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Progress of Indian summer monsoon onset and convective episodes over Indo-Pacific region observed during 2009-2014

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सार – इस शोध पत्र में 2009 से 2014 के वर्षों के लिए दक्षिण पूर्वी बंगाल की खाड़ी/अंडमान समुद्री (महासागर) क्षेत्रों से लेकर भारत के सुदूर दक्षिण पश्चिमी भाग (केरल) में ग्रीष्मकालीन मॉनसून के प्रारंभ होने की प्रगति की जाँच की गई। इन वर्षों के लिए मई और जून के पूर्वाद्ध के लिए डूंडी उपग्रह अभिग्राही स्टेशन सें अभिलेखित किए गए मेघ चित्रों के साथ-साथ सिनॉप्टिक मौसम सूचना, इनसेट/कल्पना-1 का इस विश्लेषण में उपयोग किया गया। इसमें NOAA उपग्रहों से प्राप्त OLR आंकड़ों और NCEP/NCAR से उपरितन वायु पुनर्विश्लेषित पवनों का भी उपयोग किया गया। इस अध्ययन की अवधि में मॉनसून प्रारंभ होने की तारीखों के साथ-साथ महासागर से केरल तक मॉनसून के आगे बढ़ने के लिए अपेक्षित समय में अत्यधिक भिन्नता देखी गई। इस प्रकार की भिन्नताओं के कारणों का पता लगाने का प्रयास किया गया है। परिणामों से पता चला है कि इन पर वर्ष 2009, 2010, 2013 और 2014 में उत्तरी हिन्द महासागर में तथा वर्ष 2011 और 2012 में पश्चिम उत्तरी प्रशांत महासागर क्षेत्र में बने तीव्र विक्षोभों का योगदान रहा है। सिनॉप्टिक विश्लेषण के माध्यम से इनके प्रभाव को बताते हुए और इन घटनाओं के प्रत्येक मामले की समीक्षा करते हुए मॉनसून के प्रारंभ होने के समय और इनकी प्रगति की प्रेक्षित भिन्नताओं में इन संवहनी घटनाओं की भूमिका को बताने के लिए इनमें केन्द्र बिन्दु को सीमाबद्ध करते हुए विश्लेषण किए गए। भारतीय ग्रीष्मकालीन मॉनसून के प्रारंभ होने की प्रगति के पूर्वानुमान में इस सूचना की उपयोगिता को भी बताया गया है।

ABSTRACT. Summer monsoon onset progress from the oceanic region of Southeast Bay of Bengal / Andaman Sea (Oceanr) up to extreme southwestern part of India (Kerala) for the years 2009 to 2014 is investigated. Synoptic weather information, INSAT/KALPANA-1 as well as cloud imageries archived from Dundee Satellite Receiving Station for May and early June for these years are used in the analysis. Upper-air reanalyzed winds from NCEP/NCAR and OLR data archived through NOAA satellites are also used. During the study period, the dates of monsoon onset as well as the time required for the advancement of onset from Oceanr to Kerala have shown a large variation. An attempt is made to investigate the causes for such variations. The results indicate that intense disturbances which formed over north Indian Ocean in 2009, 2010, 2013 and 2014 and over west-north Pacific Oceanic region in 2011 and 2012 have contributed for the same. Analysis is carried out, limiting its focus to bring out the role of these convective events in the observed variation of onset timing and its progress by taking case to case review of these events and bringing out their influence through synoptic analysis. Utility of this information in prediction of the progress of Indian summer monsoon onset is also brought out.

Key words – Monsoon onset, ITCZ, Intense disturbances, OLR.

1. Introduction

Summer monsoon (South West Monsoon : SWM) season is the most important rainy period for the agro-economically driven country like India. The monsoon onset is a crucial event since it brings first shower of the season heralding the sowing of crops. A late or early onset and break periods in the monsoon rainfall have devastative effects on agriculture even if mean rainfall in the season as a whole is normal (Raju *et al*., 2007). The onset takes place as a sudden 'burst' which is characterized by abrupt changes occurring through sudden increase in cross-equatorial flow, establishment of low-level jet and consequent sharp increase in the rainfall activity over south Kerala coast of India (Mahajan *et al*., 1986). The long-term normal date of onset of Indian summer monsoon over Kerala is 1 June with a standard deviation of about one week. In past, efforts have been made to understand and predict the onset event. Ananthakrishnan and Soman (1988) have discussed the variability of the onset over Kerala and brought out criteria to declare the same. Ghanekar *et al*. (2003) have taken a brief review of studies on this topic. Based on conventional synoptic data, they have developed a method to predict the onset date over Kerala using the information about the characteristic peak in pre-monsoon convective activity over southwest peninsular Indian region. Pai and Rajeevan (2009) have discussed the present criteria to declare the official date of onset of Indian summer monsoon over Kerala. They have also discussed the present onset prediction method of India Meteorological Department (IMD). One of the predictors (pre-monsoon rainfall peak date) used in their method is similar one to that brought by Ghanekar *et al*. (2003). In recent past, Ghanekar *et al*. (2010) have improved their earlier method by using satellite-derived Outgoing Longwave Radiation (OLR) data.

The progress of summer monsoon onset over Asia-Pacific region has been studied by various researchers in the past. The occurrence of monsoon is known to be related with the seasonal migration of near-equatorial Inter-Tropical Convergence Zone (ITCZ). During the onset phase of Indian summer monsoon, the oceanic ITCZ shows northward progression from its near-equatorial position to the continental (20° - 25° N) position (Sikka *et al*., 1986). Wang and LinHo (2002) mentioned that the large-scale onset of the Asian monsoon rainy season starts from the region of Asian marginal seas (Arabian Sea, Bay of Bengal and South China Sea). Mao *et al*. (2004) studied the relationship between the onset of Asian summer monsoon and the structure of the Asian subtropical anticyclone. On the basis of their results, Mao and Wu (2007) stated that the Bay Of Bengal Summer Monsoon (BOBSM) onset may be considered as a precursor to the subsequent establishment of the monsoon rainy season.

The progress of the onset of SWM over Indian region normally begins from the oceanic region of southeast Bay of Bengal/Andaman Sea. The progress from this oceanic region up to southern tip of India (Kerala) is an important process since it decides the date of arrival of monsoon over the mainland of India. Prior to the monsoon onset over Andaman Sea and southeast Arabian Sea, normally, sea level pressure field is dominated by two anticyclones, situated over the central Bay of Bengal and central Arabian Sea. As such, the ITCZ and the belt of low level westerlies to its south are restricted within equator and 5° N. The Bay of Bengal anticyclone weakens around the end of April and the westerlies extend to about 10° N by the first fortnight of May. This is followed by the onset of monsoon rains over Andaman Sea region. The Arabian Sea anticyclone begins to weaken only by the third week of May and disappears thereafter. With this, the near equatorial low level westerlies begin to extend over southeast Arabian Sea & the monsoon rains begin over Kerala on 1 June. This happens under normal conditions. However, there are year to year changes in these processes which occur due to many reasons.

Over the Indian region, the monsoon onset as well as its further progress occurs in multiple spells. On some occasions, after the arrival of monsoon current over Bay of Bengal, a slow progress is noticed in its further advance towards Kerala. While in some years, the monsoon advance is seen to be associated with the formation and movement of synoptic disturbances (Ghanekar *et al*., 2010). Due to these uncertainties, accurate forecasting of monsoon onset still remains a challenging task. Hence it is necessary to understand the causes creating the variability in the onset progress. Nair and Mahajan (2010) have studied a few cases when onset over Andaman Sea region occurred at on early date but showed delay or early advance up to Kerala. They have discussed the role of upper tropospheric temperature, tropospheric kinetic energy and equatorial convection in the observed variation in the onset progress.

The formation of synoptic scale weather disturbances is one of the factors causing for the year to year variation, as the rains during the onset phase accompany these events. Some of these disturbances intensify into tropical depressions / cyclones and the occurrence of these disturbances and the convective episodes associated with these events dictate the onset of monsoon on either region. Onset of monsoon in several years is known to be facilitated by the formation of a cyclonic storm at leading edge of the strong mean equatorial westerlies in the lower and middle troposphere (Krishnamurti *et al*., 1981). Feng *et al*. (2013) attempted to study influence of cyclonic/anti-cyclonic circulation and ocean heat content in the tropical West-North-West Pacific Ocean (WNWP) on BOBSM onset. They concluded that the WNWP heat content is a key factor in controlling the late/early onset of BOBSM. Hence, it may also be relevant to examine cyclonic events forming even over the region of WNWP. In view of this, the present study attempts to investigate the SWM onset process from the oceanic region of South Bay of Bengal/Andaman Sea up to Kerala for recent six years (2009 to 2014). The study discusses inter-annual variation in the monsoon advance and attempts to understand the causes for such variation by investigating synoptic weather conditions associated with the advancing phase of monsoon during the study period. Scope of study is narrowed to cover only one aspect of variation as to investigate the influence of intense weather systems formed over Indo-Pacific region on the progress of monsoon onset.

2. Data

All India Daily Weather Summaries and Weekly Weather Reports, prepared by IMD, Pune, for the months of May and June and for the years 2009 - 2014 are used to

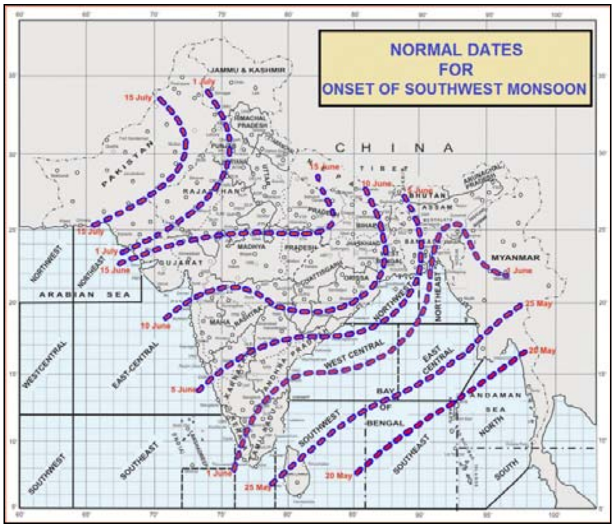


Fig. 1. Normal dates of the onset of southwest monsoon over Indian region

investigate synoptic conditions during pre-onset and onset period of the Indian summer monsoon. Additional meteorological information is downloaded on real time from the website of IMD (http://www.imd.gov.in) for the same period. INSAT satellite cloud imageries are used to study cloud conditions over Indo-Pacific region. In this analysis, daytime 0600 UTC (11:30 Indian Standard Time: IST) KALPANA-1 Visible (VISPIC) and Infra Red (IRPIC) pictures are mainly used. For the years 2012 and 2013, INSAT-3A Infra Red (IRPIC3A) as well as Visible (VISPIC3A) and for 2014, INSAT-3D Visible (VISPIC3D) cloud imageries are used. In addition, 06 UTC METEOSAT (IODC) and MTSAT Thermal Infra Red Satellite Cloud Imageries from the Dundee Satellite Receiving Station (DSRSTIR) downloaded from the website of Natural Environment Research Council (NERC) Satellite Receiving Station, Dundee University, Scotland (http://www.sat.dundee.ac.uk/) are also used. In this paper, DSRSTIR satellite pictures are presented for the year 2011 only.

Information of cyclonic storms is also taken from the website of Co-operative Institute for Meteorological Satellite Studies Space Science and Engineering Center (CIMSS), University of Wisconsin - Madison (http://tropic. ssec.wisc.edu). Daily grid-point OLR data (2.5° × 2.5° Latitude / Longitude) derived from National Oceanic and Atmospheric Administration (NOAA) polar orbiting satellites over the region bounded by the latitudes 25° N - 25° S and the longitudes 40° E - 160° E, taken from the web-site http://iridl.ldeo.columbia.edu/ SOURCES/. NOAA/.NCEP/.CPC/.GLOBAL/daily/ for the period 1 May to 10 June for the years 2009-2013 are used in the study. In addition to this, daily NCEP (National Centre for Environmental Prediction) / NCAR (National Climate Analysis Centre) reanalysed 0000 UTC upper-air winds at same resolution and period (NCWINDS) taken from http://www.esrl.noaa.gov/psd/, (Kalnay *et al*., 1996) are also used. This data is taken and analysed over the study domain bounded by the longitudes 40° E - 110° E and the latitudes 25° N - 25° S for all standard levels of the troposphere, however, the results are presented for 850 and 500 hPa levels only.

3. Results and discussion

3.1. *Onset dates over south Bay of Bengal/Andaman Sea region and Kerala*

Fig. 1 presents the long-term normal map of the onset dates of SWM over Indian region. From the figure it can be noticed that normally, the onset show north-westward progress, beginning from the oceanic region of southeast Bay of Bengal/Andaman Sea region (Oceanr) towards the Indian sub-continental region. The onset of SWM over the Indian land normally begins from the extreme southwest part of the country, *viz*., south Kerala region (Kerala). For every year, IMD gives special importance to declare the arrival of onset over these two regions and such dates declared by them are used in the present study. Table 1 gives the information about the actual and long-term normal dates of monsoon onset over Oceanr and Kerala for the years 2009 - 2014. The Table 1 also gives the departures from the respective normals over these regions as well as the time required for the advancement from Oceanr to Kerala. The table thus gives a summary of inter-annual variation in the monsoon onset progress from Oceanr and Kerala.

