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Summer monsoon onset over Andaman & Nicobar Islands: Objective criteria for operational forecaster

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सार – इस शोध पत्र में भारत मौसम विज्ञान विभाग के प्रचालनात्मक पूर्वानुमान सेवा की आवश्यकता को ध्यान में रखते हुए अंडमान निकोबार द्वीप समूह पर दक्षिण पश्चिमी मॉनसून के आने की घोषणा करने के वस्तुपरक क्राइटिरिया के समूह को प्रतिपादित करने के लिए दक्षिण पश्चिमी मॉनसून के आगे बढ़ने से जुड़े विभिन्न मौसम वैज्ञानिक प्राचलों की जाँच की गई है। वस्तुपरक क्राइटिरिया को अंडमान निकोबार द्वीप समूह पर प्रेक्षित की गई प्रतिदिन की वर्षा की मात्रा वितरण का विश्लेषण करते हुए विकसित किया गया है। 1980-2013 की अवधि के लिए ग्रिड प्वांइट बॉक्स (अक्षांश 0 से 15° उत्तर और देशांतर 80-95° पू.) के भीतर बंगाल की खाड़ी पर बहिर्गामी दीर्घ तरंग विकिरण (OLR) और पवन के विभिन्न स्तरों के NCEP/NCA दैनिक माध्य का पुनः विश्लेषण किया गया। 34 वर्षों की अवधि के ऊपर बताए गए पैरामीटरों के वर्षवार संघटित विश्लेषण किए गए जिनमें स्वतंत्र अवधि के रूप में दो वर्षों को और शामिल किया गया। अंडमान निकोबार द्वीप समूह में दक्षिण पश्चिमी मॉनसून के आरंम्भ होने की घोषणा करने के लिए निम्नलिखित मानदंडों को अपनाया गया। अंडमान निकोबार द्वीप समूह में दक्षिण पश्चिमी मॉनसून के आगे बढ़ने की तारीख 5 मई के बाद घोषित की जा सकती है बशर्ते (*i*) द्वीप समूहों में इस दिन से पहले और इस दिन वर्षा की मात्रा का वितरण काफी व्यापक रूप से हो अथवा वर्षा दूर-दूर तक हुई हो। (*ii*) निकोबार द्वीपों सहित बंगाल की खाड़ी के दक्षिण पूर्व पवन में पवन गति का यू-कंपोनेंट 925 हैक्टापास्कल 8 mps (16 नॉट्स हो) या अधिक हो। (*iii*) निकोबार द्वीप समूह सहित बंगाल की खाड़ी दक्षिण पूर्व में वेस्टरलीज की गहराई उस दिन 600 हैक्टा पास्कल हो। (*iv*) निकोबार द्वीप समूह सहित बंगाल की खाड़ी के दक्षिण पूर्व में उस दिन या उसके पहले दिन बहिर्गामी दीर्घ तरंग 210 watt/m^2 हो या कम हो। (*v*) हालाँकि बंगाल की खाड़ी में निम्न दाब तंत्र के बनने के कारण द्वीपों में लगातार दो दिनों तक काफी विस्तृत वर्षा / दूर-दूर तक वर्षा होती है जो अंडमान निकोबार द्वीप समूह में दक्षिण पश्चिमी मॉनसून के आगे बढ़ने / आने की घोषणा करने के लिए मानदंड होगा यदि 5 मई के बाद इस प्रकार की स्थिति उत्पन्न होती है।

ABSTRACT. In the present study, various meteorological parameters associated with the advance of southwest monsoon has been examined to formulate a set of objective criteria for declaring the arrival of southwest monsoon over Andaman & Nicobar (A & N) Islands, keeping in mind the India Meteorological Department's (IMD's) operational forecasting service requirements. The objective criteria have been developed by analyzing daily observed rainfall distribution over the A & N Islands, NCEP/NCAR daily mean reanalysis of winds at various levels and Outgoing Long wave Radiation (OLR) data over the Bay of Bengal within the grid point box (Lat. 0 to 15° N and Long. 80- 95° E) for the period 1980-2013. Year wise composite analysis of the above parameters were carried out for a period of thirty four (34) years with two (2) more independent years as testing period. The following criteria have been established for the declaration of onset of southwest monsoon over A & N Islands. The advance of southwest monsoon over A & N Islands could be declared after 5th May, provided, (*i*) Rainfall distribution is fairly widespread (FWS) or widespread (WS) over the group of Islands on the day and prior to the day, (*ii*) U-component of wind speed at 925 hPa is 8 mps (16 kts) or more on the day over southeast BOB including Nicobar Islands, (*iii*) Depth of westerlies over the southeast BOB including Nicobar Islands is upto 600 hPa on the day, (*iv*) OLR over the southeast BOB including Nicobar Islands is 210 Watt/m^2 or less on the day and prior to the day and (*v*) However, in cases occurrence of a low pressure system (LPS) over the Bay of Bengal resulting in FWS/WS rainfall over the Islands for 2 consecutive days, fulfillment of any two more of the enlisted criteria would suffice the declaration of advance/arrival of southwest monsoon over the A & N Islands, if such a situation occurs after 5th May.

Key words – Monsoon onset, Rainfall distribution, OLR, Westerly wind.

1. Introduction

Andaman and Nicobar (A & N) Islands are a group of Islands at the juncture of the Bay of Bengal (BOB) and Andaman Sea. It comprises two Island groups, the Andaman Islands and the Nicobar Islands, separated by the 10° Channel (150 km wide), with the Andamans to the north of this Latitude and the Nicobars to the south.

