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Characterization of southwest monsoon onset over Myanmar

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Abstract The aim of this paper was to characterize the southwest monsoon onset over Myanmar based on the model. The Regional Climate Model (RegCM3) was run for a period of 10 years (2000–2009) to simulate the meteorological fields which focused on April to July season. The model input data were obtained from the reanalyzed datasets of the National Center for Environmental Prediction (NCEP) and National Centre for Atmospheric Research (NCAR). Grell scheme with Arakawa closure for cumulus parameterization assumption was used for simulation with 45 km horizontal resolution. The results revealed that southwest monsoon onset was confirmed when the prevailing wind direction up to 600 hPa level had shifted from northeasterly to westerly or southwesterly. The southwest monsoon first arrived at southernmost Kawthoung station of Myanmar and progressed through the Deltaic and Central parts until it reached at northernmost Putao station. Over the simulation periods, the southwest monsoon onset progressed from the southernmost to northernmost parts of the country in 19 ± 10 days. The position of Intertropical Convergence Zone (ITCZ) appeared (23°N–28°N) over the Northern part of the country before the onset. Furthermore, 500 hPa ridge appeared consistently over the Deltaic area of Myanmar from 6 to 10 days before the monsoon onset. Its position is about 6° to the south of the ITCZ.

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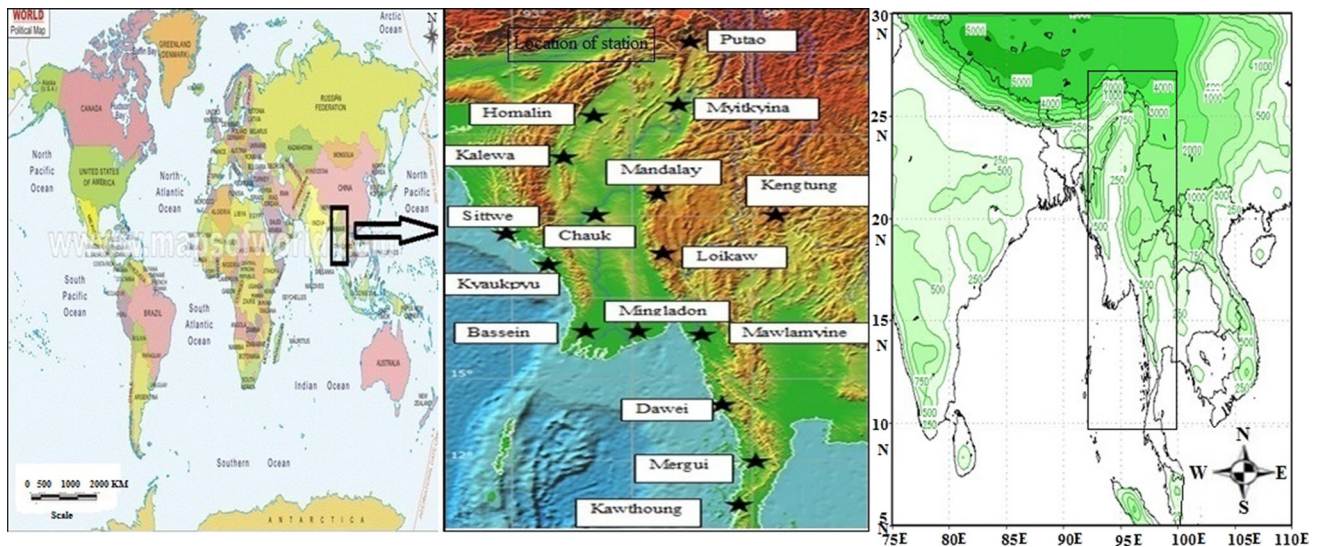
1 Introduction

About 60 % of the world's population depends on monsoon rains to meet their water demands for agriculture, industry and other development sectors (PROMISE 2003). A weak or delayed monsoon onset can lead to a shorter crop growing period thus decreasing yield and consequently cause strain on food security. More than 90 % of the annual rainfall in Myanmar occurs during the rainy season which is from May to October (DMH 2011). Myanmar is located in the northwestern part of the Indo-China Peninsula between latitudes 9.5°–29°N and longitudes 92°–102°E (Fig. 1). The weather and climate of Myanmar are strongly influenced by the monsoon from the India Ocean (southwest monsoon) and cold air mass from the East Asia continent. The climate of Myanmar is divided into three seasons; summer season (March to April), rainy season (May to October), and winter season (November to February). For weather and climatology purposes, Myanmar is divided into four areas such as Northern Myanmar area (24°–29°N), Central Myanmar area (19°–24°N), Deltaic area (15.5°–19°N) and Southern Myanmar area (19.5°–15.5°N).

The southwest monsoon onset is preceded by an increase in temperature over almost all the monsoon regions (Sangwaldach et al. 2006). During the southwest monsoon season, the monthly mean surface air temperatures exceed

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Fig. 1 Map shows the location and synoptic stations over Myanmar. The model domain and topography (in meter) covered by the model. The *inner rectangle* indicates study area (Myanmar) which is located between 9.5°N and 29°N latitudes and 92°E and 102°E longitudes

33–35 °C in the land areas of northwest India and adjoining areas (Joshi et al. 1990). The progressive development of heat low before and during the monsoon season is considered to be one of the major causative factors of the Indian summer monsoon circulation (Rao 1976). Fein and Stephens (1987) reported that the monsoon rain and winds are the end results of heating patterns produced by the sun and the distribution of land and ocean. They also stated that near the west coast of India, the winds are west-southwesterly to westerly, with speeds of 5–10 m/s, while the mean speed is 5 m/s inland. The monsoon troughs were investigated at 500 hPa level over the India during the monsoon onset before moving eastward after the monsoon onset (Sangwaldach et al. 2006). An important anatomy of the Indian summer monsoon trough is an elongated low pressure system that extends southeastward from Pakistan to Gangetic West Bengal, with southwesterly winds south of the trough line and easterlies to the north. This trough extends aloft up to about 4 km and slopes southward with height (Potty et al. 2001). Wang et al. (2009) provided a useful metric for verifying numerical model performance for simulating and predicting the Indian summer monsoon onset and to study the predictability of interannual variations of the monsoon onset. Monsoon onset over Myanmar has been considered as the beginning of the rainy season: the southwest monsoon is simply called as summer monsoon season. The southwest monsoon onset characteristics and prediction are debatable topics. They have been widely studied and research continue through the 1970s to date in southeast Asia (e.g., Reddy 1977; Subbaramayya and Bhanukumar 1978), the 1980s (e.g., Saha and Saha 1980; Kung and Sharif 1982; Deshpande et al. 1986; Joseph and Pillai 1988; Ananthakrishnan and Soman 1988), the 1990s