It is seen from Fig. 1 and Table 1 that normally onset sets in over Oceanr on 20 May and over Kerala on 1 June. However, during the study years, the earliest onset over Oceanr occurred on 17 May in 2010 and 2013 while the latest one occurred on 29 May in 2011 while, the earliest onset over Kerala occurred on 23 May in 2009 and latest on 6 June in 2014 (Table 1). Thus, it is seen that the monsoon onset over Oceanr and Kerala occurred within a time span of 17 May and 6 June. During the study period, events are observed when onset over Oceanr occurred early (delayed) but appeared delayed (early) over Kerala. The journey of the onset from Oceanr to Kerala normally gets covered in 12 days (Fig. 1 and Table 1). However, during the study years, the monsoon arrived over both these regions simultaneously in the year 2011 while, it has taken 19 days for its progress from Oceanr to Kerala in 2014 (Table 1). Hence, just within a period of six years, the date of occurrence of onset, the manner of progression as well as the time taken for the advance of monsoon from Oceanr to Kerala has shown a large variation. On this background, the techniques which

TABLE 1

Summer monsoon onset dates (for the years 2009-2014 and the normal) and the departures from normal over Oceanr and Kerala and the time duration required for the advancement of monsoon onset from Oceanr to Kerala (for individual years and the normal)

S. No.(↓)/ Col. No.(→)	Year	Onset over Oceanr		Onset over Kerala		Time duration required for onset advancement from Oceanr to Kerala (days)
		Onset date	Departure from normal (days)	Onset date	Departure from normal (days)	
(1)	(2)	(3)	(4)	(5)	(6)	(7)
1	2009	20 May	0	23 May	-9	3
2	2010	17 May	-3	31 May	-1	14
3	2011	29 May	9	29 May	-3	0
4	2012	23 May	3	05 June	4	13
5	2013	17 May	-3	01 June	0	15
6	2014	18 May	-2	06 June	5	19
	Normal	20 May	-	01 June	-	12

give long-range prediction of monsoon onset (Pai and Rajeevan, 2009; Ghanekar *et al.*, 2010) may create uncertainty in prediction. In view of this, the study attempts to investigate the factors responsible for such variations observed in the advancing phase of monsoon onset from Oceanr to Kerala, during the study period.

3.2. *3-day running mean OLR over the regions of South Arabian Sea and South Bay of Bengal*

In the new criteria of IMD, INSAT derived daily OLR, averaged over the region bounded by the latitudes 5° N - 10° N and the longitudes 70° E - 75° E is used as one of the parameters to declare the date of the onset over Kerala (Pai and Rajeevan, 2009). OLR is commonly used as a proxy of tropical convection. In present analysis, the progress of monsoon onset from Oceanr to Kerala is studied by analysing NOAA based OLR data.

Fig. 2 depicts 3-day running mean OLR, averaged over the latitudinal belt of 5° N-15° N over the regions *viz*., (1) South Arabian Sea region (SAS: 60° E - 77.5° E, black line), (2) South Bay of Bengal region (SBOB: 80° E - 92.5° E, blue line) and (3)West North Pacific Oceanic region (WNP : 130° E - 160° E, red line) for the period 1 May to 10 June for the years 2009 to 2013. The area averaged mean OLR are smoothed by taking 3-day moving averages to filter out sub-synoptic variations and to study the convective episodes associated with the seasonally migrating ITCZ over these regions. The features over WNP shall be discussed latter in section 3.4. The blue (black) arrow in all the sections of the figure indicates date of monsoon onset over Oceanr (Kerala).

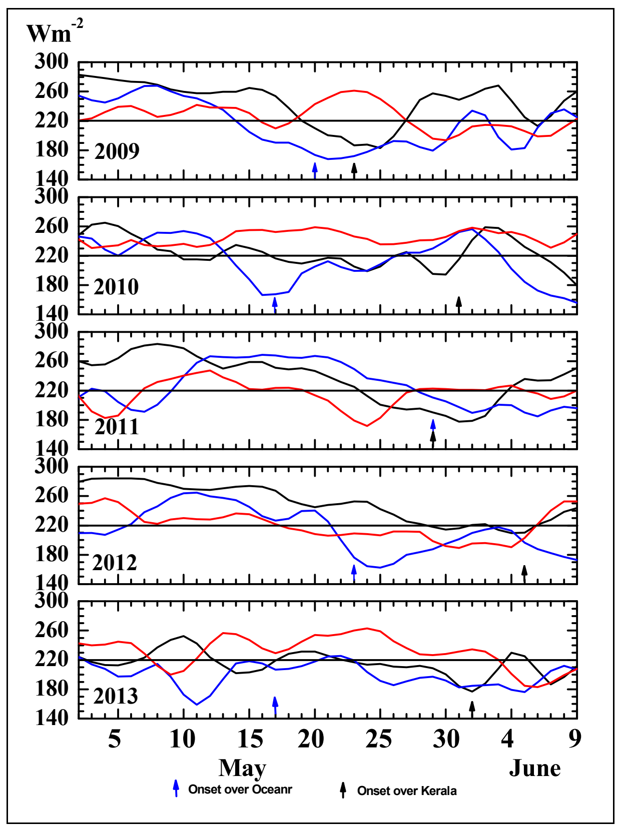
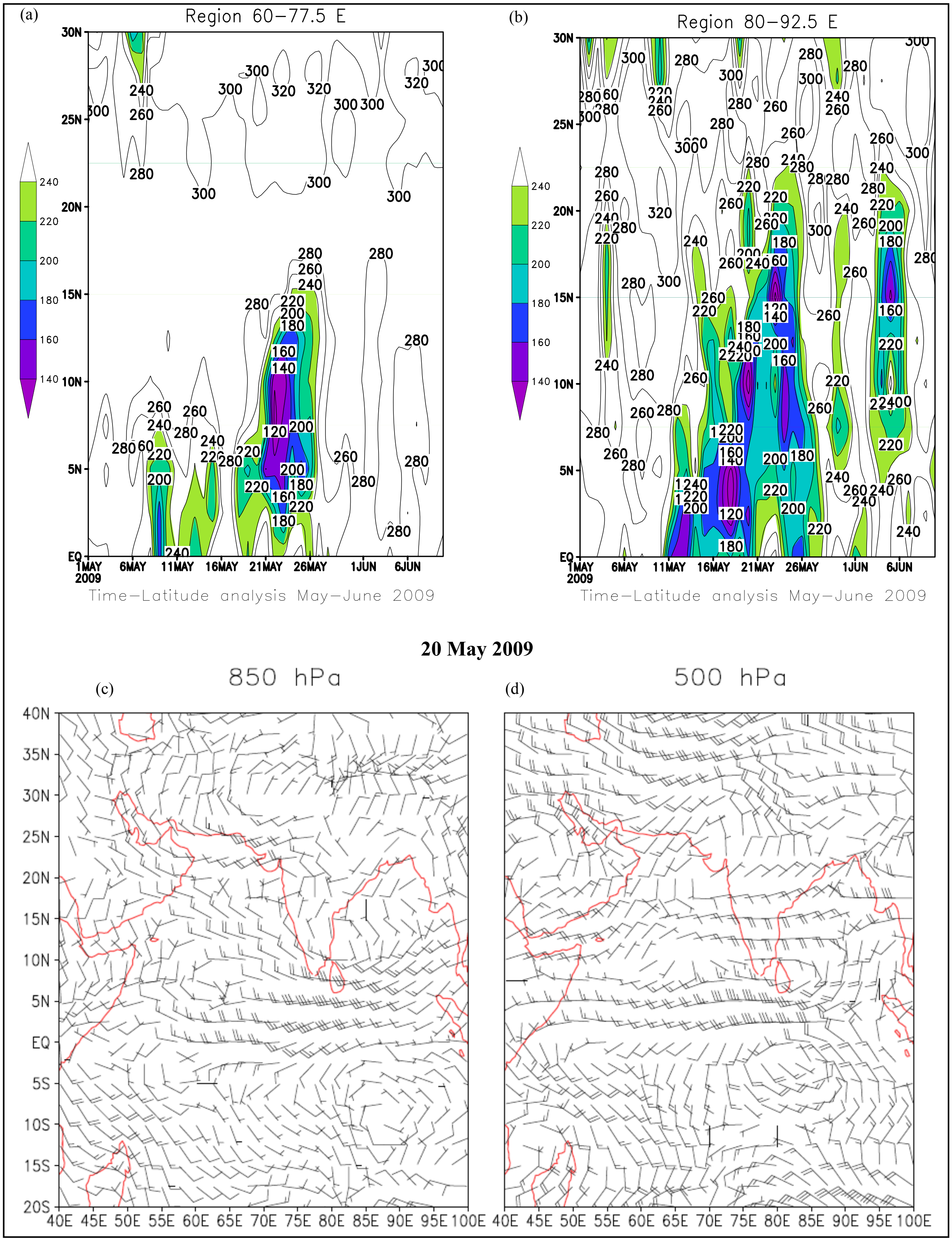


Fig. 2. 3-day running mean OLR, averaged for the latitudinal belt of 5° N - 15° N over (1) South Arabian Sea region (SAS : 60º E - 77.5º E, black line), (2) South Bay of Bengal region (SBOB: 80º E - 92.5º E, blue line) and (3) West North Pacific Oceanic region (WNP: 130º E - 160º E, red line), for the period 1 May to 10 June for the years 2009 to 2013



Figs. 3(a-d). Meridional time section of mean OLR over (a) Arabian Sea (AS : 60º E - 77.5º E) and (b) Bay Of Bengal (BOB : 80º E - 92.5º E) for the period 1 May to 10 June for the year 2009 and NCEP/NCAR 0000 UTC upper-air reanalysed winds (wind speeds are in knots) for (c) 850 hPa and (d) 500 hPa levels for 20 May, 2009

It is seen from Fig. 2 that OLR shows a seasonal decrease over both SAS and SBOB regions up to their respective onset dates, but on an average, the decrease over SAS is gradual and more systematic while that over SBOB is seen as a sharp decrease in most of the years. A distinct fall is noticed around the respective dates of onset over both these regions, dipping well below 220 Wm^{-2} in most of the years. Such low values of mean OLR around the time of onset signify presence of well-organised convective clouds associated with the ITCZ bringing the onset over the regions. The drop observed around the time of the onset is noticed to have followed by an increase in OLR values for a few days in most of the years over both the regions. Such increase in OLR (decrease in cloudiness) is due to further northward movement of ITCZ and the onset over mainland of India. The fall in OLR associated with the onset over SBOB is observed a few days before to that over SAS, except for the year 2011. It is also noticed that the year to year variations of such dips well supplement the observed (large) variations in the onset timing and progress as discussed in section 3.1 above. To investigate the possible causes responsible for such variations, synoptic features associated with the advancing phase of monsoon from Oceanr to Kerala are investigated.

3.3. *Synoptic features associated with the advancing phase of monsoon from Oceanr to Kerala*

The progress of summer monsoon onset occurs through the oceanic regions of Arabian Sea and Bay of Bengal towards the mainland of India. The Arabian Sea monsoon stream strikes the west coast of Kerala, moving further northwards towards Konkan coast (Mumbai) and Gujarat while the Bay of Bengal stream, progressing towards Assam and north-eastern parts of India, moves towards northwest India (Fig. 1). Hence, the northward progress of monsoon onset is discussed by investigating the movement of associated convective clouds over (1) Arabian Sea (covering west coast of India) region (AS : 60° E - 77.5° E) and (2) Bay of Bengal region (BOB : 80° E - 92.5° E) with the help of OLR analysis. For this, meridional time sections of daily mean OLR over these regions are prepared for the latitudes Equator (EQ)-30° N, for the period 1 May to 10 June and for the years 2009 to 2013. Although these sections are prepared up to 30° N, the discussion about the progress of onset is mainly done for the advancing phase of monsoon from Oceanr to Kerala (the gateway of monsoon over mainland of India) by assessing the associated synoptic features.