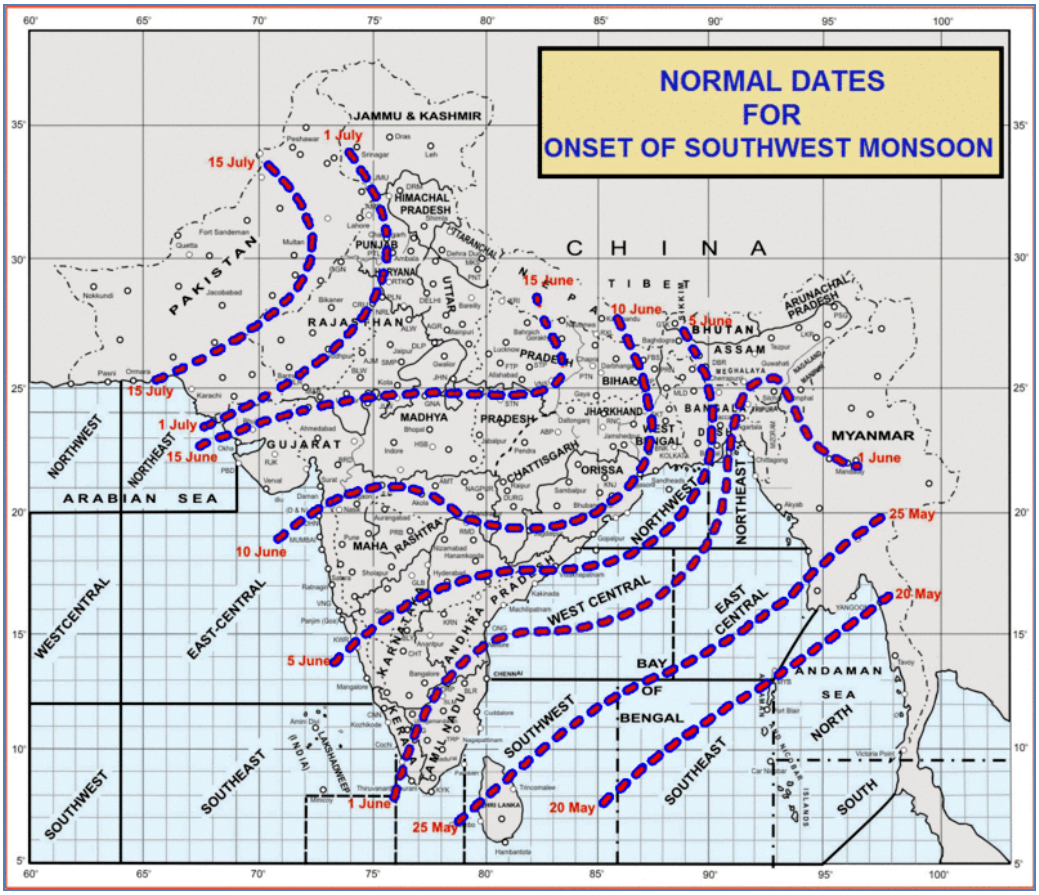


Fig. 1. Normal date of monsoon onset over India

The Andaman Sea lies to the east and the BOB to the west. A & N Islands has a tropical humid climate and has no distinct winter season. The rainy season happens twice in a year, (*i*) under the influence of southwest monsoon during mid-May to end of September and (*ii*) under northeast monsoon during November to January. The southwest monsoon touches the Indian soil first in the A & N Islands and then proceeds towards the Indian mainland. Thus it is important to monitor and objectively declare the date of arrival of southwest monsoon current over south Andaman Sea and commencement of the rainfall season over A & N Islands. This is because of the fact that, in order for the southwest monsoon rains to commence over the region, the cross equatorial winds need to reach and converge initially which is an indicator of the various large scale changes in the atmospheric and oceanic circulation pattern over southeast Asian region towards building up of the monsoon circulation (Wang *et al.*, 2004).

India Meteorological Department (IMD, 1943) declares the onset of monsoon over India operationally starting from A & N Islands. Conventionally, operational forecasters declare the dates of onset of monsoon over A & N Islands on a subjective manner considering a sharp increase in rainfall and its characteristic sustenance for a few days and associated atmospheric and oceanic features as there is no objective criterion for the same over A & N Islands. Thus, following a Recommendation by the Annual Monsoon Review (AMR) meeting of IMD in 2014, the authors analyzed the relevant data and arrived at a set of criteria as described in this paper. Also their operational feasibility and validity have been put into trial for 2 years, *viz.*, 2014 & 2015 southwest monsoon commencements and were found to be both feasible and valid. In 2016, based on a follow up recommendation by AMR, IMD adopted the criteria proposed in this paper for declaring the arrival of southwest monsoon over A & N Islands operationally.

During onset of monsoon over this Island area, significant changes are noticed on east-west oriented convection pattern, cloud characteristics, Sea condition etc., besides the circulation pattern over the Indo-Pacific

region. As the monsoon approaches, the easterly trade winds over equatorial Indian & Pacific regions weaken and the westerly zonal winds set in over the region (Sikka and Gadgil, 1980). During the onset, rain covers a wide area of the Island after the low level cross-equatorial flow gets established from the Somali coast to south Andaman Sea across south Bay of Bengal. There is an appreciable acceleration of cross equatorial flow across the Somali coast and westerly zonal flow over the equatorial Indian Ocean. The westerly zonal flow extends up to 600 hPa. This phenomenon is usually accompanied by the formation of a lower tropospheric shear zone across the Bay of Bengal to the southeast Arabian Sea (Pai and Rajeevan, 2009).

Large scale changes in the circulation features in association with the onset phase of Indian summer monsoon has also been documented by Ananthakrishnan *et al*. (1983); Pearce and Mohanty (1984); Ananthakrishnan and Soman (1988); Soman and Krishna Kumar (1993); Joseph *et al.* (1994, 2006) and Ramesh Kumar *et al*. (2009). Sikka and Gadgil (1980) and Webster *et al.* (1998) noticed that during onset of Indian summer monsoon there is northward progress of a deep convection from the equatorial to continental regions. Study of Indian monsoon on satellite perspective has also been reported by Simon *et al*. (2006) and Ghanekar *et al.* (2010).