(e.g., Joseph et al. 1994; Rajeevan and Dube 1995), and recent decade (e.g., Ghanekar et al. 2003). The monsoon onset over Myanmar is defined by DMH (2011) as a start of a period of 5 consecutive days with daily rainfalls equal or exceeding 2 mm and the westerly jet moved from south to north of Himalayas at 200 hPa level and 500-hPa ridge moved from south to north of Myanmar. According to Htway and Matsumoto (2011), monsoon onset is defined as the first day of three consecutive rainy days with daily rainfall amount of 2.54 mm or more.

Most previous studies of the monsoon onset have been used a more-or-less smooth annual cycle of gridded (2.5° by 2.5°) outgoing long wave radiation (OLR; e.g., Mao et al. 2004) or US Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP; Xie and Arkin 1997; 1998) data (Murakami and Matsumoto 1994). A few studies have considered spatially averaged daily rainfall at the regional scale, such as over the Indo-China (e.g., Zhang et al. 2004). At this scale, the monsoon onset is usually viewed as a multi-stage phenomena, progressing from the Indo-China Peninsula and South China Sea (SCS) in early to mid-May, eastward to the Philippines Sea (mid-June) and lastly, to the Central Northern Tropical Pacific Ocean (mid-July) (Wu and Zhang 1998; Wu and Wang 2000, 2001; Wang and LinHo 2002; Ding et al. 2004). The interannual variability of large-scale monsoon onset is strongly associated with El Nino Southern Oscillation (ENSO). The warm (cold) ENSO events in the preceding spring related to late (early) onset (Wu and Wang 2000; Zhang et al. 2002; Moron et al. 2009). The formation of the monsoon trough in the Bay of Bengal provides favorable conditions not only for rainfall, but also for tropical cyclones (TCs) (Wang et al. 2013). Recently, Fosu and

Wang (2014) studied the Bay of Bengal coupling of pre-monsoon tropical cyclones with the monsoon onset in Myanmar. The study focused on the Madden–Julian Oscillation (MJO) which exhibits a strong interannual variability with the monsoon onset in Myanmar. The use of Regional Climate Model (RegCM3) in investigating the onset of monsoon rainfall over Myanmar is very limited. In this regard, an attempt was made to investigate the southwest monsoon onset over Myanmar using the model.

In this paper, we determine the interannual variability and total areal coverage of southwest monsoon onset over Myanmar. A recent study has found that southwest monsoon onset in the vicinity of the Bay of Bengal (BoB) has advanced by 5–10 days since 1979 (Kajikawa et al. 2012). Because, the date of southwest monsoon onset is vital as an agricultural country like Myanmar, agricultural activities are controlled not only by the amount of rainfall, but also by the duration of the rainy season. Since the season is strongly associated with the occurrence of the southwest monsoon, it is important to determine its onset. Such information will help in decision-making of stakeholders, e.g., preparation for planting crops. In Myanmar, those who make their living from the land welcome the season, where the rains largely contribute to the crops they produce. However, excessive rainfall in a short period of time causes flash floods that not only damage crops and drown livestock, but also harm inhabitants of the area. Numerical simulations based on the model are increasingly used to onset monsoon climate variables associated with large-scale climate forcing along with statistical methods. The model is widely used in different parts of the globe to understand regional climate processes, monsoon dynamics, seasonal climate variability and regional climate change. So far, various versions of the model were used in different regions for various purposes (Lynch et al. 1995; Seth and Giorgi 1998; Gao et al. 2001; Pal et al. 2000; Afiesimama et al. 2006; Marcella and Eltahir 2008; Davis et al. 2009; Abiodun et al. 2008; Song et al. 2008; Zou and Zhou 2013). There is need for an accurate prediction of southwest monsoon onset over Myanmar which triggers the rainfall season. So, the characteristics of the monsoon onset will help formulate a more accurate basis for prediction of the onset dates. The model makes it possible to investigate the factors affecting the southwest monsoon onset. The model is commonly used in simulating climate variability over various regions in the world. Not only the model is helpful in understanding the weather systems over the domain, but its ability to predict the southwest monsoon onset is invaluable particularly in the agricultural sectors in Myanmar. The present study focuses over Myanmar and utilizes explanations from meteorological office of 16 stations across the country. The aim of this paper is to characterize southwest monsoon onset over Myanmar at the station-wise scale based on the model. In this study, the RegCM3 model is used to elucidate factors for determining southwest monsoon onset using synoptic maps on Myanmar climate, focusing on May to October rainy season.

2 Data and methodology

2.1 Model descriptions

The RegCM3 model is used to estimate the characteristics of southwest monsoon onset over Myanmar for the present study. Several studies have been carried out using model, as referenced in Giorgi et al. (1998).The model was originally developed at the National Center for Atmospheric Research (NCAR) and continuously upgraded at the International Centre for Theoretical Physics at Trieste, Italy. The model is a 3D hydrostatic, sigma coordinate, primitive equation regional model with up to 23 vertical levels and a horizontal resolution of 10–90 km. The model maintains much of the dynamical core of the fifth generation Pennsylvania State University (NCAR) Mesoscale Model (Grell et al. 1994). The model now employs NCAR's Community Climate Model, version 3 (CCM3), radiative transfer package (Kiehl et al. 1996). The model also applies Zeng's bulk aerodynamic ocean flux parameterization, where sea surface temperatures (SST) are prescribed (Zeng et al. 1998). Finally, the most current developments and description of the model were introduced by Pal et al. (2000, 2007). The lateral boundaries require periodic forcing following one-way nesting technique. With a grid resolution of 45 km (ds), 99 grids along longitude (jx) and 82 grids along latitude (iy), the domain covered by the model. Based on preliminary runs, the recommended time step of 150 s gave unstable results. It was decided to use 120 s; other time step parameters remaining the same. The operating system was UBUNTU while the Fortran Compiler is Intel. Thus, it was imperative to use ibyte equal to 1 in order to be able to display the results in graphics formats.