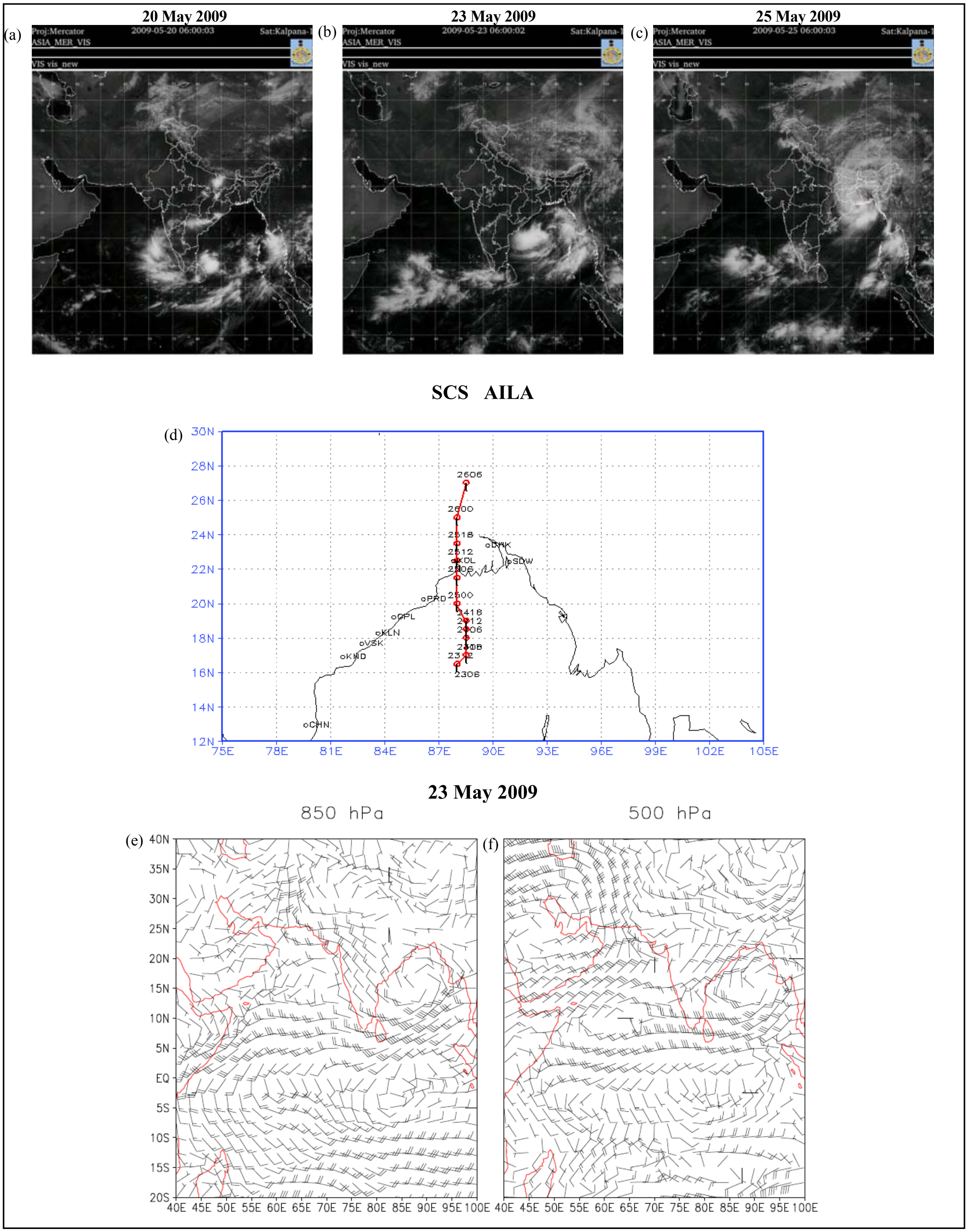
Based on the OLR analysis over AS and BOB (shown in a and b sections of the Figs. 3, 5, 11, 13 and 7 for the years 2009 to 2013 respectively), movement of organised convective clouds (identified through OLR < 220 Wm^{-2} over these regions) associated with the northward migrating ITCZ is investigated. These regions have zonal extension of more than 10°, which is in accordance with that of Sikka and Gadgil (1980) for identifying Maximum Cloud Zone (MCZ). Tracks of the intense systems, formed around the period of monsoon advance are also presented and investigated. In addition, Satellite cloud imageries for selected dates, are referred to discuss cloud conditions while upper-air charts showing wind analysis (NCWINDS, wind speeds given in knots) are presented to assess the flow patterns and the strength of monsoon.

The study covers only one aspect in understanding the cause for observed variation in the progress of monsoon onset from Oceanr to Kerala and that is to take account of the influence of intense weather systems formed over Indo-Pacific region. In this respect, it is found that the onset features show a few similarities for some pair of years but exhibited uniqueness in some way or other. Hence, all these cases are discussed separately, making a brief description of associated synoptic features giving emphasis to the intense disturbances formed over North Indian Ocean and over North West Pacific Ocean around the period of onset progress from Oceanr to Kerala only.

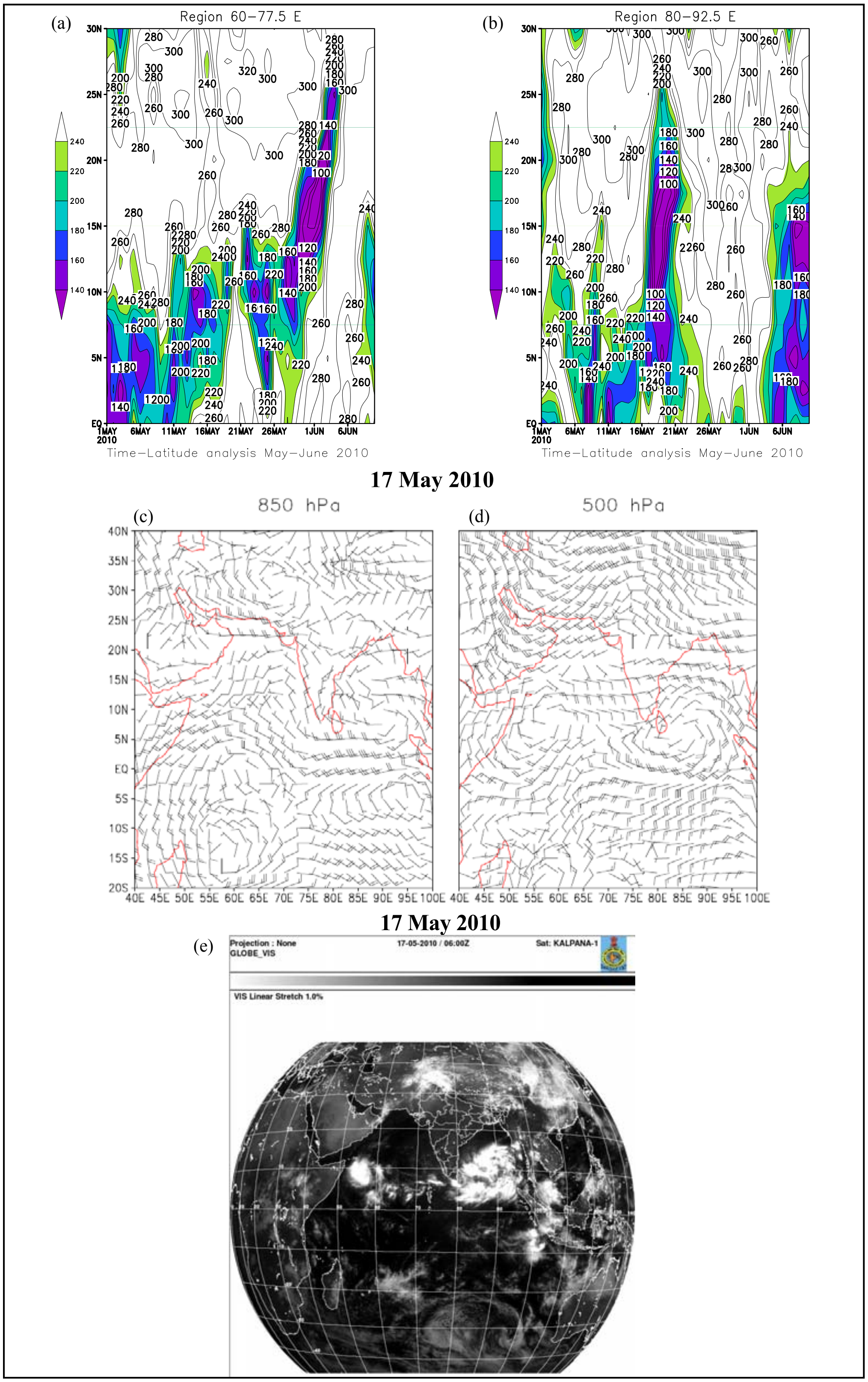
It was observed that around this period, during 2009, 2010, 2013 and 2014, intense weather disturbances were formed over north Indian Oceanic region. Hence, the onset features for this group of years are discussed in the beginning and the discussion for the other two years (2011 and 2012) is done subsequently. The features of the year 2014 are discussed based on synoptic weather information and satellite cloud imageries only.

3.3.1. *Features of onset 2009*

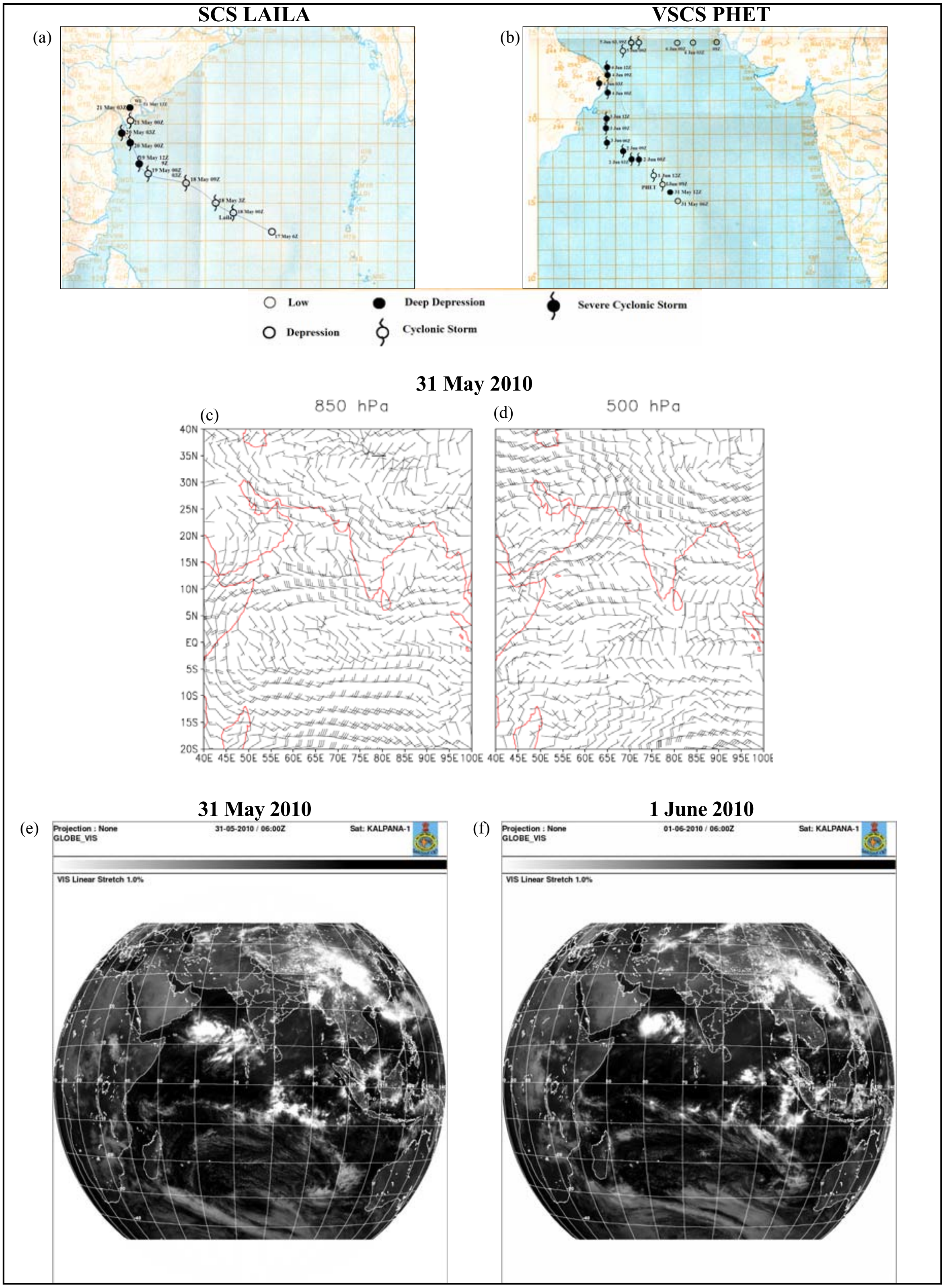
During 2009, the onset over Oceanr occurred on 20 May. The meridional time section of mean OLR over BOB, shown in Fig. 3(b) depicts a rapid northward movement of OLR < 180 Wm^{-2} (with pockets of OLR < 160 Wm^{-2}) from about 18 May reaching up to 12° N by 20 May. Such low OLR values signify presence of deep convective clouds associated with the onset. Figs. 3 (c&d) present NCWINDS for 20 May, 2009 for 850 and 500 hPa levels respectively. At 850 hPa, westerlies are noticed over southern Bay of Bengal to the north of equator, extending up to 10° N [Fig. 3(c)]. While at 500 hPa an east-west shear line is noticed over the same region [Fig. 3(d)]. Fig. 4 (a) presents VISPIC for the same day. From the cloud picture, organised clouds associated with the Bay of Bengal branch of monsoon are noticed. Cloudiness is also witnessed over southeast and east-central Arabian Sea off west coast of India. Subsequently under favourable conditions, a low pressure area formed over southeast Bay of Bengal region



Figs. 4(a-f). INSAT (KALPANA-1) Satellite 0600 UTC Sector Visible cloud imageries for (a) 20 May, (b) 23 May and (c) 25 May, 2009, (d) Track of the cyclone 'SCS AILA' while (e) and (f) same as Figs. 3 (c&d) respectively but for 23 May, 2009



Figs. 5(a-e). (a) and (b) same as that of Figs. 3 (a) and (b) respectively but for the year 2010 while (c) and (d) same as that of Figs. 3 (c&d) respectively but for 17 May, 2010 and (e) INSAT (KALPANA-1) Satellite 0600 UTC Full Disc Visible cloud imagery for 17 May



Figs. 6(a-f). (a) Track of the cyclone SCS LAILA, (b) Track of the cyclone VSCS PHET while (c) and (d) same as that of Figs. 3 (c&d) respectively but for 31 May, 2010 and (e) and (f) same as that of Fig. 5 (e) but for 31 May and 1 June, 2010 respectively on 22 May which further concentrated into a depression on 23 May with centre located at Lat. 16.5° N/ Long. 88.0° E [Fig. 4(d)]. With this development, monsoon onset took place over Kerala on 23 May.

