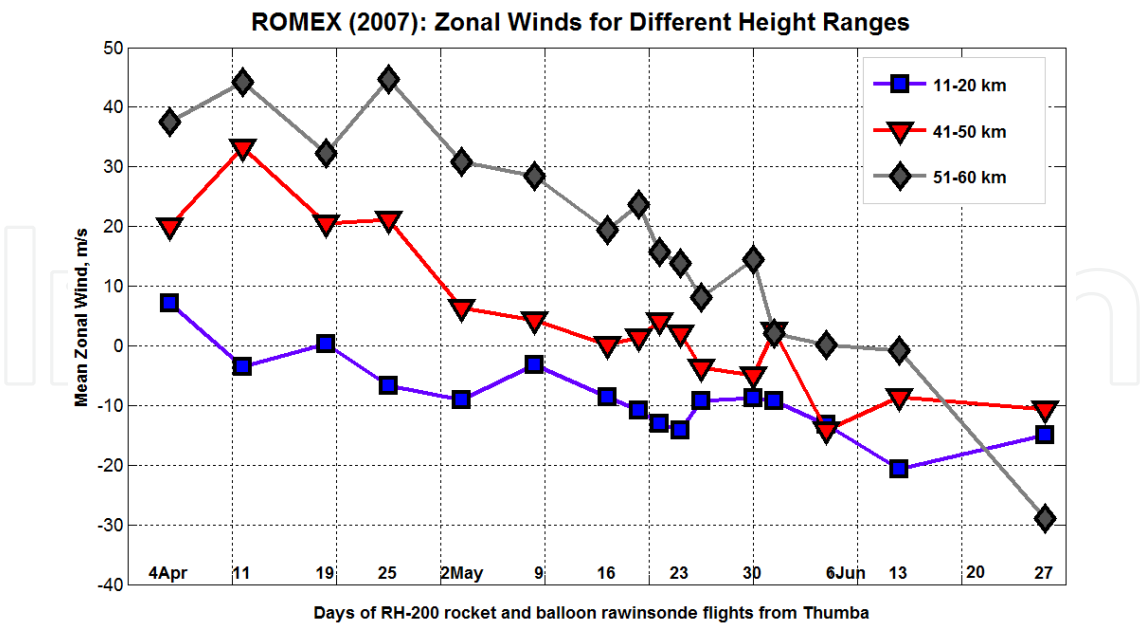


Fig. 20. Time series of mean zonal winds for height ranges, 11-20 km, 41-50 km and 51-60 km during ROMEX campaign period.

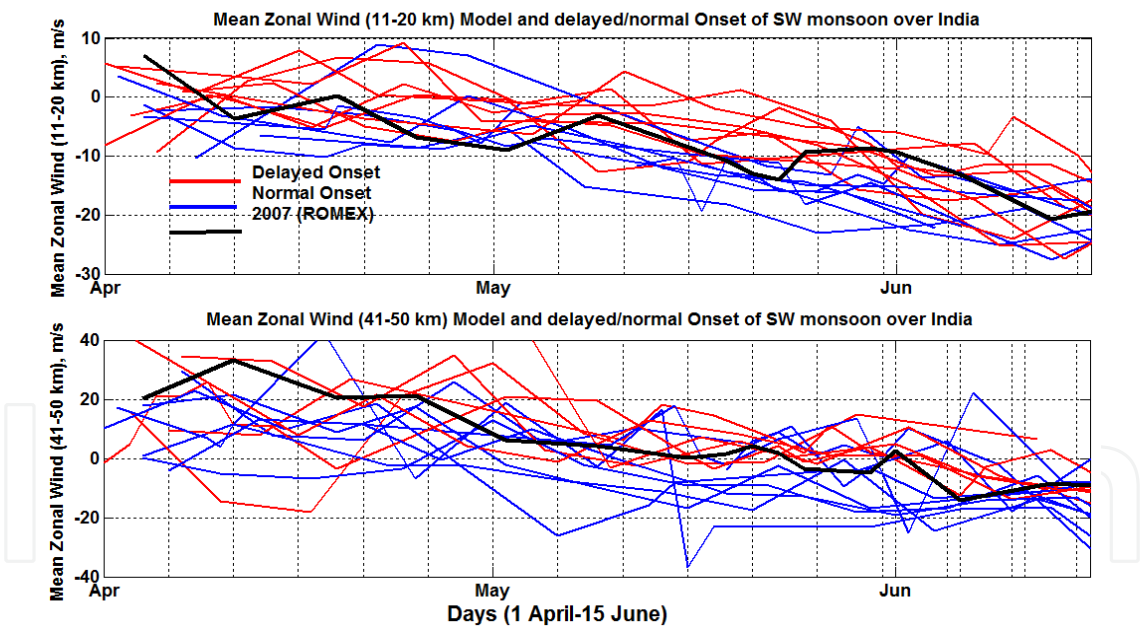


Fig. 21. Trends of mean zonal winds for 11-20 km and 41-50 km height ranges from long period (1971-90) balloon/rocket data differentiated for normal (blue) and delayed (red) monsoon and how the ROMEX data for 2007 fares as a test case (black).