There are three convective parameterization schemes that can be used with the model, these are: modified-Kuo scheme (Anthes 1977), Grell scheme (Grell 1993) and MIT-Emanuel scheme (Emanuel 1991; Emanuel and Zivkovic-Rothman 1999). In this study, the Grell Scheme (Grell, 1993) was used for analysis of the data. The Grell parameterization is implemented using one of two closure assumptions: the Arakawa and Schubert closure (Grell et al. 1994), and the Fritsch and Chappell closure (Fritsch and Chappell 1980).The Grell scheme with Arakawa closure was selected for cumulus parameterization because it considers cloud as two steady-state circulations:

an updraft and a downdraft. No direct mixing occurs between the cloudy air and the environmental air except at the top and bottom of the circulations. The mass flux is constant with height and no entrainment or detrainment occurs along the cloud edges. The originating levels of the updraft and downdraft were given by the levels of maximum and minimum moist static energy, respectively. It was activated when a lifted parcel attains moist convection.

2.2 Data

The National Center for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) reanalyzed datasets (NNRP2) were used as input for RegCM3. The weather elements were used in the model such as the horizontal winds, relative humidity, rainfall and the geopotential height at standard meteorological levels and surface pressure. The NNRP2 is available 6 hourly with a grid resolution of $2.5° \times 2.5°$. Other datasets are required to develop the model. The Optimum Interpolation Sea Surface Temperature (OISST) available at weekly intervals was the option selected. As for land use, the GLCC BATS was adapted interpolation in every 2 min. Topography was from GTOPO30 and the interval opted was 2 s.

The observed rainfall of 16 synoptic stations was obtained from DMH (Myanmar) during periods of 2000–2009. Some of these synoptic stations also function as agrometeorological stations are well scattered over Myanmar. Synoptic data are not available particularly for the periods of 2001–2005, the rainfall data from agrometeorological stations were resorted for this study. In addition, observed wind data (2000–2009) from 7 synoptic stations out of the 16 stations of Myanmar were used in connection with the southwest monsoon onset. The southwest monsoon onset over 16 stations and its characteristics were identified from the model simulation (Fig. 1).

2.3 Model simulation

The model was run using the data from April 7 to July 1 over a period of 2000–2009. From observations, the earliest onset in Myanmar is mid-May while the latest onset is early-June. Therefore, the simulations started at April 7 for model spin up. The model outputs were 6 hourly. As a first attempt to identify the monsoon onset and its progress all over Myanmar, the horizontal winds at 850 hPa were closely monitored whether the winds shifted from northeasterly or easterly to southwesterly or westerly. The first date is at a certain grid where shifting was regarded as the monsoon onset (Fig. 2a).

Once monsoon the onset was detected using 850 hPa winds, the vertical cross sections of the horizontal winds at 5° intervals along longitude from 85°E–105°E were also analyzed in order to have an idea where the monsoon was located for a given day and to what extent (Fig. 2b). The analyses were made 1 week before the identified onset and continued 1 week after the onset or a total of 2 weeks. The southern and northern limits of the monsoon could be distinguished from these maps. Vertical cross section of the horizontal winds for a given station was displayed over 1–2 week periods within the onset happened.

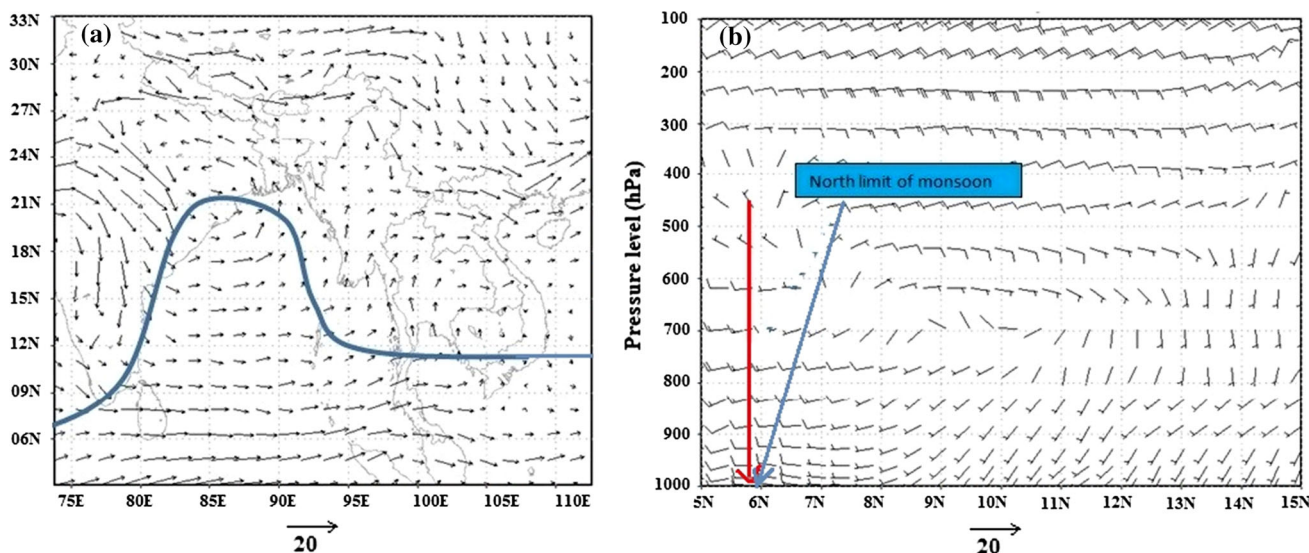Other weather elements such as relative humidity or water vapor mixing ratio, temperature, rainfall and

Fig. 2 a Horizontal winds at 850 hPa on 0000Z May 20, 2009 with *blue line* separating the area of southwesterly winds from northerly winds. b Vertical cross section of horizontal winds along longitude at 90°E on 0000Z May 19, 2009; *red and blue arrows* indicate northern limit of monsoon (NLM)

outgoing longwave radiation (OLR) were analyzed using the meteograms. The period covered started 3 or 4 days before the onset and ended 3 or 4 days after the onset or a total of 8 days. Figure 3a, b displays these weather elements. The first panel depicts the trend of the vertical profile of wind speed and direction, temperature and relative humidity from surface to 500 hPa levels. The top panel displays how the relative humidity or temperature changed and evolved during the 8-day period. The second panel indicates the 1000–500 hPa thickness which is the vertical distance between the two pressure levels. This related to the mean temperature of the layer; the greater thickness, warmer the air. The third panel shows the Total-Totals Index (TTI) which was a measure of the vertical stability of the atmosphere. The fourth panel depicts the trend of sea level pressure. A strong change in sea level pressure signifies changes in wind direction temperature and humidity.