The OLR analysis over AS show a sudden northward movement of low OLR on 21 May with OLR < 180 Wm^{-2} spreading over the latitudinal belt of about 4° N to 12° N [Fig. 3(a)], showing further decrease with OLR < 160 Wm^{-2} (with pockets of OLR < 120 Wm^{-2}) up to about 24 May over there. The NCWINDS for 23 May, 2009 depicts that at 850 hPa, cross-equatorial flow over western Arabian Sea (off Somali Coast) is noticed to have strengthened with strong westerlies over the belt 5° N to 10° N running from Somali Coast to south peninsular India and becoming south westerlies over the Bay of Bengal region [Fig. 4(e)]. Such moist winds are further seen to enter into associated cyclonic circulation of the prevailing low pressure system over the Bay. While at 500 hPa, zone of strong westerlies is seen little southward lying over the belt 2.5° N to 7.5° N [Fig. 4(f)]. Associated cloudiness with the system and the onset can be seen through VISPIC for 23 May [Fig. 4(b)]. The system further intensified into a Severe Cyclonic Storm (SCS) AILA, the track of which is given in Fig. 4(d). The system moved in a near northward direction throughout its life period very rapidly which can be well noticed through rapid northward movement of low OLR < 200 Wm^{-2} up to 20° N over BOB by 25 May [Fig. 3(b)] and through the satellite cloud imageries shown in Figs. 4 (a-c).

Thus, in 2009, onset over Oceanr occurred at normal time while it arrived over Kerala 9 days before the normal time. The formation of SCS AILA influenced the advancement of the monsoon onset from Oceanr accelerating further advance and bringing it up to Kerala just in 3 days.

3.3.2. *Features of onset 2010*

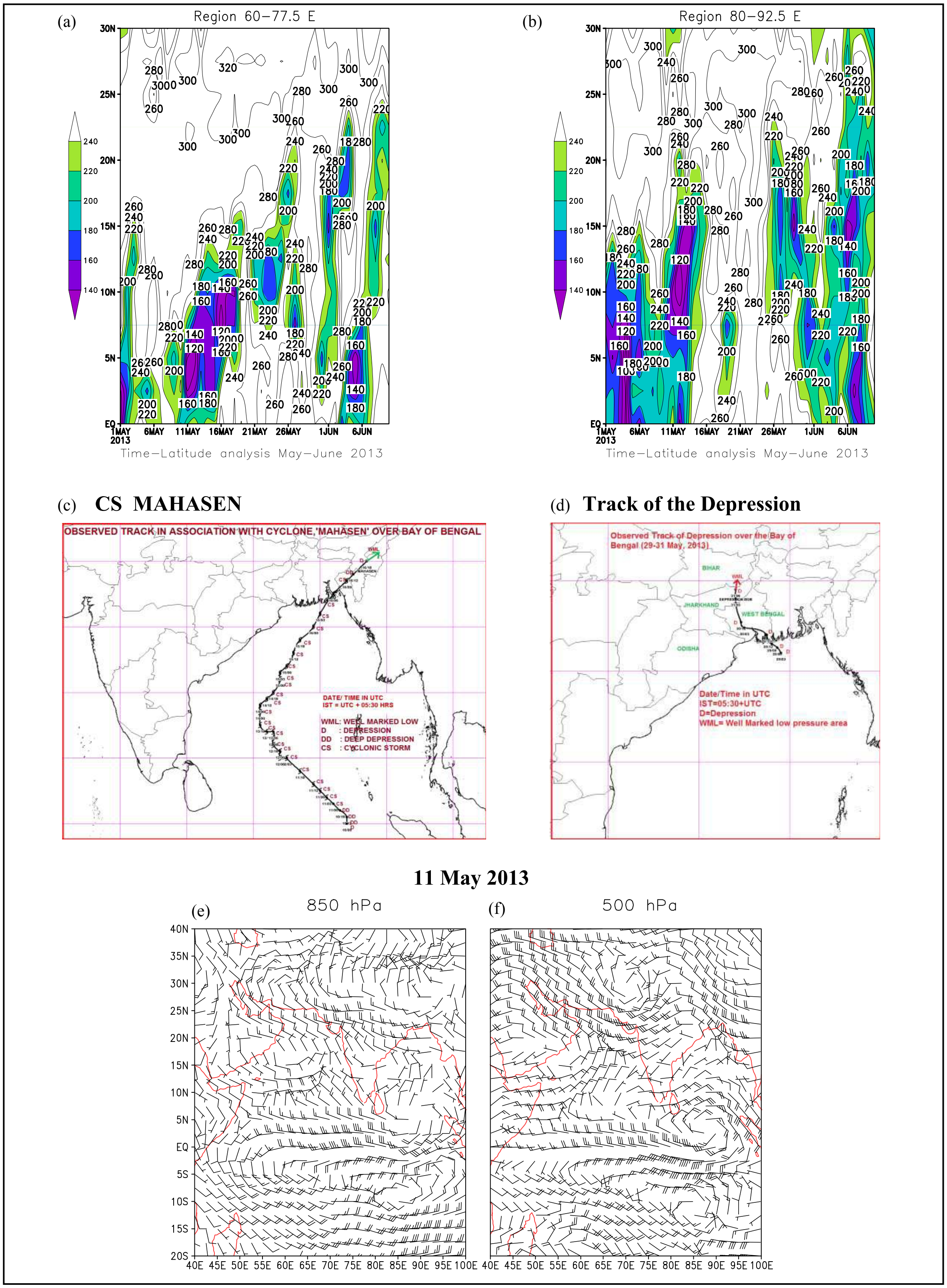
During 2010, on 16 May, a low pressure area formed over the southeast Bay of Bengal region. In association with this, the onset of SWM occurred over Oceanr on 17 May and the system intensified into a depression. On this day, a sudden northward movement of low OLR < 220 Wm^{-2} is noticed over BOB in the latitudinal belt 2° N - 17° N, within which, OLR < 180 Wm^{-2} in the belt 3° N -15° N are also seen [Fig. 5(b)]. From the NCWINDS for 17 May at 850 hPa, cyclonic circulation associated with the system is seen over southern Bay of Bengal region [Fig. 5(c)], tilting south westwards with height and seen over western SBOB with increased strength of the winds at 500 hPa [Fig. 5(d)]. The cloudiness associated with the system and the onset over Oceanr can be seen through VISPIC for 17 May [Fig. 5(e)]. The system intensified very rapidly into SCS LAILA moving west-northwestward over the Indian land weakened further [Fig. 6(a)]. After its weakening, from 23 May, conditions became unfavourable for further advance of the monsoon for a few days. Consequently from 26 May, an increase in OLR values with OLR > 240 Wm^{-2} and even > 260 Wm^{-2} are seen over entire BOB [Fig. 5(b)].

From 28 May, the cross-equatorial flow started strengthening again (figure not shown). On 30 May, 2010, a low pressure area formed over southeast and adjoining east central Arabian Sea. The system moving in north-west direction concentrated into a depression on 31 May with centre near lat. 15.0° N / long. 64.0° E [Fig. 6(b)] and the monsoon onset over Kerala took place on the same day. The NCWINDS for 31 May for 850 hPa depicts strong cross-equatorial flow near Somali Coast with strong westerlies running from the Somali Coast to south peninsular India over the belt 5° N to 10° N [Fig. 6(c)] while, a cyclonic circulation is witnessed over south central Arabian Sea region at 500 hPa level [Fig. 6(d)]. The cloudiness associated with the system and the onset can be seen from VISPIC for the same day [Fig. 6(e)]. Over AS from 29 May onwards, the zone of OLR < 200 Wm^{-2} (and even less of the order of 120 Wm^{-2}) shows a rapid northward movement reaching up to 25° N by 1 June [Fig. 5(a)]. The system further intensified as a Very Severe Cyclonic Storm (VSCS) PHET [Fig. 6(b)]. VISPIC for 1 June shows the cloudiness associated with the system [Fig. 6(f)]. VSCS PHET moved further north-westwards, away from Indian coast, causing increase in OLR (> 240 Wm^{-2}) from 2 June to about 8 June south of it [Fig. 5(a)].

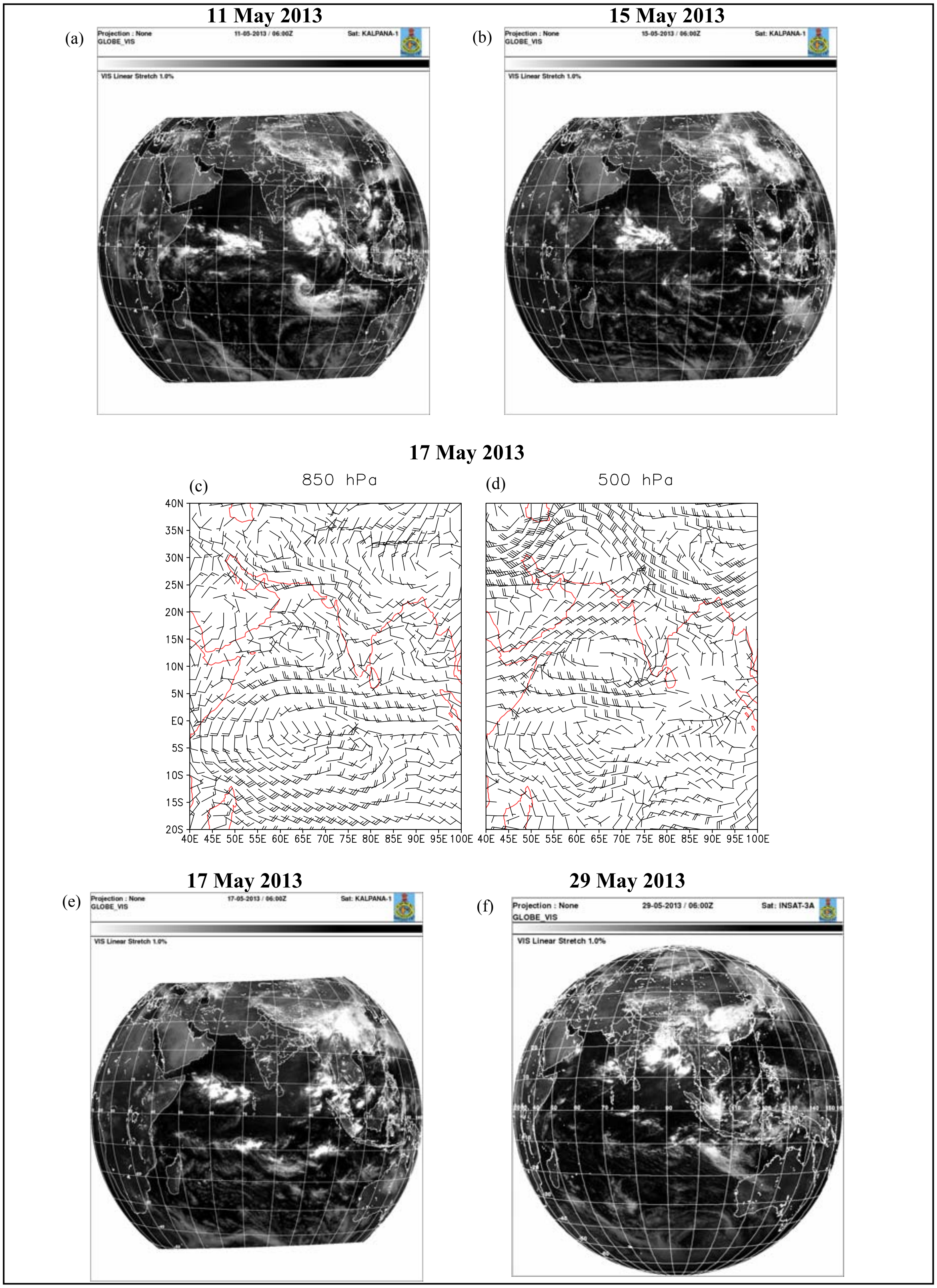
Thus, in 2010, the onset over Oceanr occurred during the formative period of SCS LAILA, whose weakening caused stagnation of monsoon for about 10 days. The onset over Kerala took place in association with formation of yet another storm VSCS PHET near the west coast of India. Further north-westward movement of the system led to clearing of cloudiness well south of PHET. Thus, formation of the two cyclonic storms LAILA and PHET brought the onset before normal time over both the regions of Oceanr and Kerala respectively, besides stagnation in between.