Nair and Mahajan (2010) studied the features associated with the early monsoon onset over Andaman Sea and the changes that take place during its subsequent advance over Kerala for a few years. But there was no attempt for objective criteria for monsoon onset over A & N Islands. Therefore, this paper is aimed at establishing a set of objective criteria for onset of monsoon over A & N Islands on the basis of weather parameters and realized rainfall over the region. The weather parameters for the study has been selected based on all the above mentioned past literature as well as on the operational experience gained in several years. During the monsoon onset over India, dramatic changes are known to occur in the large-scale atmospheric structure over the monsoon region. Some of the well known ones associated with the onset are a rapid increase of the daily precipitation rate and an increase in the kinetic energy, especially of the low-level flows (Krishnamurti, 1985). Normal dates of the onset of the monsoon over different parts of India as given by the India Meteorological Department (1943) are shown in Fig. 1. This is based on the long-term average pentad (five-day non-overlapping) rainfall graphs prepared for 140 observatory stations. The middle date of the pentad, which shows an abrupt increase in rainfall, was taken as the monsoon onset date for each station. Climatologically; the monsoon sets in over the Andaman & Nicobar Islands on 20th May, over the extreme southern part of peninsular India (Kerala) by 1st June and covers the entire country by 15th July.

It is recognized that the most significant regional feature of the BOB monsoon onset is the sudden development of the deep convection and its associated westerly flow (Wang and LinHo, 2002) and (Wang *et al.*, 2004). Studies by Ananthakrishnan and Soman (1988); Pai and Rajeevan (2009) defined onset dates of the monsoon season in different parts/stations using a wide range of criteria that includes rainfall, surface and upper level winds, Outgoing Longwave Radiation (OLR) and upper-tropospheric water vapour, etc. Wang *et al.* (2004) have shown that the summer monsoon onset over Kerala can be faithfully determined objectively by use of the 850 hPa zonal winds averaged over the central south China Sea (Lat. 5-15° N and Long. 110-120° E). Joseph *et al.* (2006) used rainfall, wind field and OLR for declaring monsoon onset over Kerala. IMD now presently uses the said criteria for declaring monsoon over Kerala on operational basis. In this study we have explored the possibility for defining the monsoon onset over A & N Island by using a similar approach as in Joseph *et al.* (2006).

2. Data and methodology

For this study authors have explored the possible meteorological parameters along with domain. Four meteorological parameters namely pressure, upper air wind, OLR and realized rainfall has been analyzed along with area of domain. Domain (Lat. 0-15° N and Long. 80-95° E) has been considered for the study. As the study is confined to A & N Islands, the data of Thailand & Malaysia were not considered. Also it has been observed that on several occasions, the commencement of monsoon rains over Thailand & Malaysia is more linked to the onset over South China Sea than that over the Indian Seas. Mean Sea Level Pressure (MSLP) data over the region has been analyzed but it has not shown any significant N-S pressure gradient. Hence pressure data has been excluded from the final analysis in the study. For this study, we have used the National Centre for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) daily mean reanalysis data for wind on a 2.5°×2.5° grid at the standard pressure levels (925, 850, 700 and 600 hPa) for the 34 years period from 1980 to 2013 over the BOB grid point over the latitude between 0.0 to 15.0° N and longitude 80 to 95° E. As Islands and the area under study being dominated by the tropical Ocean, the spatial variation of meteorological parameters is found to be small. Hence the coarser grid of 2.5°×2.5° readily available has been utilized. Authors define monsoon onset over A & N Islands as the reference point P-0 (lag 0) which was the actual date of onset. The date of

actual monsoon onset over A & N Islands identified by India Meteorological Department (IMD) for each year is used as a guidance and the variables are analyzed from 08 days prior to onset date as P-8 and for 3 days after onset as P+3 to the reference point (lag 0).

The monsoon advance over the region occurs with the establishment of the Inter Tropical Convergence Zone (ITCZ) extending from the Arabian Sea to western parts of north Pacific Ocean. As such, going by the atmospheric wind pattern, the area between equator and to the south of ITCZ, where monsoon current prevails would be dominated by westerlies/south westerlies in which the meridional component are quite negligible. Hence only zonal component has been considered for determination of objective criteria. To decide lower level winds, both 925 hPa & 850 hPa winds were considered. However, considering the Seas/Islands area where friction is less and correlation between wind speed of this level very high (0.85) it has been decided to take u-component of wind at 925 hPa. OLR value is the daily average OLR value. Anomaly has not been considered in present study as the data analysis for a long period has been carried out and not for a specific event. In the present study main focus is given to the increase, decrease and persistence of cloud cover in terms of OLR.

Normal date of onset over A & N Island is 20th May. We have calculated the parameters from 1st May for three years 1988 (onset was earlier), 2005 (onset was late) and 2009 (onset was normal). It has been observed from the study that during 1988 for Nicobar Islands it became conducive in the beginning of the May whereas for Andaman Islands depth of westerly and OLR criteria was not satisfied during initial days of the month. Similarly for 2005, the depth of westerlies and OLR value particularly for Andaman Islands were not favourable. Hence, the decision for sticking to P-8 is justified. Moreover, from the past records also we can see that climatologically the monsoon has never advanced over the Andaman Sea prior to 10th May. Wang and Lin (2002) identified two phases in the evolution process of the Asian summer monsoon. The first phase begins with abrupt increase in rainfall over the South China Sea in mid-May, which is associated with the establishment of ITCZ extending from the Arabian Sea to western parts of north Pacific Ocean across south China Sea. Ding (2004) divided the whole onset process of northern Hemispheric summer monsoon into 4 stages in which in the first stage, the earliest onset is often observed in the central Indo-China region in late April or early May or in some cases the onset may begin in the southern or western part of the Indo-China peninsula. It is in the second stage that the monsoon advances into southern parts of Bay of Bengal (*via* northward progression) and south China Sea (eastward extension), which is identified to occur during mid-May to end of May. For the Asian Monsoon as a whole, the first transition of the atmosphere takes place over the South China Sea (Hsu *et al.*, 1999).