The next two panels represent the winds at 10 m and temperature at 2 m. The outgoing longwave radiation (OLR) was the simulated infrared radiation at the top of the atmosphere. A low outgoing longwave radiation (OLR) was due to enhanced convective activity over the area. The last panel shows the precipitation amount from the model simulation. The red bars indicated the portion of precipitation likely to come from convection. The meteograms provided insight on the change of meteorological properties that could be associated with the onset of southwest monsoon. Composite rainfall over Myanmar was prepared based on the average daily rainfall from 1981 to 2010. The study focused on only monsoon evolution of Myanmar. The evolution of monsoon begins with composite average rainfall from May to October in each year. May 20 is an average onset date and its starts a zero composite onset day. The position of the ITCZ, 500-hPa ridge and other weather systems were investigated to arrive at the systematic relationship between the weather system and monsoon onset. The rainfall patterns over Myanmar are controlled by the seasonal migration of the ITCZ that migrates to north–south across the region. The strong convective zone moves toward the northwest by April when the ITCZ begins to strengthen across Myanmar. The movement of the mean position of the ITCZ to the Indian sub-continent and relatively rapid "onset" and "retreat" of the monsoon constitute other characteristic features of the Indian summer monsoon (ISM).

2.4 Validation of the model

The southwest monsoon onset was identified by using model which compared with the DMH (Myanmar) method. The DMH (Myanmar) defined the monsoon onset as a start of a period of 5 consecutive days with daily rainfall equal or exceeds 2 mm.
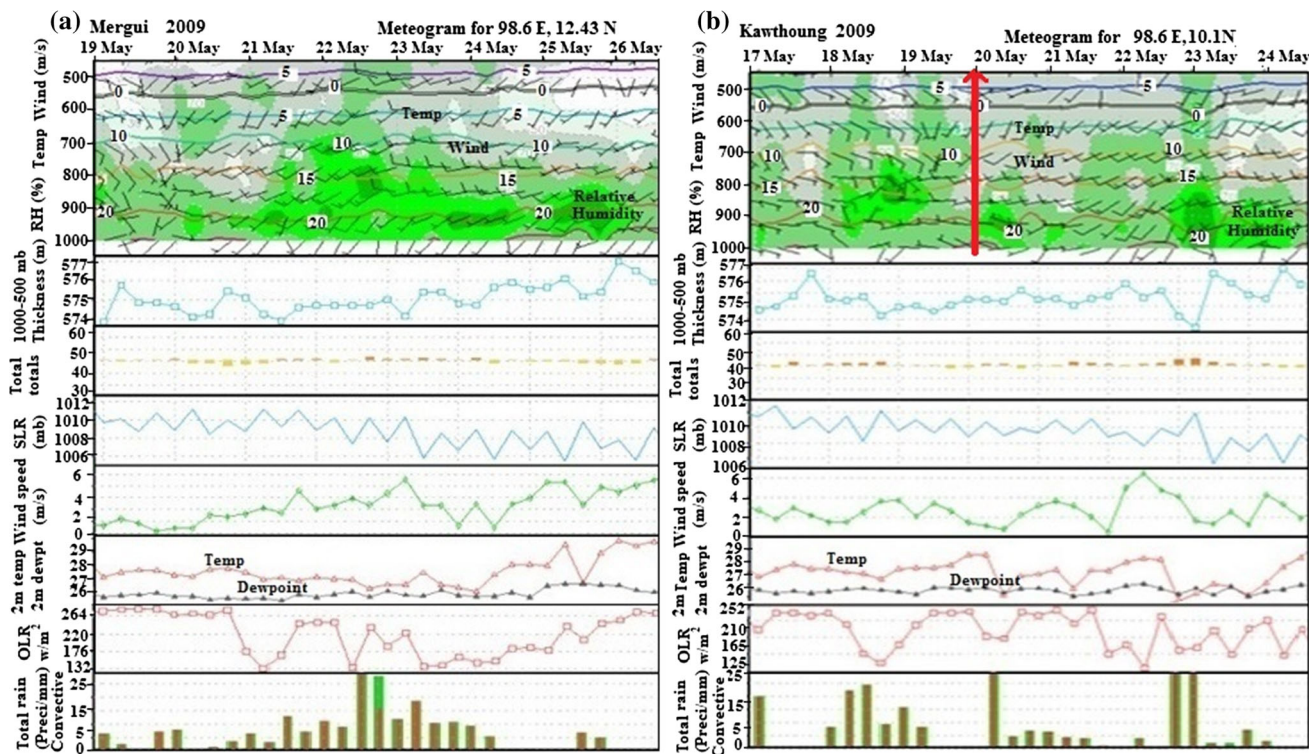

Fig. 3 **a** Meteogram over Mergui station from May 19 to May 26, 2009. **b** Meteogram for Kawthoung station from May 17 to May 24, 2009; *red arrow* shows onset date

The two methods were distinguished by the following statistical parameters:

- Average onset date for each station.
- Earliest/latest monsoon onset for each station.
- Comparison of observed rainfall and winds with the model.
- Time periods for 1 station, first observed monsoon onset started to the last observed monsoon onset during the same year.
- Correlation between the two methods.

3 Results and discussion

3.1 Identification of southwest monsoon onset over the Myanmar

The general progression of the average onset date of southwest monsoon from the Bay of Bengal and Andaman Sea through the Southern, Deltaic, Central and Northern part of Myanmar are shown in Fig. 4. On the average 10-year data (2000–2009), it took about 19 days for the southwest monsoon to progress from the southernmost tip station toward the northernmost tip station. It occurred on May 12 at the southernmost station and moved at about 7 days per Northern limits until it reached on May 31 the uppermost station. In between the dates, the southwest monsoon occurred over the Deltaic and Central Myanmar. To gain a better understanding of the monsoon onset and corresponding weather parameters; the results of the study in 2009 for Kawthoung station are highlighted. The Kawthoung station is southernmost in location and experienced the onset date of southwest monsoon on May 20, 2009. Vertical wind profile

at 100 hPa intervals, from near the ground 1000 hPa up to 100 hPa high up in the air for Kawthoung station, was delineated to characterize wind direction and speed from May 11 to May 21, 2009 (Fig. 5a).