3.3.3. *Features of onset 2013*

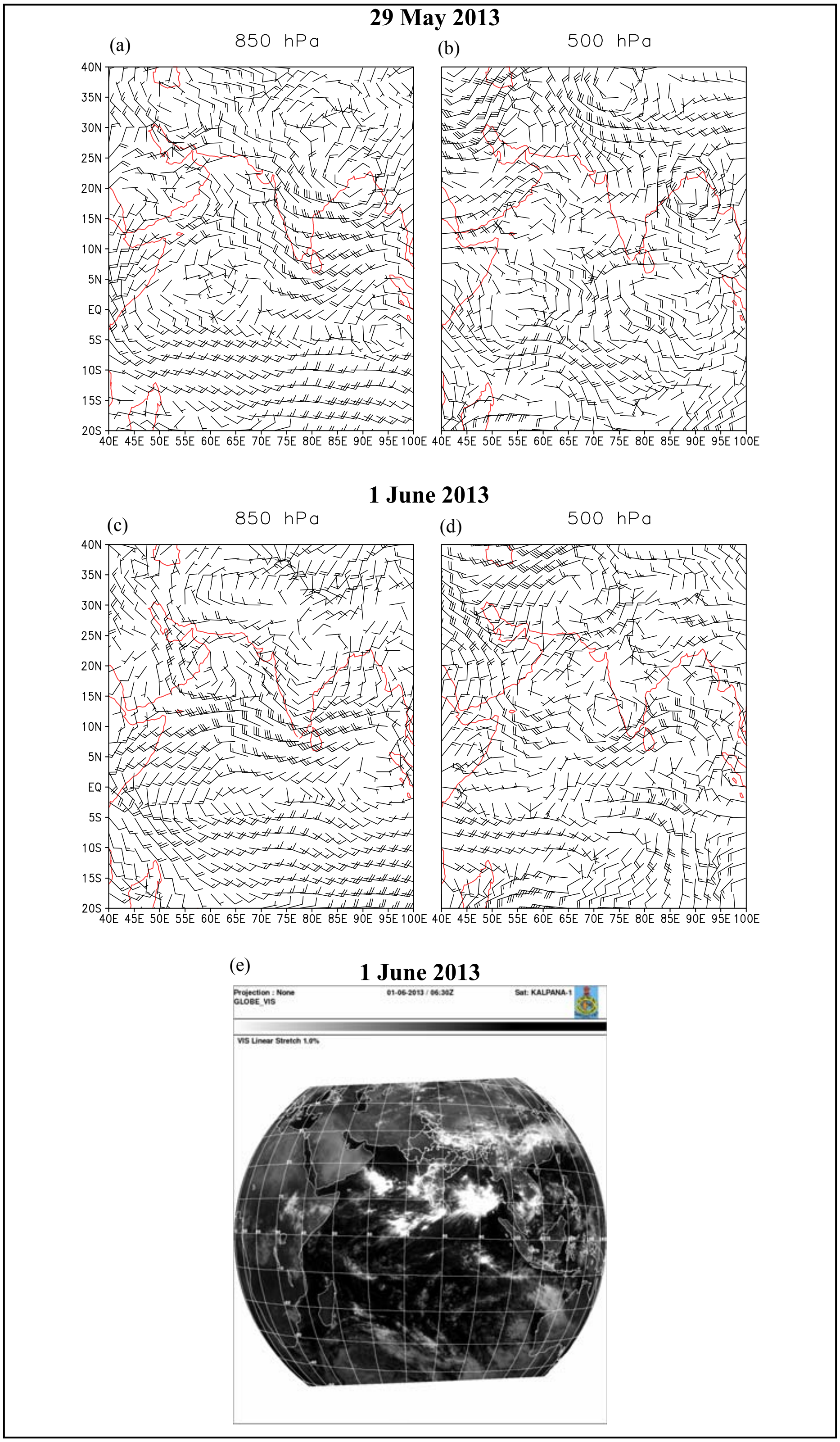
During 2013 on 8 May, a low pressure area formed over southeast Bay of Bengal which subsequently intensified as a Cyclonic Storm (CS) MAHASEN on 11 May. The system kept a long track. Movement of convective clouds associated with the system can be well judged through OLR analysis over BOB [Fig. 7(b)] in agreement with the track of the system [Fig. 7(c)].



Figs. 7(a-f). (a) and (b) same as that of Figs. 3 (a&b) but for the year 2013, (c) Track of the cyclone CS MAHASEN, (d) track of the Depression while (e) and (f) same as that of Fig. 3 (c) and (d) but for 11 May, 2013 respectively



Figs. 8(a-f). (a) and (b) same as that of Fig. 5 (e) but for 11 May and 15 May, 2013 respectively while (c) and (d) same as that of Fig. 3 (c) and (d) but for 17 May, 2013 and (e) same as that of Fig. 5 (e) but for 17 May, 2013 while (f) INSAT 3A Satellite 0600 UTC Full Disc Visible cloud imagery for 29 May, 2013



Figs. 9(a-e). (a) and (b) same as that of Fig. 3 (c&d) but for 29 May, 2013 respectively; (c) and (d) same as that of Fig. 3 (c&d) but for 1 June, 2013 respectively while (e) same as Fig. 5 (e) but for 0630 UTC of 1 June, 2013

Figs. 7(e&f) show NCWINDS for 11 May for 850 hPa and 500 hPa winds, through which, associated cyclonic circulation of the system can be seen while associated (intense) cloudiness can be seen from VISPIC for 11 May [Fig. 8(a)]. The system exhibited a re-curving path [Fig. 7(c)] crossed Bangladesh coast on 16 May. The cloudiness associated with the system on 15 May can be seen from VISPIC [Fig. 8(b)].

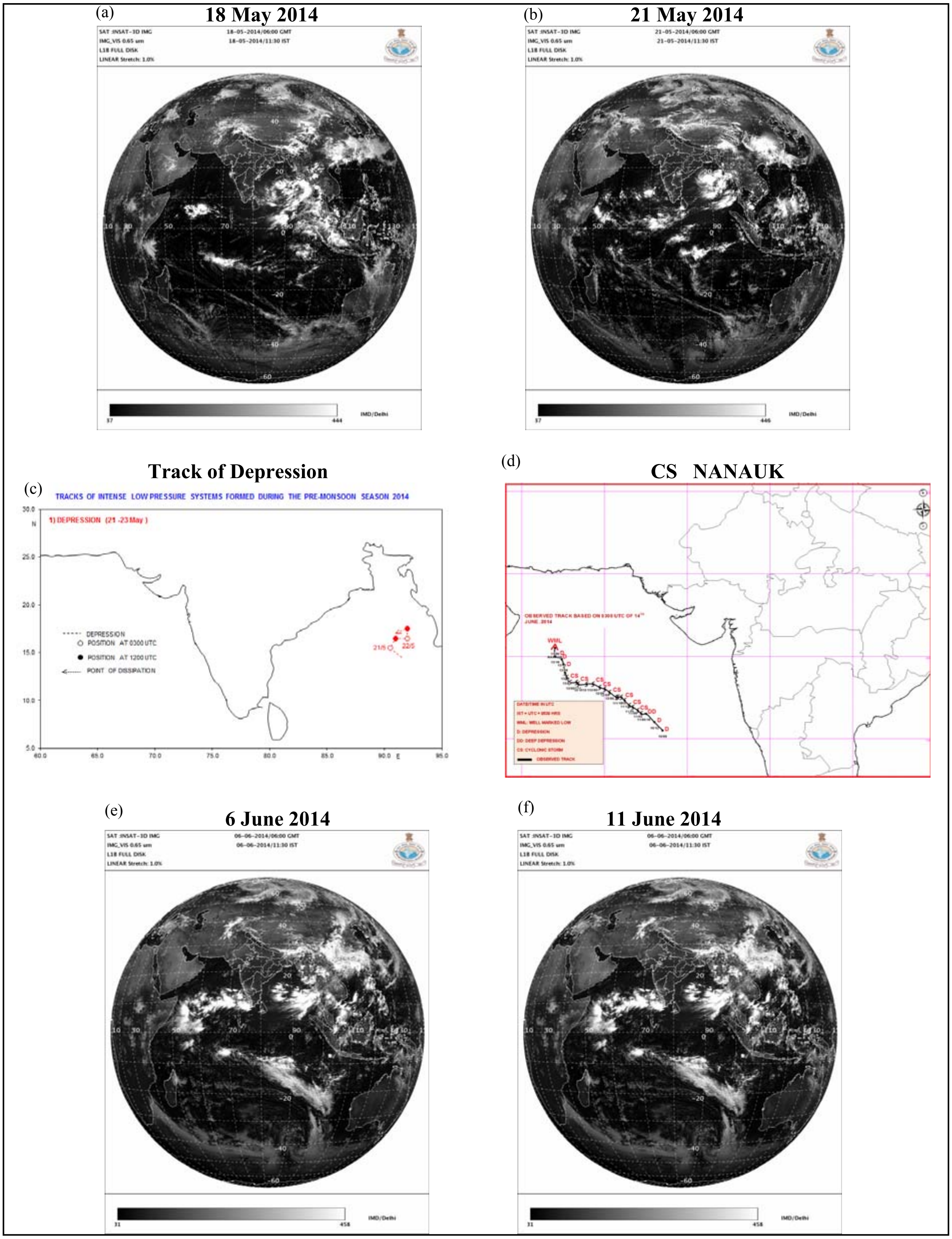
The genesis of CS MAHASEN began rather early (from 8 May) with respect to the normal onset time and over near equatorial region (5° N). It became cyclone on 11 May moving towards north, got detached from the near equatorial ITCZ. Hence it could not bring the onset over Oceanr at this early time. From OLR analysis over BOB, high OLR > 260 Wm^{-2} are noticed over the latitudinal belt of 3° N - 8° N from 13 to 17 May [Fig. 7(b)]. While from the satellite cloud pictures a band of convective clouds was noticed to get enhanced and well organised at near-equatorial Indian Oceanic region (not shown). After cessation of the system, monsoon onset took place over Oceanr on 17 May which is supplemented through a fall in OLR dipping below 220 Wm^{-2} over the latitudinal belt 2° N - 8° N during 17-19 May over BOB [Fig. 7(b)]. From NCWINDS for 17 May, at 850 hPa, enhanced cross-equatorial flow is seen along Somali Coast with westerlies running from Somali Coast to southern tip of India and further over South Bay of Bengal region while a trough is seen over east central Bay north Andaman Sea region [Fig. 8(c)]. Also, a cyclonic circulation is seen over east-central Arabian Sea at 850 hPa level, tilting southward with height and seen over southeast Arabian Sea at 500 hPa level [Fig. 8(d)]. The cloudiness associated with the onset over Bay region can be seen from VISPIC for 17 May [Fig. 8(e)]. The onset showed further little advance after which, stagnation occurred for a few days. This is well supplemented through an increase in OLR > 260 Wm^{-2} over BOB up to 25 May [Fig. 7(b)].

Subsequently, a low pressure area formed on 28 May over west central and adjoining northwest Bay of Bengal which further concentrated into a depression on 29 May over north Bay of Bengal near lat. 21.0° N and 89.5° E [Fig. 7(d)]. With the formation of system, the Bay branch of monsoon current got activated giving further advance over the Bay region. The cloudiness associated with the system over Bay region can be seen from VISPIC3A for 29 May [Fig. 8(f)]. From NCWINDS for 29 May, cyclonic circulation associated with the system can be seen at both the levels of 850 hPa and 500 hPa [Figs. 9(a&b) respectively). The system moving north-westwards crossed West Bengal coast on the same day. From OLR analysis, OLR < 200 Wm^{-2} with pockets of OLR < 160 Wm^{-2} are noticed over the BOB in the latitudinal belt 10° - 20° N during 26-30 May [Fig. 7(b)]. The system further moved nearly northward and weakened as a well-marked low pressure area on 31 and further became less marked on 1 June. From 31 May, OLR < 200 Wm^{-2} show a rapid northward movement over BOB from about 2.5° N reaching up to 25° N by end of section [Fig. 7(b)]. While over AS, OLR of similar order show abrupt northward movement from 31 May from about 3° N reaching up to 22.5° N by 2 June [Fig. 7(a)]. Consequently, the Arabian Sea branch of the monsoon current got activated and showed further advance on 31 May while onset over Kerala took place on 1 June. From NCWINDS for 1 June, at 850 hPa, cross-equatorial flow is noticed to have strengthened with strong southwesterly to westerly winds over the belt 5° N to 12.5° N, running from Somali Coast to south peninsular India and further over the Bay region [Fig. 9(c)]. A feeble cyclonic circulation is seen over Orissa, Chhattisgarh region from which a trough is noticed to extend toward the south tip of India. While at 500 hPa level, a cyclonic circulation is witnessed over south west Peninsular India and adjoining southeast Arabian Sea region [Fig. 9(d)]. VISPIC for 0630 UTC of 1 June exhibits cloudiness associated with the onset [Fig. 9(e)].