Following these lines, we may expect the onset over the Andaman Sea & Islands only after 10th May. However, in order to check whether there is any such event in which the set criteria gets satisfied prior to 10th May, a few years, especially those in which the operationally declared onset had been earlier most and later most have been examined for the criteria, staring from 1st May. It is found that the criteria are not getting satisfied in any of these years.

Operationally declared dates are considered as reference for arriving at the criteria in this study because of the fact that, even in the absence of a set of objective criteria, the experience of the weather forecasters has been widely acceptable in declaring the arrival of monsoon over the region, so far. It might vary only by a few days, if one is to strictly follow the criteria. The objective criteria thus derived might help the forecasters henceforth to identify the onset event un-ambiguously as well as to forecast the probable date from the numerical weather predictions.

For rainfall distribution, daily observed rainfall data of all the seven stations, 3 for Nicobar Islands [Car Nicobar (CNB), Nancowry (NNY) and Kondul (KDL)] & 4 for Andaman Islands [Hut Bay (HTY), Port Blair (PBL), Long Islands(LGI) and Mayabandar (MYB)] have been considered for the analysis period of 1980-2013.

The value of daily averages of OLR data on a 2.5°×2.5° grid, obtained from NCEP/NCAR reanalysis data set (Kalnay *et al.*, 1996) has been considered. The value is the best estimate for the representation of the grid. The low value of OLR indicates the dense overcast clouds over the region and as the value increases the density and distribution of clouds decrease. It is also used as a proxy for large-scale convective activity over the BOB grid over the latitude between 0.0 to 15.0° N and longitude 80.0 to 95.0° E. The daily average OLR data has been considered for the period 1980 to 2013 over A & N Islands.

Based on onset dates of the Indian summer monsoon over A & N Islands, we have considered the onset period into three sub phases, *viz.*, pre-onset, onset and post-onset of southwest monsoon phase in each year of the study period. The onset is considered the day of actual onset; pre-onset and post-onset of southwest monsoon phases respectively for 8 days before and 3 days after the actual onset of southwest monsoon dates thus making the onset period as twelve (12) days in each year. IMD operational