Southeasterly direction wind blowing from May 11 to 19, 2009 and the wind changed to southwesterly direction on May 20, 2009 at the upper levels (Fig. 5b). The westerly component was consistent for the succeeding days. Hence, the southwest monsoon onset for Kawthoung station was chosen to be 20 May, 2009. The wind enters from the Bay of Bengal and Andaman Sea, which lies between India and Myanmar. The shifting of the wind from southeasterly to southwesterly direction at 850–600 hPa levels are shown more clearly from the first panel of the meteograms (Fig. 3b).

The wind direction was southeasterly with wind speed of 10 knots at 600 hPa level from May 17 to 19. The wind shifted to southwesterly direction on May 20, with a wind speed of 5 knots. This direction was sustained thereafter with a speed increasing from 5 to 10 knots. Meteograms are shown for each meteorological station showing rainfall, wind speed and direction, outgoing longwave radiation (OLR). The southwest monsoon arrived first at the Kawthoung station among the 16 stations included in the study period. The earliest onset date was on May 6, 2007 while the latest date was on May 20, 2009. The average onset date (May 12) varied by ±4 days. In comparison, Putao (the northernmost station) the earliest onset date was on May 20, 2002 and 2003 and the latest onset date was on June 12, 2005 and 2009. The average onset date (May 31) widely varied by ±9 days (Table 1).

The earliest southwest monsoon onset occurred in 2007 while the latest monsoon onset observed in 2009 during the study periods (Fig. 6). The earliest onset occurred on May

Fig. 4 Average onset dates of southwest monsoon over the domain (2000–2009) using the model. The *blue lines* indicate onset isochrones
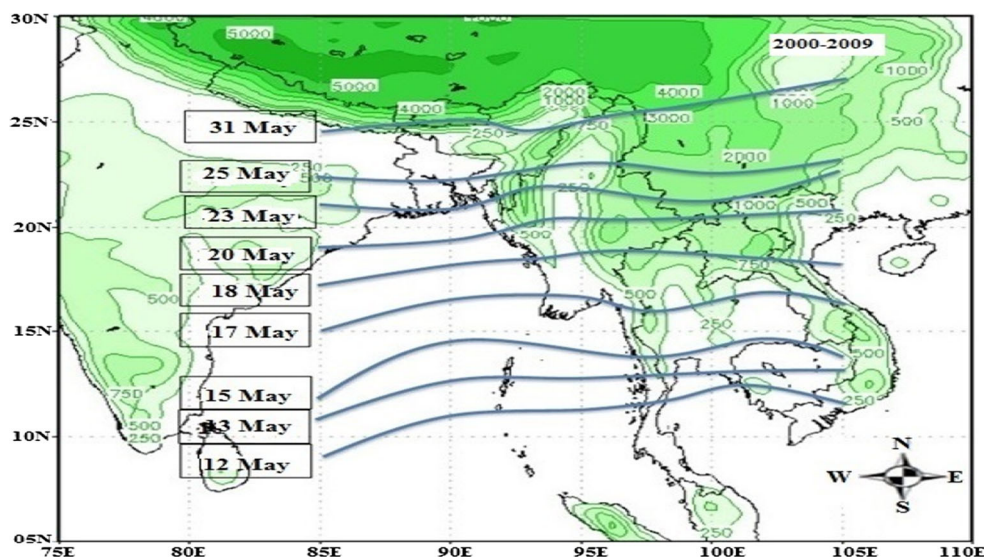
Fig. 5 Vertical wind profiles over Kawthoung station from May 11 to May 21, 2009 (*upper panel*) and from May 22 to May 31, 2009 (*lower panel*). The *green circle* represents southwesterly wind direction and *red arrow* shows onset date
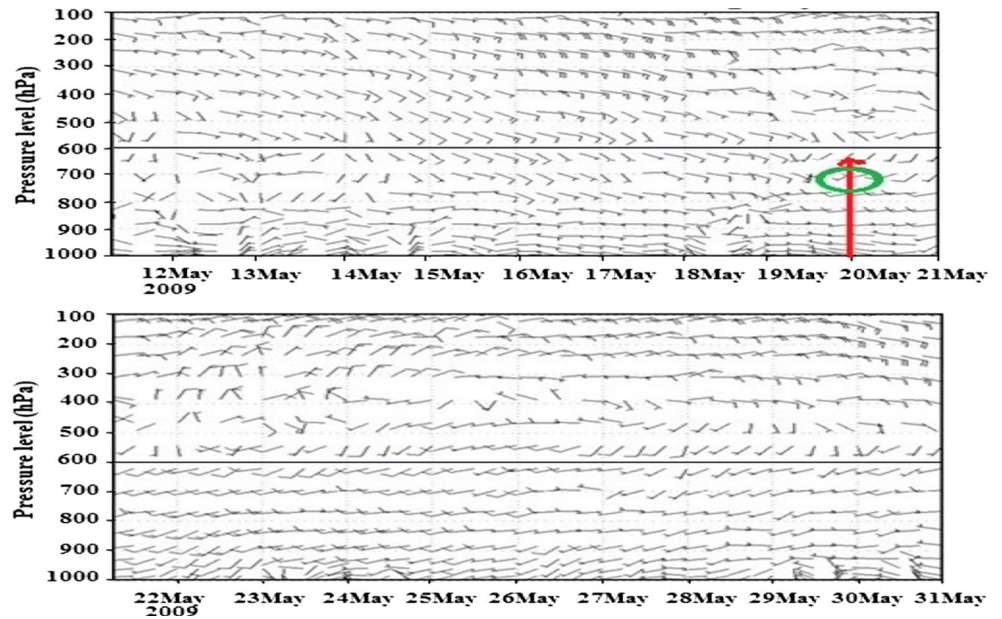

Table 1 Southwest monsoon onset dates over the period 2000–2009 in Myanmar from the model outputs