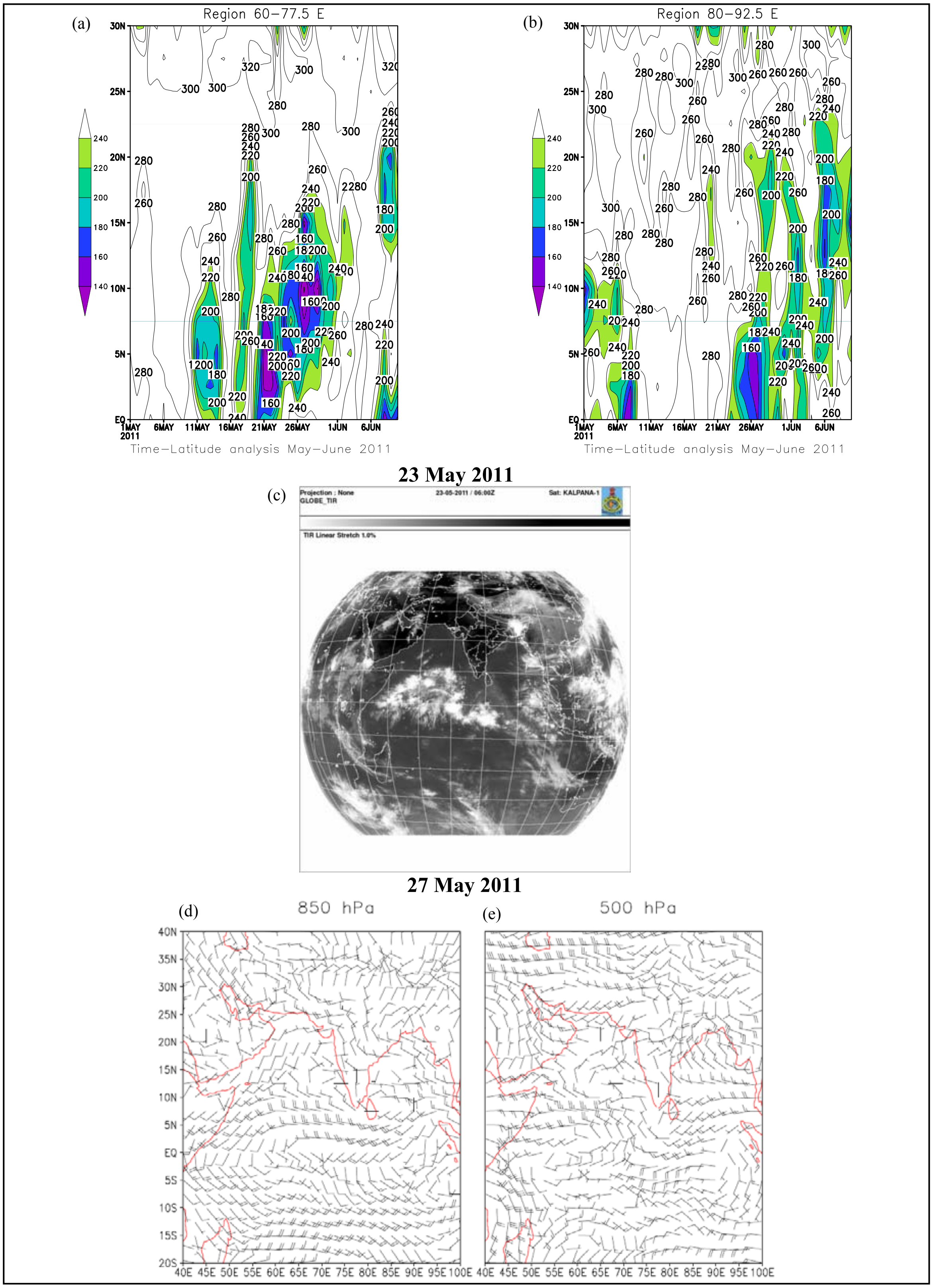
Thus, during the year 2013, since the formation of CS MAHASEN occurred at an early time for the season, it did not lead to persistent strong low level monsoon winds over the Oceanr region and hence could not bring the onset over there with it (simultaneously). After its weakening, onset took place over Oceanr (3 days earlier than normal) followed by stagnation in monsoon advance for a few days. While, subsequent formation of a depression, formed over northern latitude (west-central Bay) between 28-30 May, facilitated further progress of onset over the Bay. Subsequent to weakening of the depression, onset took place over Kerala at normal time.

3.3.4. *Features of onset 2014*

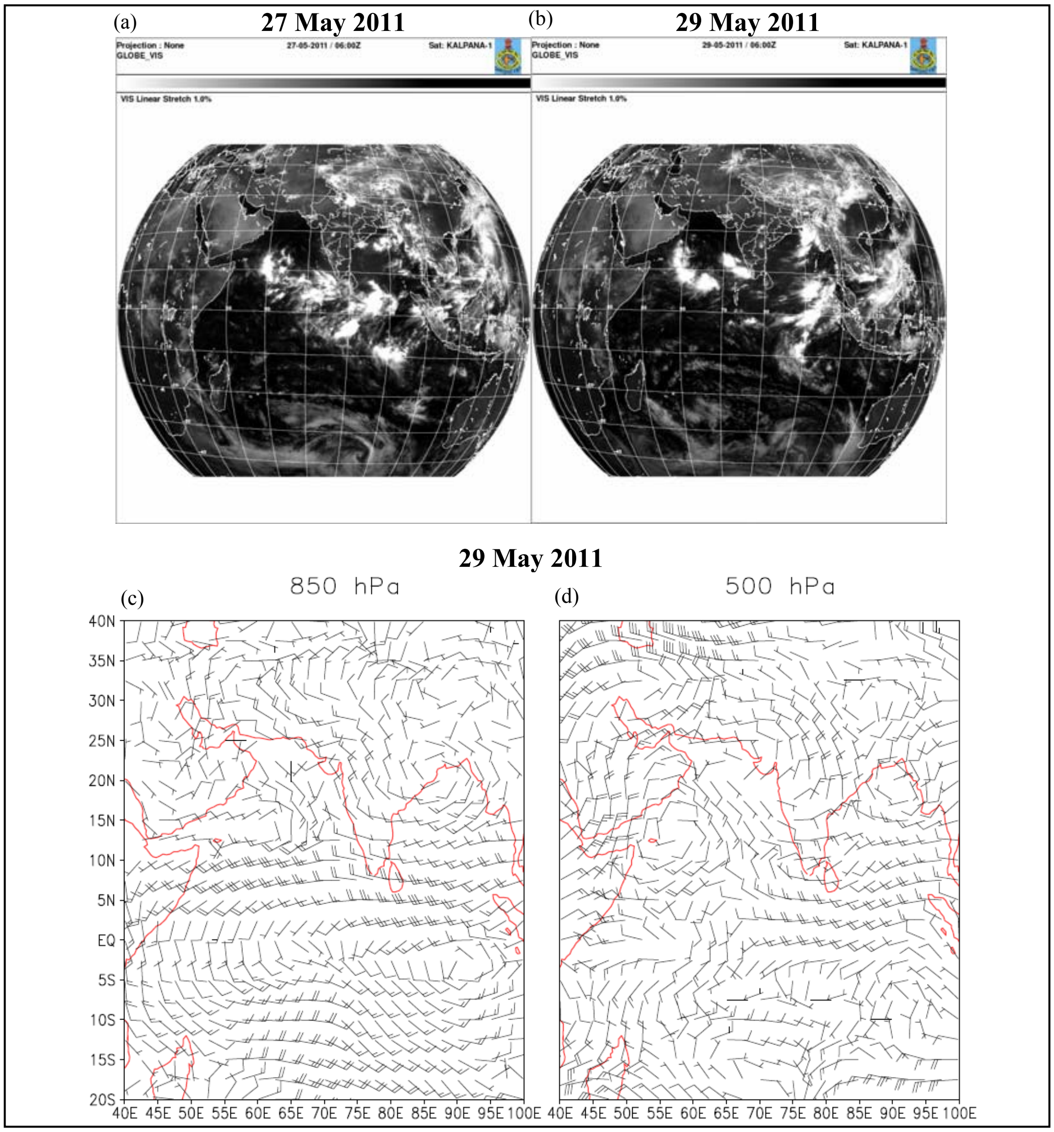
In 2014, in association with an upper air cyclonic circulation (persisting from 17 May), over south Andaman Sea and neighbourhood extending up to 4.5 kms a.s.l., the advance of SWM occurred over Oceanr on 18 May. The cloudiness associated with the onset over Oceanr can be seen from VISPIC3D for 18 May [Fig. 10(a)]. Further, under influence of the circulation, a low pressure area formed over east central Bay of Bengal and neighbourhood on 19 May. It intensified into a depression over east central Bay of Bengal on 21 May [Fig. 10(c)]. VISPIC3D for 21 May depicts the cloudiness associated with the system [Fig. 10(b)]. The system initially moved north-north-eastwards and then changing its course moving south-westwards, started weakening from 23 May. With this, SWM advanced over central Bay of Bengal on 23 May. After cessation of the



Figs. 10(a-f). (a) and (b) INSAT 3D Satellite 0600 UTC Full Disc Visible cloud imagery for 18 May and 21 may, 2014 respectively while Tracks of (c) the Depression and (d) the cyclone NANAUK while (e) and (f) same as that of Fig. 10 (a) but for 6 June and 11 June, 2014 respectively



Figs. 11(a-e). (a) and (b) same as that of Figs. 3 (a&b) but for the year 2011 respectively; (c) same as that of Fig. 5 (e) but Infra Red imagery for 23 May, 2011 while (d) and (e) same as that of Figs. 3 (c&d) but for 27 May, 2011 respectively



Figs. 12(a-d). (a) and (b) same as that of Fig. 5 (e) but for 27 May and 29 May, 2011 respectively while (c) and (d) same as that of Fig. 3 (c) and (d) but for 29 May, 2011 respectively

system, there was a lull in the advance of monsoon for a few days.

With appearance of organized ITCZ along 7° N latitude and with the presence of an east-west shear zone roughly along 10° N latitude at 700 hPa, on 2nd June, SWM showed further advance into some parts of south Arabian Sea, Maldives-Comorin areas. The shear zone persisted for a few days and on 6 June the SWM set in over Kerala. Fig. 10(e) presents VISPIC3D for 6 June showing cloudiness associated with the onset. Subsequent to this, a cyclonic storm CS NANAUK formed on 11 June [Fig. 10(d)]. Associated cloudiness is shown through VISPIC3D for 11 June [Fig. 10(f)].

Thus, in 2014, the onset over Oceanr occurred during the formative period of the depression, formed over the Bay region, 2 days before the normal time. However, in the absence of favourable conditions / active intense system in subsequent period of few days, onset was delayed over Kerala (by 5 days). Due to this, the journey of onset from Oceanr to Kerala has taken longest time duration (19 days) during the period of study. The onset over Kerala occurred just before the formation of CS NANAUK, which formed at the leading edge of the advancing monsoon current.

In past, Rao (1976 and reference therein) have found a pronounced tendency of the formation of low pressure systems at the leading edge of the monsoon current, either in Arabian Sea or Bay of Bengal at the time of monsoon onset along the west coast. They have even noted cases when onsets were without any surface low pressure systems and would have been confined to the perturbations in the upper air. In comparison with their observation, the present study has found that around the time of onset in the recent years of 2009, 2010, 2013 and 2014, intense weather disturbances were formed over the north Indian Oceanic region (Arabian Sea or/and Bay of Bengal). Depending upon their location of formation, movement and their intensity, these systems by and large influenced the onset process from Oceanr to Kerala as discussed. In most of the cases, the formation of these cyclonic disturbances at the leading edge of monsoon, low level current found to promote the onset of monsoon over Oceanr and Kerala. It is also seen that during 2011 and 2012, the onset occurred without formation of any Depression/Cyclone over north Indian Ocean. However, these years exhibited some interesting facts. The features of onset observed during these years are as follows.

3.3.5. *Features of onset 2011*

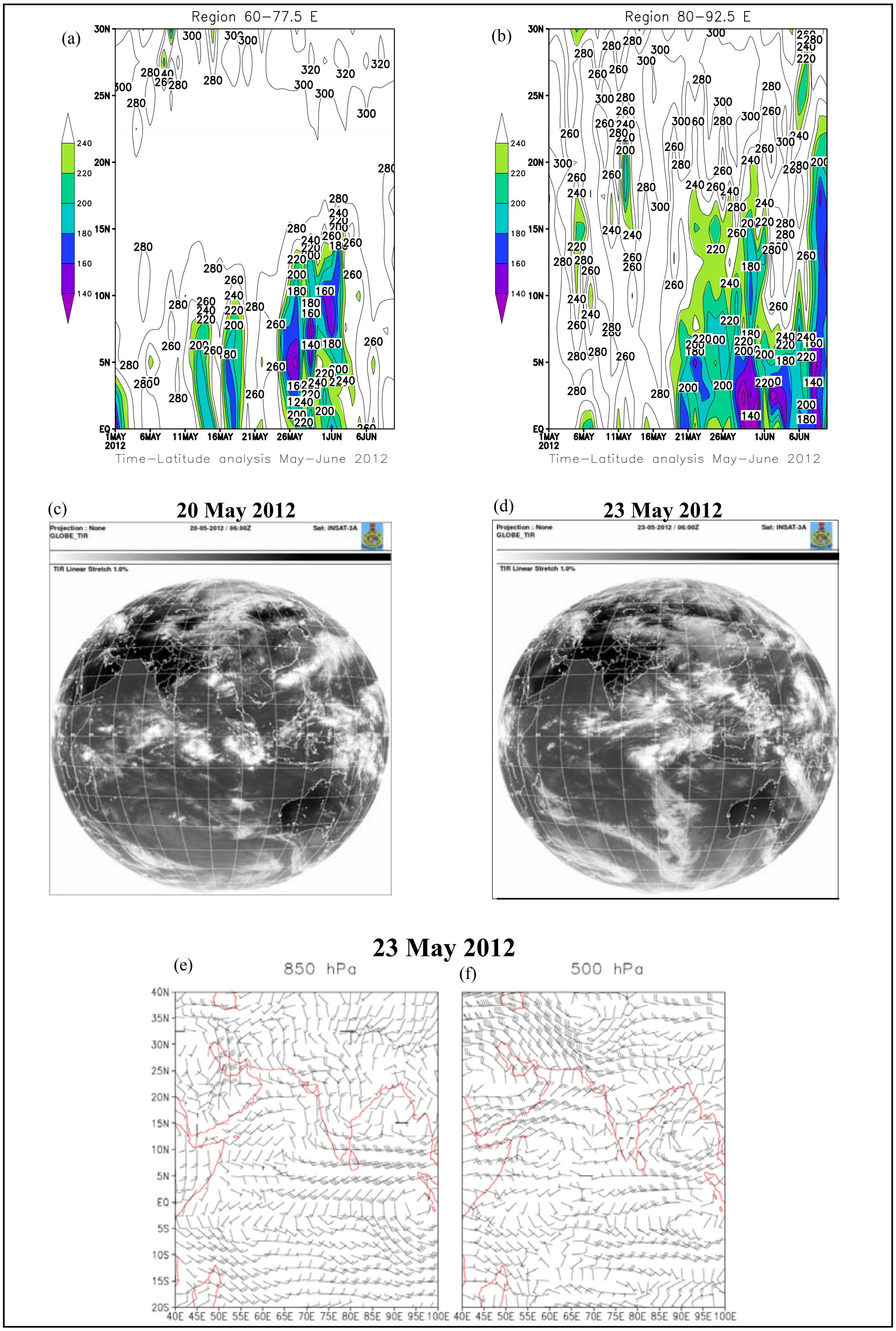
In 2011, the onset over Oceanr has shown a large delay. The OLR analysis over BOB clearly depicts the adverse conditions through high values of OLR > 260 Wm^{-2} during 11 to 22 May (signifying absence of well-organized clouds) around the normal time of onset over there [Fig. 11(b)]. From 23 May, OLR show a decrease going below 260 Wm^{-2} over BOB [Fig. 11(b)] while from about 22 May, a systematic northward movement of OLR < 200 Wm^{-2} is noticed from near equatorial region over AS [Fig. 11(a)]. Fig. 11(c) shows IRPIC for 23 May. Though the satellite cloud picture shows cloud organization over AS, the cloudiness over BOB is noticed to be suppressed and cloud organization is seen at southern latitude. The conditions changed significantly after 25 May. A sizable fall in OLR (< 200 Wm^{-2}) is noticed over BOB around 26 May. On 27 May, an upper air cyclonic circulation formed over north Bay of Bengal extending from 1.5 km above mean sea level to mid-tropospheric levels. Figs.11 (d&e) depict NCWINDS for 27 May for 850 and 500 hPa respectively. It is seen that at 850 hPa, organized south-westerlies to westerlies are noticed over south Arabian Sea region from Somali Coast to Kerala and further extending Bay of Bengal region with a cyclonic circulation over Sri Lanka and west Bay of Bengal region. Such organized winds are seen to extend up to 500 hPa level and a trough is seen over southwest Bay and Maldive Comorin region. Fig. 12(a) shows VISPIC for 27 May depicting well-organised band of clouds from about west-central Arabian Sea through southern Bay of Bengal running towards the northwest Pacific Oceanic region roughly to the location 15° N, 120° E like a feeder band of an intense system (which shall be discussed in section 3.4), tagged by it.