Fig. 21 shows the statistical data of mean zonal winds between 11-20 km and 41-50 km distinguished in terms of normal and delayed monsoon with red and blue lines respectively. Over these climatological pattern of variation the ROMEX line for 2007 is superimposed. It is clear that the 2007 data fits closer to the blue lines which are for the normal monsoon onset days.

4. Conclusion

4.1 The rainfall during the SW monsoon period (June-September) constitutes the main source of water in India for agriculture (particularly pertaining to the 'Kharif' crops), hydroelectric power generation and drinking water requirements. There is a large inter annual and intra seasonal variation of this water resource due to variations in the monsoon genesis and progress. While the spatial distribution of monsoon rainfall is caused due to fast response parameters and local impacts, both the onset date and the season's integrated rainfall are caused by slowly varying boundary conditions and forcings like that of the sea surface temperature, snow cover etc. Hence the variation of sea surface temperature is taken up here for prognosis studies.

4.2 Based on the AQUA satellites all weather microwave sensor data a near real-time interactive computer model has been developed to extract daily minimum global SST values of 1440x720 pixels, each pixel covering 25 km x 25 km of lat-long area. The programme also selects specific oceanic region like the Nino-4 and Nino-BP to compute daily mean SST over the region and can add into previous days data to generate a real time trend. Such trends of previous years during 2003-2010 are used to study the variations and its influence on the onset dates and the seasonal rainfall. In the background of the statistics or the real-time model the data of current year is analysed up to April 2011. The progress of the absolute SST values and its trend indicate a near normal monsoon during 2011 somewhat similar in characteristics that of 2008.

4.3 There have been many studies to link the occurrence of major El Nino and La Nina events with the changes in the monsoon onset date. Such analysis is carried out in this report also and it is found that the strong El Nino/La Nina events have a negative/positive effect on monsoon. But considering the whole range of seasonal mean SOI it is found that statistically the positive SOI values have positive impact but negative SOI values have both positive and negative impacts. Thus the SOI index has only limited applicability as a predictor parameter. Hence the main purpose of this study is to make a more quantitative assessment at pixel level of the SST linked monsoon variability.

4.4 A novel sensitivity analysis is carried out by selecting a broader Pacific Ocean region called Nino-BP (defined by the author). Within this region the pixels are counted and placed in temperature bins of values 25-31 °C. The resultant matrix provides daily number of pixels distributed over these temperature bins. This pixels numbers are plotted as time-bin contours or as bar graphs. The main result from this analysis shows that larger number of pixels distributed in temperature bins ≤ 28 °C during pre monsoon or during monsoon months has a positive impact on the onset date and total seasonal rainfall. Reverse applies for larger number of pixels in temperature bins of value > 28 °C.

4.5 As collateral and useful information on the prospects of onset date, the time sequence of mean zonal wind values over TERLS between 11-20 km and 41-50 km height ranges provide the possible transition date about 4-5 days in advance by comparing its real time trend with a statistical model of long period balloon and rocket data during 1971-90.

5. Acknowledgement

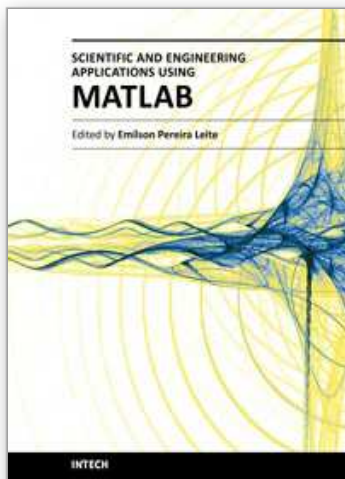
AQUA/AMSR-E data are produced by Remote Sensing Systems and sponsored by the NASA Earth Science REASoN DISCOVER Project and the AMSR-E Science Team. Data are available at <http://www.remss.com>. Author acknowledges the help provided by Dr. K.

V. S. Namboodiri, TERLS, Vikram Sarabhai Space Centre, Thiruvananthapuram, India in coordinating the ROMEX campaign and the financial support provided by Chairman, Indian Space Research Organization (ISRO) Headquarters, Bangalore, India for the ROMEX campaign.

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Scientific and Engineering Applications Using MATLAB

Edited by Prof. Emilson Pereira Leite

ISBN 978-953-307-659-1

Hard cover, 204 pages

Publisher InTech

Published online 01, August, 2011

Published in print edition August, 2011

The purpose of this book is to present 10 scientific and engineering works whose numerical and graphical analysis were all constructed using the power of MATLAB® tools. The first five chapters of this book show applications in seismology, meteorology and natural environment. Chapters 6 and 7 focus on modeling and simulation of Water Distribution Networks. Simulation was also applied to study wide area protection for interconnected power grids (Chapter 8) and performance of conical antennas (Chapter 9). The last chapter deals with depth positioning of underwater robot vehicles. Therefore, this book is a collection of interesting examples of where this computational package can be applied.

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S. C. Chakravarty (2011). Sea Surface Temperature (SST) and the Indian Summer Monsoon, Scientific and Engineering Applications Using MATLAB, Prof. Emilson Pereira Leite (Ed.), ISBN: 978-953-307-659-1, InTech, Available from: <http://www.intechopen.com/books/scientific-and-engineering-applications-using-matlab/sea-surface-temperature-sst-and-the-indian-summer-monsoon>

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