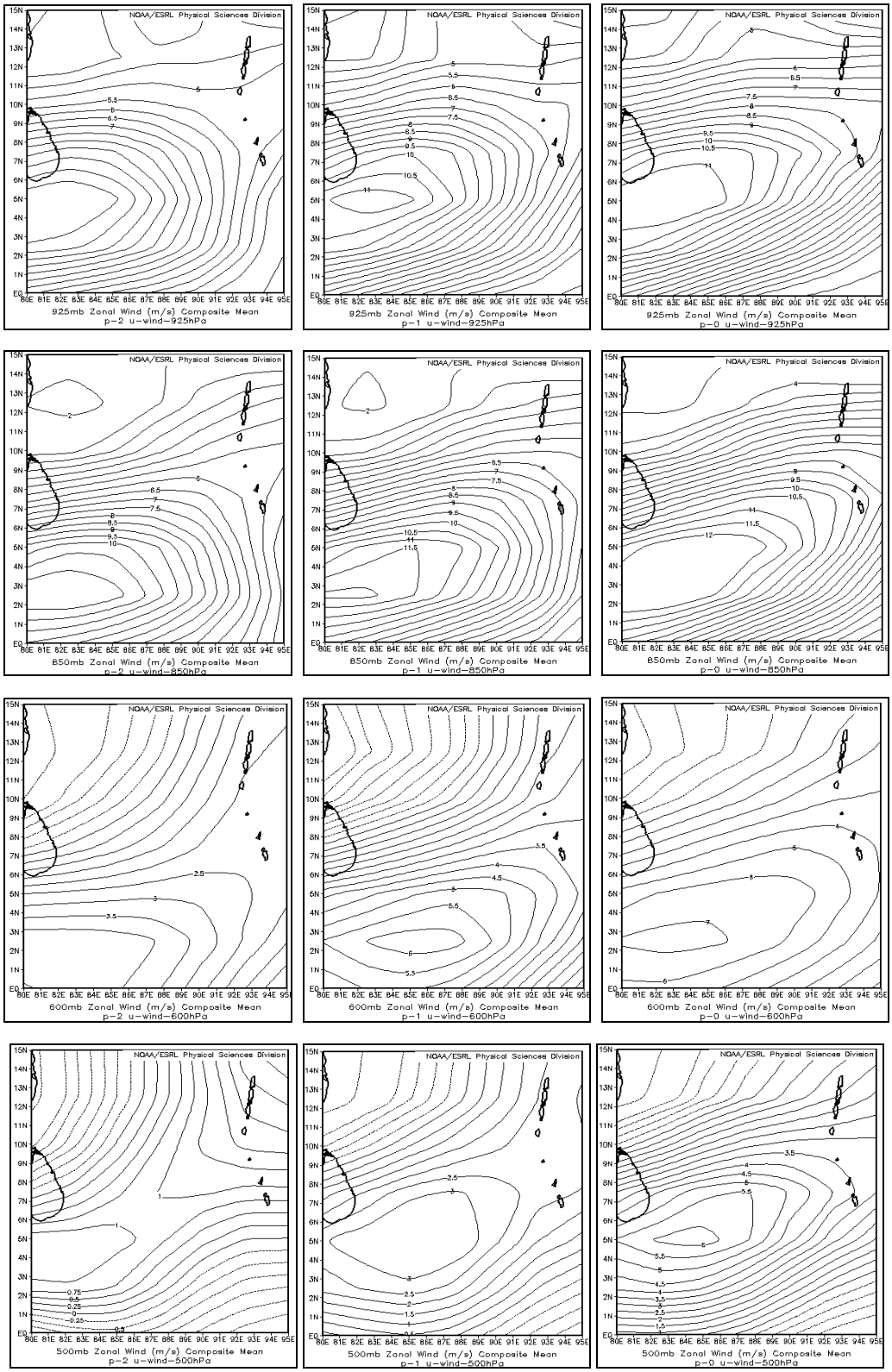


Fig. 2. Composite winds at selected levels *viz*., 925, 850, 600 & 500 hPa to illustrate the strengthening and deepening of westerlies over and around the A & N Islands during the advance of southwest monsoon

TABLE 1(a)

Wind speed at 925 hPa over Nicobar Islands (1980-2013) on the day of onset

Range (in mps)	Frequency	Percentage (%)	Descending cumulative percentage (%)
<4	2	6	100
4-7	8	24	94
8-11	12	35	70
>11	12	35	35

TABLE 1(b)

Wind speed at 925 hPa over Andaman Islands (1980-2013) on the day of onset

Range (in mps)	Frequency	Percentage (%)	Descending cumulative percentage (%)
<4	5	15	100
4-7	8	24	85
8-11	14	41	61
>11	7	20	20

date of onset of monsoon over A & N Islands for a particular year has been considered to be P-0 day (lag 0) which was the actual date of onset; before onset the previous 8 days were considered to be P-1, P-2, P-3, P-4, P-5, P-6, P-7 and P-8 days. Similarly, after the onset the next three days were considered as P+1, P+2 and P+3 days. We have analysed 34 years data of each of the parameters namely OLR, zonal wind (u) components and depth of westerlies for the pressure levels 925, 850, 700, 600 and 500 hPa individually during the 1980-2013. Analysis of rainfall was also carried out to find out distribution pattern similarly for onset, pre-onset and post onset phases of southwest monsoon for the same study period as mentioned above. All the parameters were examined individually for the specified monsoon period of 12 days in each year to find out their characteristics in relation to monsoon onset. The average value of OLR at a grid point of 2.5°×2.5° over the study area on daily basis has been analyzed for the period 1980 to 2013. While analyzing the OLR, main emphasis was given to the variability and persistence of OLR over the particular grid area and broadly over A & N Islands separately.

On analysis of the findings for the specified 12 days' southwest monsoon onset period over A & N Islands as mentioned above, it has been found that there is a gradual increase of convection, zonal wind flow, increase in depth of westerlies over an area bounded by latitudes 0 and 15.0° N and longitudes east of 85.0° E along with rainfall distribution over the stations of A & N Islands during the period P−2 to P+2 days. Hence, length of the southwest monsoon period under study has been reduced to five days period to find out characteristics of chosen parameters for defining the objective criteria of onset of southwest monsoon over A & N Islands.

3. Results and discussion

3.1. *Characteristics of parameters for objectively defining date of monsoon onset over A & N Islands*

3.1.1. *Wind fields*

Wind speed at different levels (925, 850, 700, 600 and 500 hPa) has been analysed during onset of monsoon. For determination of zonal wind speed (u-component) at lower level. Zonal wind at both 925 hPa and 850 hPa levels has been considered. The correlation of strength of wind at 925 hPa and 850 hPa is found very high. It is 0.85 for Nicobar Islands and 0.94 for Andaman Islands. Fig. 2 displays the composite winds (1980-2013) over the region of analysis on days P-2, P-1 and P-0 (actual onset date declared by IMD) at 925, 850, 700, 600 & 500 hPa levels. The individual years' wind analysis is not re-produced here. It has been observed from the analysis that in most of the years, winds are showing increase in intensity at 925 hPa from P-2 day to P-0 day. Again depth of westerly during time of onset is mainly upto 600 hPa. There has been some deviation from these two criteria. The possible reason may be the formation of Low Pressure Area over Bay of Bengal or Andaman Sea. It is observed that out of 34 years period, in 24 years, the onset over Nicobar Islands occurred with wind speed 8 mps or more. In other words, 70% occasion of monsoon onset over Nicobar occurred with prevailing u component of wind 8 mps at 925 hPa [Table 1(a)]. Similarly, on 62% occasions, monsoon onset over Andaman occurred with prevailing ucomponent of wind 8 mps at 925 hPa [Table 1(b)]. On analysis, it has also been observed that the depth of westerly during onset date were upto 600 hPa in most of the years (33 out of 34 years in Nicobar Islands and 29 out of 33 years in Andaman Islands).

3.1.2. *OLR fields*

The OLR fields for the selected domain has been analysed for the period under consideration. The value of cloud top temperature represents the depth of convection over the area. The CTT< 220 °K (-53 °C), between 220 °K to 235 °K (-53 °C to -62 °C) and 62 °K to 255 °K (-62 °C to -82 °C) represent very deep convection, deep

TABLE 2(a)

OLR over Nicobar Islands (1980-2013)

Range (in watt/m^2)	Frequency	Percentage (%)	Ascending Cumulative percentage (%)
≤130	1	3	3
131-150	4	12	15
151-170	5	15	30
171-190	8	24	54
191-210	7	21	75
211-230	5	14	89
>230	4	11	100

Table 2(b)

OLR over Andaman Islands (1980-2013)

Range (in watt/m^2)	Frequency	Percentage (%)	Ascending Cumulative percentage (%)
≤130	1	3	3
131-150	1	3	6
151-170	7	21	27
171-190	8	24	51
191-210	7	21	72
211-230	5	14	86
>230	5	14	100

convection and background convective clouds respectively (Remy and Ramanathan, 2000). Tables 2(a&b) describes about the cloud cover in terms of OLR over A & N Islands with monsoon onset over Nicobar and Andaman Islands respectively. It has been observed from the Tables 2(a&b) that 75% onset cases over Nicobar Islands and 72% onset of southwest monsoon over Andaman Islands were associated with OLR value of 210 watt/m^2 or less.