From 27 May, OLR over BOB region show further drop, to about 160 Wm^{-2} over the latitudinal belt EQ to 5° N in presence of a cyclonic circulation over the region which persisted till 29 May. Over AS, OLR < 200 Wm^{-2} (and even < 160 Wm^{-2}) are noticed to move northward reaching up to 15° N by 2 June [Fig. 11(a)]. On 29 May, the cross equatorial flow over the Arabian Sea further strengthened and an upper air cyclonic circulation formed over southeast Arabian Sea off Kerala coast between 3.1 and 5.8 km above mean sea level. Also, the prevailing upper air cyclonic circulation over north Bay of Bengal seen to extend up to 3.1 km above mean Sea level. Figs. 12 (c&d) present NCWINDS for 29 May for 850 and 500 hPa levels respectively. At 850 hPa, strong monsoon westerlies are noticed up to 12.5° N over Arabian Sea and west cost of India. While, the Bay of Bengal region is observed to be dominated by westerlies with stronger winds up to about 7.5° N. In consequence to these changes, monsoon onset over Kerala occurred on 29 May. Similarly, the onset over Oceanr occurred on the same day. Fig. 12(b) shows VISPIC for 29 May showing the cloudiness associated with the onset.

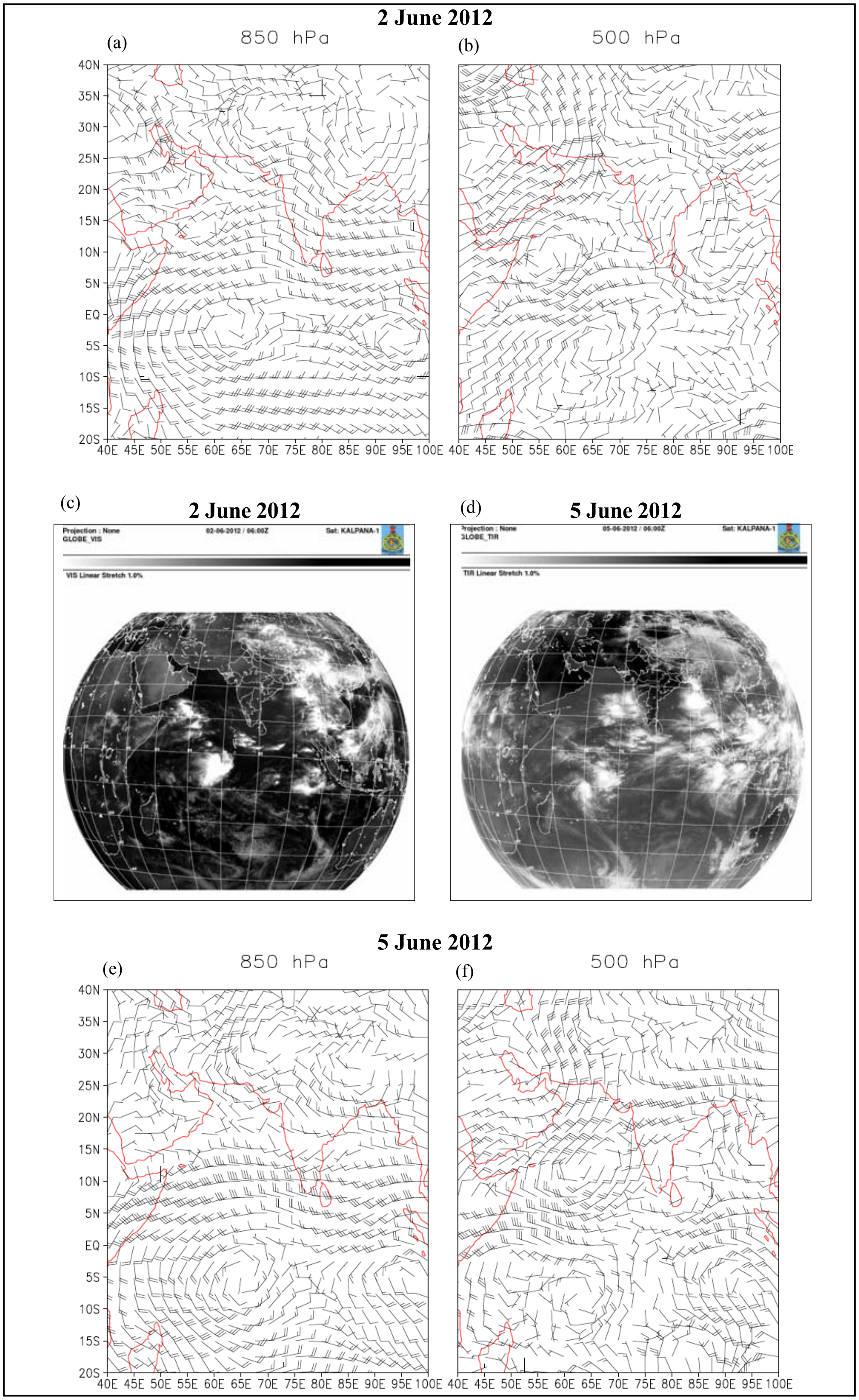
Thus in 2011, the onset over Oceanr and Kerala occurred almost simultaneously. Hence, the monsoon advance from Oceanr to Kerala has not followed the normal pattern. It occurred 3 days before normal date for Kerala but delayed by 9 days over Oceanr. Also, around the time of onset, no intense disturbance was formed over the Indian region. The advancing branch of monsoon current is seen to have influenced by system of northwest Pacific Oceanic region.

3.3.6. *Features of onset 2012*

In 2012, it can be seen through OLR analysis that prior to about 19 May, high OLR > 240 Wm^{-2} prevailed over BOB [Fig. 13(b)]. IRPIC3A for 20 May depicts a band of well-organised clouds over western equatorial Indian Ocean [Fig. 13(c)]. The cloud band is seen to south of eastern equatorial Indian Ocean, running towards the northwest Pacific Oceanic region (which shall be discussed in section 3.4). The conditions began to change from 21 May. A sudden fall in OLR is noticed when OLR < 220 Wm^{-2} are seen to progress rapidly from EQ to north of 15° N by 22 May, followed by a northward march of OLR < 180 Wm^{-2} from 22 to 25 May over the region 2.5° N to north of 15° N [Fig. 13(b)]. The onset over Oceanr occurred on 23 May. NCWINDS for 23 May depict strong westerlies up to about 10° N over Bay of Bengal region at 850 hPa level [Fig. 13(e)] while a cyclonic circulation is seen at 500 hPa, over the region of



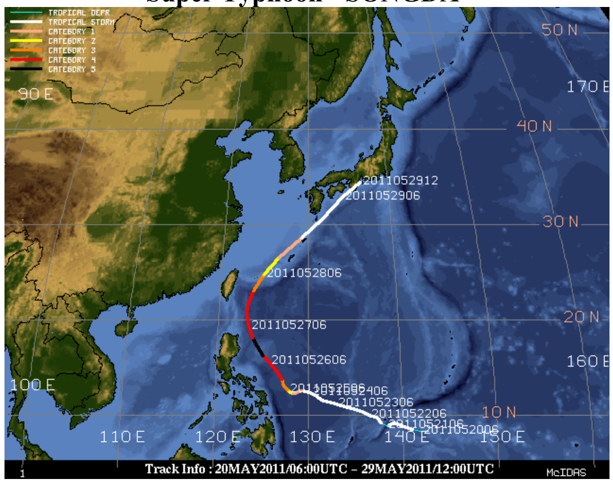
Figs. 13(a-f). (a) and (b) same as that of Figs. 3 (a&b) but for the year 2012 respectively while (c) and (d) same as that of Fig. 8 (f) but Infra Red Cloud Imagery for 20 May and 23 May, 2012 respectively and (e) and (f) same as that of Figs. 3 (c&d) but for 23 May, 2012 respectively



Figs. 14(a-f). (a) and (b) same as that of Figs. 3 (c&d) but for 2 June, 2012 respectively; (c) and (d) same as that of Fig. 5 (e) but for 2 June and Infra Red for 5 June, 2012 respectively while (e) and (f) same as that of Figs. 3 (c&d) but for 5 June, 2012 respectively

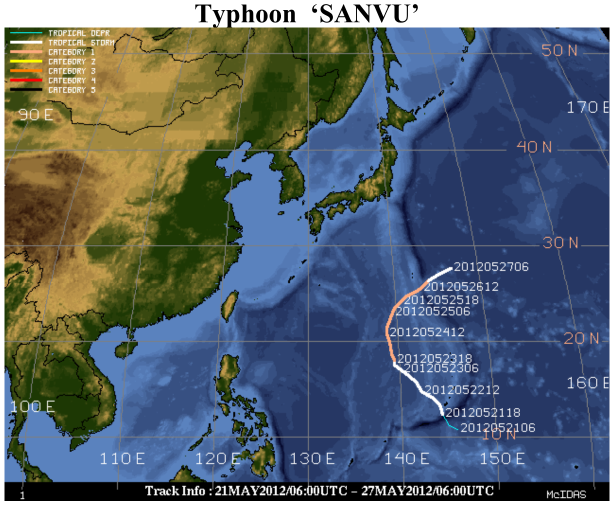
Super Typhoon 'SONGDA'

(a)



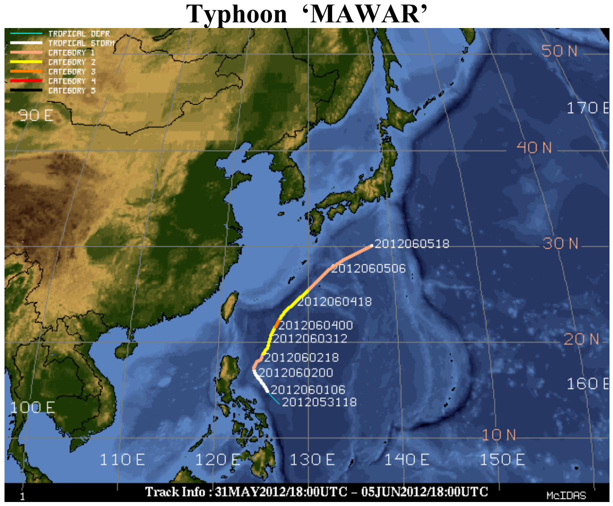
Typhoon 'SANVU'

(b)



Typhoon 'MAWAR'

(c)



Figs. 15(a-c). Tracks of the Typhoons (a) Super Typhoon SONGADA in 2011, (b) Typhoon SANVU and (c) Typhoon MAWAR in 2012