Station name	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	Ave
Kawthoung	14-May	17-May	12-May	14-May	9-May	9-May	16-May	6-May	9-May	20-May	12-May
Mergui	15-May	17-May	12-May	14-May	11-May	9-May	19-May	6-May	9-May	23-May	13-May
Dawei	15-May	18-May	13-May	16-May	11-May	12-May	19-May	6-May	17-May	24-May	15-May
Mawlamyine	15-May	18-May	14-May	16-May	11-May	12-May	19-May	6-May	17-May	26-May	15-May
Bassein	15-May	23-May	16-May	16-May	11-May	21-May	19-May	6-May	17-May	26-May	17-May
Mingladon	15-May	23-May	16-May	16-May	11-May	21-May	19-May	6-May	17-May	26-May	17-May
Kyaukpyu	19-May	23-May	17-May	17-May	13-May	21-May	21-May	10-May	17-May	26-May	18-May
Loikaw	19-May	23-May	17-May	17-May	15-May	21-May	21-May	11-May	17-May	26-May	18-May
Sittwe	19-May	23-May	17-May	17-May	15-May	21-May	21-May	11-May	17-May	2-June	19-May
Chauk	19-May	25-May	17-May	17-May	16-May	23-May	21-May	13-May	19-May	6-June	20-May
Kengtung	19-May	25-May	18-May	17-May	16-May	23-May	23-May	17-May	19-May	6-June	21-May
Mandalay	19-May	25-May	18-May	17-May	16-May	23-May	25-May	17-May	19-May	6-June	21-May
Kalewa	21-May	25-May	18-May	19-May	18-May	23-May	25-May	20-May	19-May	7-June	22-May
Homalin	24-May	25-May	19-May	19-May	20-May	23-May	25-May	21-May	21-May	9-June	23-May
Myitkyina	26-May	2-June	20-May	19-May	21-May	23-May	28-May	23-May	21-May	9-June	25-May
Putao	27-May	5-June	20-May	20-May	22-May	12-June	28-May	7-June	10-June	12-June	31-May
Progression from Kawthoung-Putao	13	19	8	6	12	34	12	32	32	22	19

arrived simultaneously in Kawthoung, Mergui, Dawei, Mawlamyine, Bassein and Mingladon stations (Fig. 6a). In other years, for example in 2009; the onset arrived on different dates over these stations (Fig. 6b). Between the earliest and latest onset of each of the 16 stations during the study period, the range is from 14 days in Kawthoung to 24 days in Chauk station. This signifies that the arrival of monsoon over each station has all most 24 days difference as in case of Chauk station. The average onset as in the case of Chauk station does not exactly same in the

equidistant from early and late onsets. The average onset date for Chauk station was on May 20, the earliest onset happened on May 13 while the latest was on June 6. The average onset does not lie halfway between earliest and latest onsets. Those are true in the other stations particularly in the Northern part of Myanmar.

During the early onset of southwest monsoon in the year 2007, the average position of ITCZ was around 25°N over Northern Myanmar 6 days before the southwest monsoon onset (Fig. 7a). The average position of the 500 hPa ridge
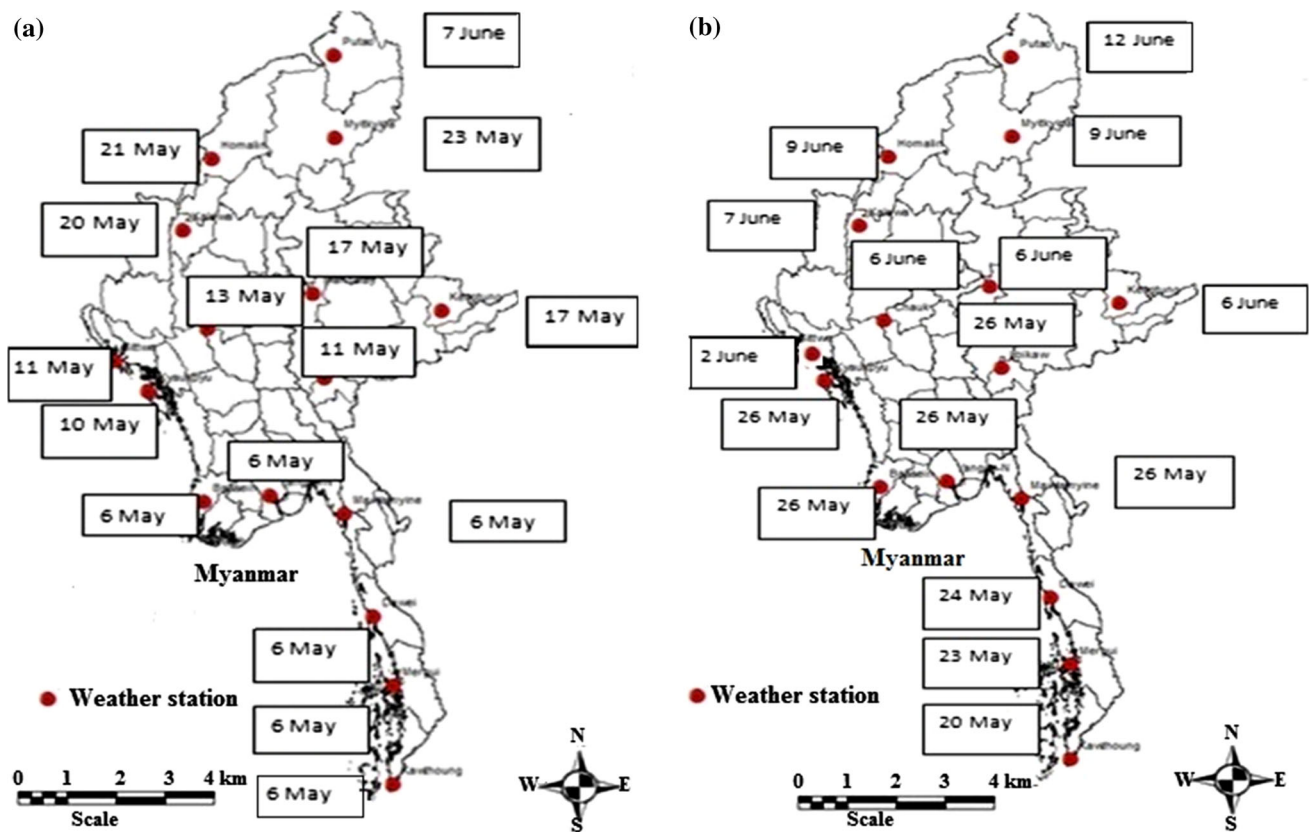
(a)

(b)

Fig. 6 **a** The earliest onset dates of southwest monsoon in Myanmar occurred in 2007 based on model simulation. **b** the latest onset dates of southwest monsoon in Myanmar occurred in 2009 based on model simulation

axis was detected over Deltaic Myanmar area at 16.9°N and shifted to Southern Myanmar area at 14.08°N (Fig. 7b). During the year 2009, the southwest monsoon onset occurred lately, the average position of ITCZ was 23°N–26°N over the Northern Myanmar 10 days before the southwest monsoon onset (Fig. 7c). Moreover, the average position of 500-hPa ridge axis was also spotted over the Deltaic Myanmar area at 16.9°N and shifted down to 15°N (Fig. 7d).