3.1.3. *Rainfall distribution*

Analysis of the results indicates that onset of monsoon over this region are associated mainly with fairly widespread (FWS) rainfall or widespread (WS). On a few occasions onsets occurred with scattered rainfall distribution (SCT distribution means when the number of stations reporting rainfall of 1 mm or more is upto 50% of the total number of stations, FWS distribution is when the percentage is 51-75% and WS distribution when the percentage is more than 75%). During 1980-2013 period, monsoon onset was associated with FWS rainfall on 26 times in Nicobar Islands and 30 times in Andaman Islands [Tables 3(a&b)].

4. Fixing threshold of objective criteria for onset of monsoon over Andaman & Nicobar Islands

Based on the above results, the following criteria have been chosen for onset of monsoon over A & N Islands. The parameters may be observed from actual observations/model analysis fields and satellite derived products on operational basis.

(*i*) Rainfall distribution of fairly widespread (FWS) or widespread (WS) over the area/region.

(*ii*) U-component of wind speed at 925 hPa of 8 mps or more.

(*iii*) Depth of westerly over the region/area may be upto 600 hPa.

(*iv*) Outgoing Long wave Radiation (OLR) over the region/area may be 210 watt/m^2 or less.

On the basis of above chosen criteria monsoon onset over Nicobar and Andaman Islands calculated for the study period are shown in Table 3(a&b) respectively. The graphs (Only 3 graphs are reproduced here, due to space constraints) with superimposition of all the above parameters are shown in Figs. 3(a&b) for Nicobar and Andaman respectively.

5. Findings of objective criteria for onset

It is found that in many of the years of study period under consideration (1980-2013), IMD's operational onset date did not coincide with peak values of the selected parameters chosen for determination of the criteria. In some years peak values/threshold value occurred one/two days before/after the actual onset date. In Fig. 3(a) and Fig. 3(b), → indicates actual onset date and ⟹ indicates the onset date based on objective criteria. Correlation coefficients of dates based on objective criteria and IMD's operational onset is 0.97 for Nicobar and 0.98 for Andaman Islands.

The onset, based on objective criteria coincided with the declared onset dates of all the years except 1992, 2001, 2002 and 2005 for Nicobar Islands and 1981, 1991, 1996, 2005 for Andaman Islands where one or two of the criteria does not satisfied. However, these mentioned years where the objective criteria were not satisfied, are

TABLE 3(a)

Composite table for monsoon onset over Nicobar Islands

Year	IMD's operational onset over Nicobar islands in May	Onset based on objective criteria over Nicobar (May)	Mean zonal wind* (metre/sec)	Depth of westerlies (in hPa)	Mean OLR (watt/m^2)	% of station reporting rainfall
1980	20	22	10	600	210	WS
1981	18	17	10	600	150	FWS
1982	26	28	14	600	150	FWS
1983	27	27	14	600	210	FWS
1984	22	21	9	600	190	FWS
1985	22	21	14	600	150	WS
1986	20	19	14	600	190	FWS
1987	29	31	8	600	190	WS
1988	10	8	8	600	190	WS
1989	18	16	10	600	150	WS
1990	19	17	13	600	210	WS
1991	24	26	9	600	150	FWS
1992	20	19	6	600	230	FWS
1993	17	19	9	600	150	WS
1994	21	20	8	600	190	WS
1995	14	12	12	600	190	WS
1996	17	15	8	600	250	FWS
1997	16	15	12	600	130	WS
1998	15	16	10	600	210	FWS
1999	20	20	12	600	150	FWS
2000	15	15	12	600	190	WS
2001	15	15	8	600	230	FWS
2002	14	15	11	600	230	WS
2003	16	14	15	600	190	FWS
2004	13	11	9	600	210	FWS
2005	26	26	6	600	210	WS
2006	17	19	10	500	150	WS
2007	10	9	11	500	170	WS
2008	10	9	8	500	170	WS
2009	20	21	3	500	170	WS
2010	17	17	10	500	130	WS
2011	29	29	11	600	230	FWS
2012	23	21	8	600	190	WS
2013	17	16	9	600	210	WS