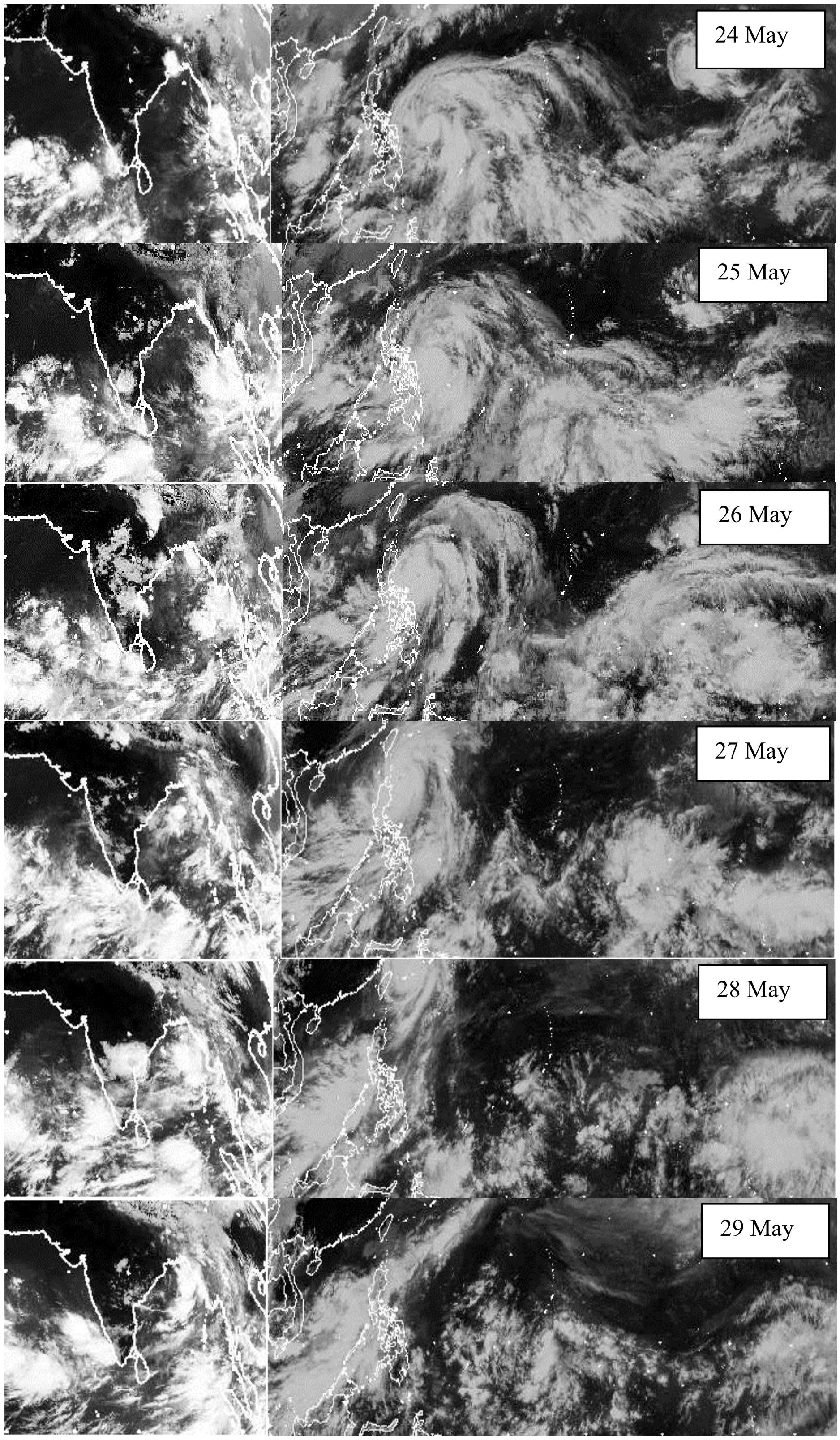


Fig. 16. Hovmoller diagram of DSRS satellite cloud mosaics over Indo-Pacific region for 24 to 29 May, 2011

Oceanr [Fig. 13(f)]. INPIC3A for 23 May shows cloudiness associated with the onset [Fig. 13(d)].

Subsequent to the onset over Oceanr, the winds over Bay of Bengal region got further strengthened for a few days with prevalence of a cyclonic circulation over southwest Bay of Bengal and neighborhood in the mid and upper tropospheric levels from 26 to 30 May. While over AS, OLR < 200 Wm^{-2} values show a gradual northward movement from 26 May, up to 2 June reaching up to about 15° N latitude [Fig. 13(a)]. The NCWINDS for 2 June depicts that at 850 hPa level, the cross-equatorial flow has strengthened leading to prevalence of strong monsoon zonal flow over Arabian Sea from Somali Coast to southern tip of India and further over Bay of Bengal region [Fig. 14(a)]. At 500 hPa level, a cyclonic circulation is seen over Arabian Sea while a trough over south Bay region where the extent of strong monsoon winds is seen up to 5° N [Fig. 14(b)]. The associated cloudiness can be seen through VISPIC for 2 June [Fig. 14(c)] which indicates similar features as observed from Fig. 12(a) for 27 May. A band of clouds from Arabian Sea is seen running towards west-north Pacific Oceanic region similarly controlled by a synoptic system (which shall be discussed in section 3.4). Subsequently, a sharp northward march of OLR < 220 Wm^{-2} is noticed reaching up to 15° N in association with the onset of SWM over Kerala which occurred on 5 June [Fig. 13(a)]. From NCWINDS for 5 June, at 850 hPa level, strong monsoon flow is seen from Somali Coast up to southern tip of India extending over Bay of Bengal region up to about 10° N [Fig. 14(e)]. While at 500 hPa, cyclonic circulation is noticed over Arabian Sea [Fig. 14(f)]. Fig. 14(d) depicts IRPIC for 5 June showing cloudiness associated with the onset.

Thus in 2012, onset was delayed by 3 days over Oceanr and by 4 days over Kerala than the normal time. Around the time of onset, no intense disturbance formed over Indian region. However, the changes in mid-tropospheric flow are found to be responsible for the onset process. The advancing branch of monsoon current is seen under influence of synoptic systems of northwest Pacific Oceanic region as noticed in 2011.

As per the above discussion, in 2011, the onset over Oceanr showed a delay but simultaneously appeared over both the regions, appearing over Kerala before normal time. While in 2012, it was delayed over both the regions. Such variation in the onset has occurred in absence of formation of any intense disturbance over Indian region. But it was observed that around the period of onset, intense disturbances (Typhoons) formed over the adjacent area of northwest Pacific Ocean during these two years. Taking into consideration of this fact, the features of convective episodes over northwest Pacific region are also investigated for the study period giving special emphasis to these events.

3.4. *The convective activity over West North Pacific region during the study period*

In Fig. 2, the red curve gives the 3-day running mean OLR, averaged for the latitudinal belt 5° N - 15° N for the period 1 May to 10 June for the years 2009 to 2013 over WNP. It is seen that the region of WNP does not show significant seasonal change similar to what is observed in case of SAS and SBOB regions. Also, around the dates of onset over Oceanr (marked by blue arrow) and Kerala (marked by black arrow), when low OLR are noticed over the regions of SBOB and SAS respectively, the OLR over WNP either show increase or do not decrease and seen to vary in out of phase fashion in most of the cases. It is observed that around the period of monsoon advance from Oceanr to Kerala, during 2009, 2010 and 2013, intense disturbances were formed over Indian region and affected the progress of monsoon onset as discussed. During these years around the time of onset, the out of phase variation is seen more prominently. As an example, the out of phase variation is prominently seen in 2009 when the onset occurred in association with intense weather system SCS AILA. In 2009, the OLR over SBOB and SAS are noticed to fall well below 200 Wm^{-2} around the respective time of onsets over Oceanr and Kerala, while the OLR over WNP show a sharp increase going above 240 Wm^{-2} and the out of phase variation is prominently seen at the time of onset over Kerala (23 May). Hence, it can be inferred that when the regions of SBOB and SAS over Indian monsoon domain show enhanced convection in association with the monsoon onset over Oceanr and Kerala respectively the WNP region is noticed to show suppressed / reduced / no increase in the convection around the time of their respective onsets.

During 2011 and 2012, when intense systems were absent over Indian region, coincidently, it was noticed that typhoons were formed over northwest Pacific Oceanic region around the time of onset. As a preliminary attempt, information of these typhoons is taken from CIMSS website and the tele-connection of these events with the onset progress over Indian region is investigated. In 2011, Super Typhoon (STy) SONGDA [Fig. 15(a)] and in 2012, Typhoon (Ty) SANVU [Fig. 15(b)] and Ty MAWAR [Fig. 15(c)] were formed. All these typhoons showed re-curving path during their course. Though they formed far away from Indian region, the observations suggest that these systems influenced the advancement of the monsoon current over the north Indian Ocean.

The STy SONGDA, which formed in 2011, kept a long track. It is seen from Fig. 2 that in this year, when the system was active, low OLR < 200 Wm^{-2} are noticed over WNP region showing presence of deep convection associated with the system. While over SBOB region, high OLR > 220 Wm^{-2} are noticed up to about 26 May. From the satellite picture shown in Fig. 12(a) for 27 May, 2011 and as discussed in section 3.2.5, the Bay branch of monsoon was seen to be suppressed and limited to near equatorial latitude. Such feature is prominently seen during when STy SONGDA was active and took a westward journey towards the region of Philippines. After the re-curvature and further weakening of the system moving north-eastward, OLR over SAS and SBOB fell below 200 Wm^{-2} while that over WNP seen to exceed 220 Wm^{-2}. Consequently, advance of monsoon over Indian region is observed appearing simultaneously over both the regions of Oceanr and Kerala.

The above feature may be more clearly visualised through the Hovmoller plot of the satellite cloud mosaics made up from the strips of DSRSTIR imageries over north Indian Ocean and north-west Pacific Oceanic regions joined together. Fig. 16 shows the plot showing sequence of strips of DSRSTIR pictures over Indo-Pacific region for the period 24-29 May, 2011. It is already seen that, up to 25 May, when STy SONGDA was moving west-north-westwards towards Indian region, the Bay of Bengal region remained almost free of clouds which is well supplemented through the mosaic for 24 May. After 25 May, when the system started re-curving, such impact of the system (suppressing the Bay branch of the monsoon) is seen to have diminished. Instead, from 26 May, a band of clouds is noticed running from Arabian Sea region towards the system as a feeder band through the south Bay of Bengal region. While from 27 May onwards, a clear shift in the near equatorial ITCZ over south Bay region is seen. From the day when the system showed north-eastward movement, associated cloud mass lying over north-west Pacific exhibited an influence of natural easterly flow and as such shown a tendency to move westward towards the Bay. After 28 May, when the system started moving away from the tropical latitudes, systematic increased cloudiness is noticed over the regions of Kerala and especially over Oceanr through the movement of organised clouds in the same way. On 29 May, the well-organised band of clouds running from Arabian Sea towards the system through Oceanr show further northward movement in such a way that it seems as if the band has been dragged by the movement of the system. This results into the advancement of onset of SWM over both Kerala and Oceanr on 29 May simultaneously. Hence as discussed above, the large delay over BOB (of 9 days) can be attributed to the formation and movement of STy SONGDA.

Similarly as seen from INSAT images in 2012, when Ty SANVU was active, during its westward journey, Bay branch of monsoon was suppressed and seen at southern latitude [Fig. 13(c)]. After re-curvature and further weakening of Ty SANVU, monsoon showed progress over Indian region arriving at Oceanr. Whereas, when Ty MAWAR was active, stagnation in further advance of monsoon onset from Oceanr to Kerala is observed with similar suppression of Bay branch of monsoon [Fig. 14(c)]. After the re-curvature and weakening of Ty MAWAR, monsoon onset took place over Kerala. These features are also very well captured through DSRSTIR images for the same period (Figures not shown).

The association of the track of the northwest Pacific Typhoon and fluctuations in monsoon have been examined by various authors in past. Sikka (1977 and references therein) found that, during peak monsoon months, the remnants of the Typhoons, when they enter into Bay of Bengal region may give rise to the formation of well-marked systems (like monsoon depression) over north Bay leading to active monsoon conditions over India. While Kumar and Krishnan (2005) have noticed that during weak monsoon years, the tropical Pacific Typhoons show a greater tendency to re-curve and move northward (north of 20° N) relative to strong monsoon years. This further forbids the westward passage of their remnants along the Tropical Convergence Zone and their entry into Indian monsoon region especially during established period of monsoon. Hence, the re-curvature of Typhoons was observed to lead to suppressed monsoon conditions over India. The present study has shown that, around the time of onset, whenever a Typhoon formed over WNP, the progress of monsoon onset over India is affected. During active period and westward journey of Typhoon, the Bay branch of monsoon and as such the onset appears to be hampered. While, after the re-curvature or weakening of the system, further progress in the advance of monsoon onset is observed. The present results are based on only the cases of two years hence, before making concrete conclusion more number of cases should be investigated.

4. Concluding remarks

Slow changes from upper troposphere to lower troposphere are known to take place in wind, thermal and moisture fields from mid-April to mid-May (Ananthakrishnan, 1977). However, at the time of actual onset of the monsoon either over Andaman Sea or Kerala coast, rapid changes on synoptic scale herald the monsoon rains. Hence, utilizing a variety of synoptic information, based on conventional, model based as well as satellite-derived data, for the months May to early June for six recent years (2009-2014), this study has investigated the summer monsoon onset process from oceanic region of Southeast Bay of Bengal / Andaman Sea (Oceanr) up to extreme southwestern part of India (Kerala). It is found that during the study period, the dates of onset over Oceanr and Kerala have shown a variation from 17 to 29 May and from 23 May to 6 June over these regions against normal dates of 20 May and 1 June respectively. Also, the time required for the advance of monsoon onset from Oceanr to Kerala has shown a large variation of 0-19 days against the long-term normal of 12 days. The study has brought out the role of intense cyclonic disturbances formed over Indo-Pacific region in the observed variation of onset.

The analysis has further revealed that synoptic developments occurring over the regions of southeast Bay of Bengal and southeast Arabian Sea seems to be linked with the tropical northwest Pacific Ocean. It is found that depending upon the location of formation, intensity and movement of the disturbances formed over Indo-Pacific region around the time of the monsoon onset, rapid advance or revival from stagnation or even stagnations occurred in the monsoon advance from Oceanr to Kerala. The study suggests that the Global prediction models which are presently used for the onset prediction can make a proper utilization of synoptic analog based on the above information in improving their results. The formation of synoptic disturbances is known to be linked with large scale and meso-scale processes. Hence, by studying these processes through the analysis of atmospheric and oceanic observations, a suitable precursor can be deduced for the prediction of monsoon onset using the data over longer period.

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