The mesoscale weather phenomena that bring about the variability of monsoon, e.g., early monsoon onset involve the depression or low pressure area over the Bay of Bengal just before the monsoon onset. On the other hand, high-pressure systems over Myanmar in low levels (ground to 600 hPa) make the southwest monsoon arrive late. Monsoon onset date also relies on the temperature difference between southern hemisphere and northern hemisphere. If southern hemisphere cooling is late, this may cause late monsoon onset, whereas if southern hemisphere cooling is early, this may cause early monsoon onset.

Weather phenomena explained the early monsoon onset in Myanmar in the year 2007 was associated with the

formation of a depression over the North Andaman sea (May 3 to May 5, 2007) and the strengthening of the cross-equatorial flow (IMD 2012). Also, the warm sea surface temperature (SST) anomalies over the equatorial Indian Ocean were located in the south of the Bay of Bengal (BoB) which contribute towards the maintenance of weak monsoon conditions for an extended period of time (Krishnamurti 1985). In comparison, weather phenomena delayed the monsoon onset over the Myanmar in the year 2009 includes the weakening of negative sea surface temperature (SST) anomalies across the equatorial Pacific Ocean and development of positive sea surface temperature (SST) anomalies in the equatorial eastern Pacific. The average, early and late southwest monsoon onsets for each station are shown for the study (Fig. 8). The earliest southwest monsoon onset arrived at Kawthoung station and 32 days later it reached at Putao station (Table 1). It took 23 days for the latest monsoon at Kawthoung station to reach Putao station in the same manner. The progression from Kawthoung to Putao stations can be occurred as short as 6 days as in 2003 or as long as 34 days in 2005. The gaps of the southwest monsoon onset average from southernmost to northernmost parts were 20 days.
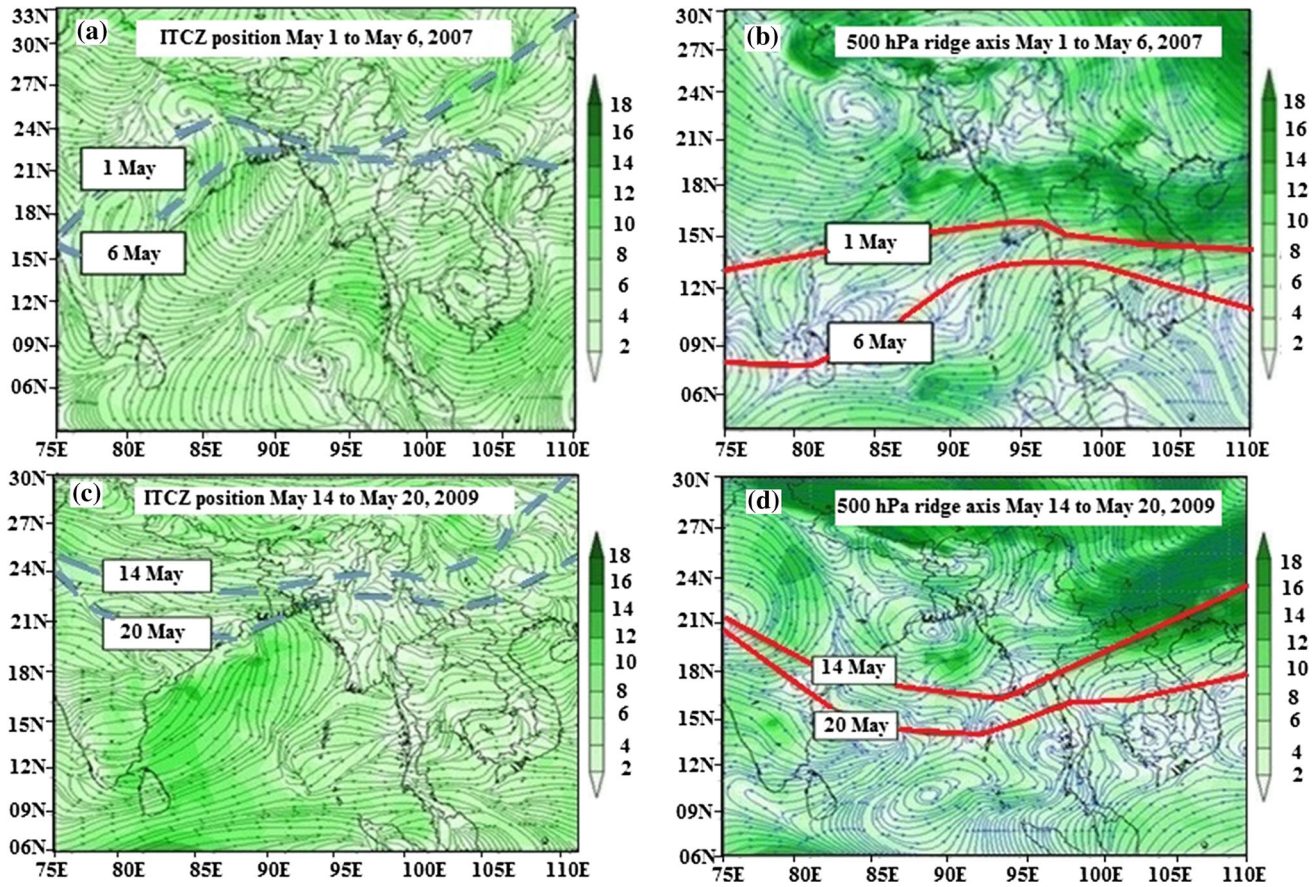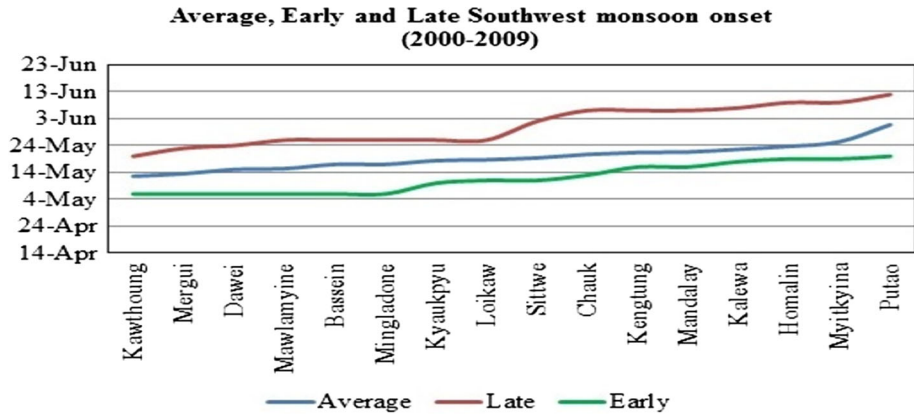
Fig. 7 **a** ITCZ position shows *thick dashed blue line* on May 1 to May 6, 2007; **b** 500 hPa ridge axis indicates *red line* on May 1 to May 6, 2007; **c** ITCZ position shows *thick dashed blue line* on May 14 to May 20, 2009; **d** 500 hPa ridge axis indicates *red line* on May 14 to May 20, 2009