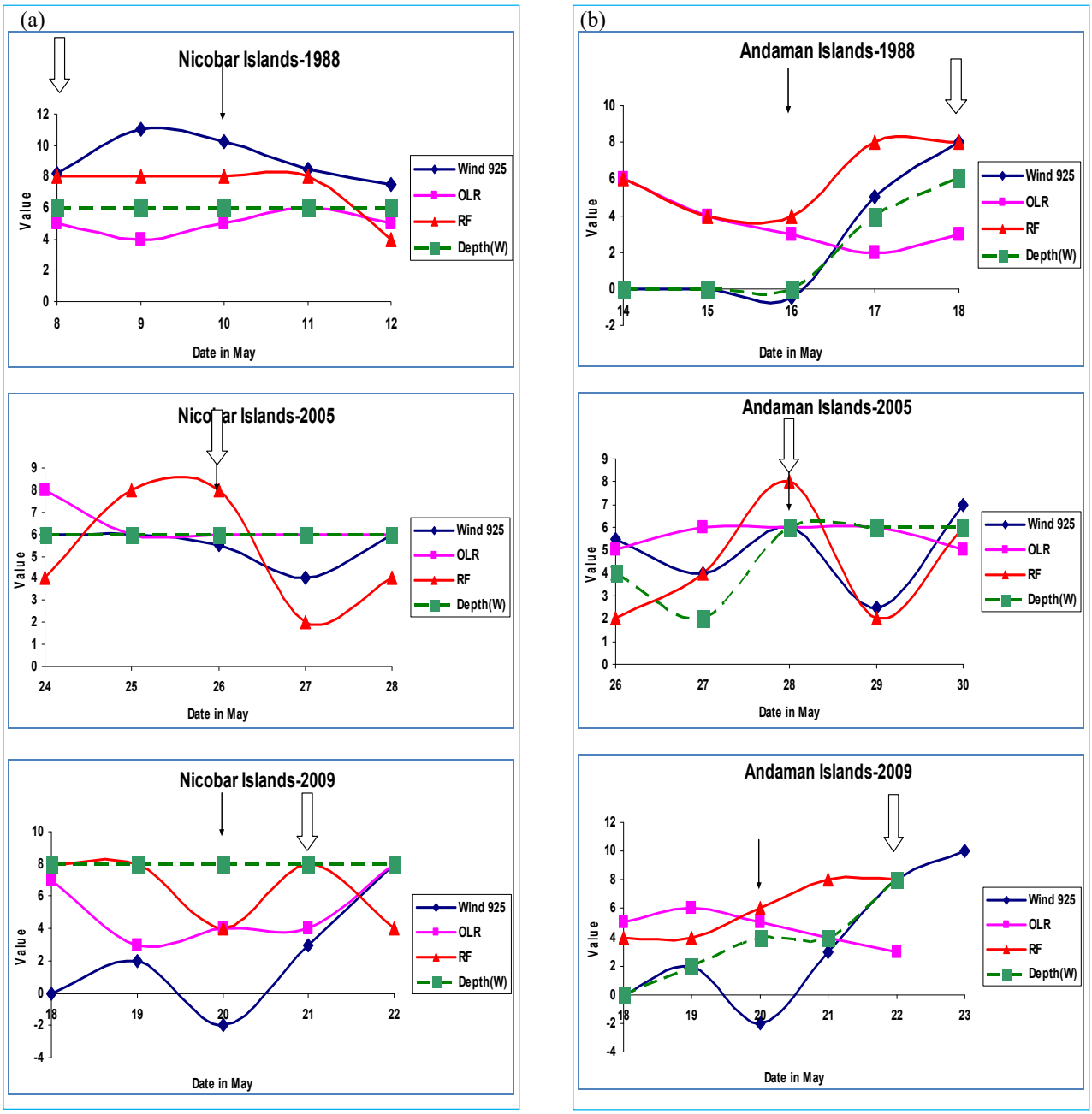
* Mean zonal wind - (+) indicate westerly & (-) indicate easterly

TABLE 3(b)

Composite table for monsoon onset over Andaman Islands

Year	IMD's operational onset over Nicobar islands in May	Onset based on objective criteria over Nicobar (May)	Mean zonal wind* (metre/sec)	Depth of westerlies (in hPa)	Mean OLR (watt/m2)	% of station reporting rainfall
1980	22	22	8	600	210	WS
1981	18	18	3	600	190	WS
1982	26	28	8	600	150	SCT
1983	27	28	9	600	190	WS
1984	28	28	9	600	190	FWS
1985	23	23	10	600	170	WS
1986	20	19	14	600	170	WS
1987	30	31	8	600	190	WS
1988	16	18	8	600	150	WS
1989	20	21	9	600	170	WS
1990	20	20	10	600	170	WS
1991	25	26	8	850	250	SCT
1992	23	23	8	600	190	WS
1993	20	20	-2	600	210	WS
1994	21	22	9	600	250	FWS
1995	14	13	11	600	130	WS
1996	20	21	3	850	210	FWS
1997	18	18	10	600	190	WS
1998	18	18	8	600	170	WS
1999	20	22	9	600	150	FWS
2000	19	17	13	600	170	WS
2001	17	17	5	600	210	WS
2002	16	17	14	600	190	WS
2003	31	31	14	600	210	WS
2004	14	14	8	600	170	FWS
2005	28	28	6	600	210	WS
2006	18	19	10	600	170	WS
2007	11	11	10	500	230	WS
2008	12	12	7	500	250	WS
2009	20	22	8	500	150	WS
2010	17	19	7	500	130	FWS
2011	30	30	8	600	250	FWS
2012	23	23	7	850	210	WS
2013	17	16	7	600	250	SCT

* Mean zonal wind - (+) indicate westerly & (-) indicate easterly



Figs. 3(a&b). Analysis of monsoon onset dates over (a) Nicobar Islands and (b) Andaman Islands - A few examples

the years when onset over these region had been declared in the presence of low pressure systems (Low, depression/cyclonic storm) over Andaman Sea and/or BOB (Table 4).

The earliest operationally declared onset which has taken place during the study period has been 10th May. Based on the presently arrived objective criteria, the most early onset date is that of 8th May in 1988. Though the set criteria could get satisfied before 5th May in association with Low pressure systems, it may not be sustainable. Hence there should not be declaration of advance of monsoon over Nicobar Islands before 5th May. In the presence of any low pressure system over the region after 5th May, in concurrence with the fulfillment of any 3 of the 4 criteria discussed above are satisfied, the advance of southwest monsoon over the region may be declared.

TABLE 4

Onset of SW monsoon over the Andaman Sea in the presence of LPS during 1980-2014

S. No.	Date of onset over Andaman Sea	Low pressure system over the Bay of Bengal	Period	Area of formation of the system	Direction of movement
1.	21st May, 1980	Deep Depression	16-25 May	Southeast Bay of Bengal	Northeast East & then North
2.	18th May, 1981	Well marked low	17-19 May	Southeast Bay of Bengal	Northeast
3.	26th May, 1982	Well marked low	16-28 May	North Andaman Sea adjoining east central and southeast Bay of Bengal	West
4.	22nd May, 1985	Very Severe Cyclonic Storm	22-25 May	Central Bay of Bengal, 15.5° N/89.0° E	West, North & then North northeast
5.	29th May, 1987	Cyclonic Storm	2-5 June	Central Bay of Bengal, 17.0° N/88.5° E	Northeast
6.	18th May, 1989	Severe Cyclonic Storm	23-27 May	West central and adjoining east central Bay of Bengal, 19.0° N /90.5° E	West & then North
7.	24th May, 1991	Cyclonic Storm	31 May- 2 June	East central and southeast Bay of Bengal	North-northwest & then North-northeast
8.	20th May, 1992	Cyclonic Storm	15-20 May	Southwest and southeast Bay of Bengal, 11.5° N/87.5° E	Northeast to North-northeast
9.	16th May, 1997	Very Severe Cyclonic Storm	14-21 May	Southeast Bay and adjoining Andaman Sea centered near 7.5° N/90.5° E	North and then North-Northeast
10.	15th May, 1998	Severe Cyclonic Storm	17-20 May	Southern parts of central Bay and adjoining south Bay centered near 14.5° N/88.0° E	North- Northeast
11.	14th May, 2002	Deep Depression	11-12 May	South Andaman Sea centered near 12.5° N/96.0° E	North-Northeast
12.	16th May, 2003	Very Severe Cyclonic Storm	10-19 May	South east Bay of Bengal centered near 6.0°N/90.5°E	Northwest ,then North, East and Northeast
13.	13th May, 2004	Very Severe Cyclonic Storm	16-19 May	East central Bay of Bengal centered near 17.0°N/91.5°E	Northwest, East and then Northeast
14.	17th May, 2006	Very Severe Cyclonic Storm 'Mala'	25-29 May	South Andaman Sea centered near 9.5° N/90.5° E	Northwest, North-Northeast and Northeast
15.	10th May, 2007	Cyclonic Storm 'Akash'	13-15 May	East central Bay of Bengal and neighbourhood centered near 15.0° N/90.5° E	North to Northeast
16.	20th May, 2009	Severe Cyclonic Storm 'Aila'	23-26 May	East central Bay of Bengal and neighbourhood centered near 16.5° N/88.0° E	North
17.	17th May, 2010	Severe Cyclonic Storm 'Laila'	17-21 May	Southeast Bay of Bengal and neighbourhood centered near 10.5° N/88.5° E	West-northwest – north-North-northeast
18.	17th May, 2013	Cyclonic Storm 'Viyaru'	10-16 May	Southeast Bay of Bengal and neighbourhood centered near 5.0° N/92.0° E	Northeast
19.	18th May, 2014	Depression	21-22 May	East central Bay of Bengal centered near 15.5°N/90.5°E	Northeast and then Northwest

TABLE 5

Mean difference, SD and bias between IMD's operational dates and date based on objective criteria

Year	IMD's operational onset over Nicobar islands in May	Onset based on objective criteria over Nicobar (May)	Bias	IMD's operational onset over Andaman islands in May	Onset based on objective criteria over Andaman (May)	Bias
1980	20	22	-2	22	22	0
1981	18	17	1	18	18	0
1982	26	28	-2	26	28	-2
1983	27	27	0	27	28	-1
1984	22	21	1	28	28	0
1985	22	21	1	23	23	0
1986	20	19	1	20	19	1
1987	29	31	-2	30	31	-1
1988	10	8	2	16	18	-2
1989	18	16	2	20	21	-1
1990	19	17	2	20	20	0
1991	24	26	-2	25	26	-1
1992	20	19	1	23	23	0
1993	17	19	-2	20	20	0
1994	21	20	1	21	22	-1
1995	14	12	2	14	13	1
1996	17	15	2	20	21	-1
1997	16	15	1	18	18	0
1998	15	16	-1	18	18	0
1999	20	20	0	20	22	-2
2000	15	15	0	19	17	2
2001	15	15	0	17	17	0
2002	14	15	-1	16	17	-1
2003	16	14	2	31	31	0
2004	13	11	2	14	14	0
2005	26	26	0	28	28	0
2006	17	19	-2	18	19	-1
2007	10	9	1	11	11	0
2008	10	9	1	12	12	0
2009	20	21	-1	20	22	-2
2010	17	17	0	17	19	-2
2011	29	29	0	30	30	0
2012	23	21	2	23	23	0
2013	17	16	1	17	16	1
Mean	18.7	18.4	0.32	20.6	21.03	-0.38
SD	5.06	5.72	1.4	5.1	5.32	0.95
Mean difference	0.32	-	-	-0.38	-	-

Table 5 provides the Mean difference, SD and bias between IMD's operational dates and date based on objective criteria.

6. Conclusions

The study suggest that, after 5th May, the onset of monsoon over Andaman and Nicobar Islands may be declared on the very first day of fulfillment of the following criteria provided their persistence is likely for at least subsequent two days.

(*i*) Rainfall distribution of fairly widespread (FWS) or widespread (WS) over the area/region.

(*ii*) U-component of wind speed at 925 hPa of 8 mps or more.

(*iii*) Depth of westerly over the region/area may be upto 600 hPa.

(*iv*) Outgoing Long wave Radiation (OLR) over the region/area may be 210 watt/m^2 or less.

(*v*) However, in case of onset of monsoon with LPS, at least three criteria out of four may be considered for onset of monsoon over this region, provided this occur after 5th May.

As per the new proposed criteria, the normal dates of advance of southwest monsoon over Nicobar & Andaman Islands are 18th May & 21st May with a Standard Deviation of 6 & 5 days respectively.

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