**Fig. 8** Average, early and late southwest monsoon onset dates based from the model

3.2 The northern limit of monsoon (NLM)

The vertical wind profile from latitudes 5°–15°N and longitudes 85°E, 90°E, 95°E, 100°E and 105°E were analyzed to determine the northern limit of monsoon (NLM) for particular interval dates of May 20 to June 12, 2009, respectively, at 0000Z. The red arrow indicates the northern limit of the monsoon (NLM) which is 6°N along the

85°E at 0000Z, on May 20, 2009 (Fig. 2b). The winds from the surface up to 600 hPa levels are westerly or southwesterly direction.

Based on synoptic maps were generated per simulated day starting from May 20 onwards until the northern limit of monsoon (NLM) was identified in the study. For instance, May 20 from 85°E–105°E the northern limit of monsoon (NLM) moves northward starting at 6°N–11°N latitudes.

Fig. 9 Southwest current monsoon progress over the Myanmar for the year 2009. The *black solid lines* indicate northern limit of southwest monsoon in 2009
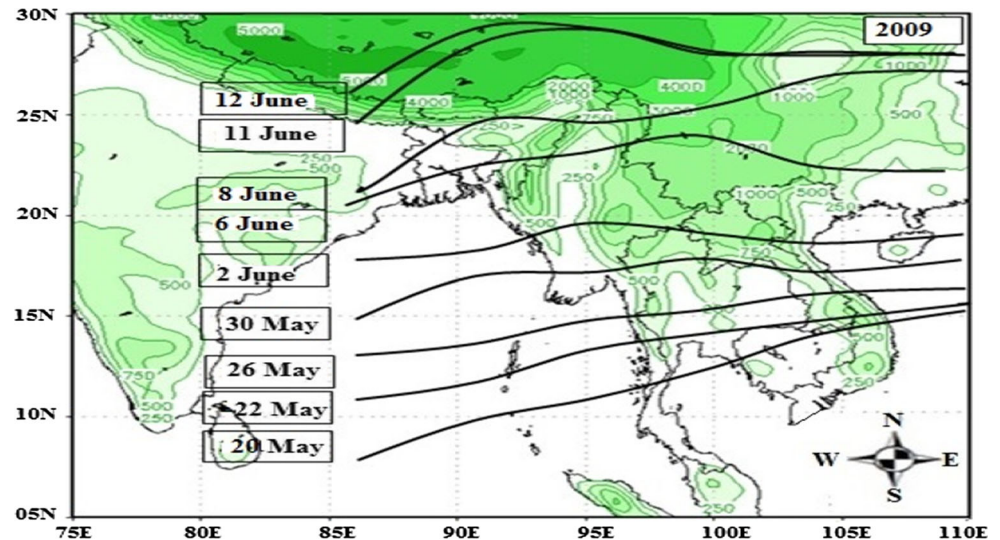
This indicates that the monsoon propagated eastward with a relatively slight northward component. The monsoon current northern limit at 85°E longitude progressed northward from 6°N latitude on May 20, 2009 to 26°N latitude on June 12, 2009 as the day advances (Fig. 9).

3.3 Observation of winds

This study is limited to examine the observation of surface winds. In order to avoid the daily effects of sea breeze on the wind directions, the observed winds were taken at 0300Z. Only 7 stations were considered and the analyses were confined within 10 day average wind speed before and after the monsoon onsets. The numbers of southerly, westerly and southwesterly winds were also taken into consideration during the 10 day before and after the onsets (Table 2).

For all stations (except, Putao), for all years (except, 2001) the 10 m wind speed are found to increase after the onset date. In the case of Putao station, the winds did not change significantly before and after the southwest monsoon onset. There was only 0.3 mph difference in speed before and after the onset and the average speed in all years were less than 3 mph, which is considered as calm (WMO 2004). The year 2001 was an exception because there was a decrease or no change in wind speed before and after the onset in all stations except Putao station. Nevertheless, the average wind speed in Putao station was less than 3 mph. However, results of the model depicted low wind speed in the study.

3.4 Comparison between model vs DMH (Myanmar)

DMH (Myanmar) observes the southwest monsoon onset by areas and they do not identify by the station.

Meanwhile, 10-year periods were considered for the study. The onset dates as determined by the DMH (Myanmar) and model were plotted as shown in Fig. 10. The onset dates according to model tend to agree with those declared by the DMH (Myanmar). Since more points are located above the black line, this observation indicates that the onset dates more likely occurred later in the model than those of the DMH (Myanmar).

Figure 11a shows the onset date in 2000 for Southern area as declared by DMH (Myanmar) was on May 13 while the model output shows 2 days: May 14 and May 15, 2000. The results revealed that the Southern Myanmar area is about 666 km long (19.5°N–15.5°N) and comprises three stations which have different onset dates. Nonetheless, the difference is not too much. The onset based on the model was 1–2 days later than that declared by DMH (Myanmar). The Deltaic area of Myanmar onset date is on May 15 and coincided with the model output. The Deltaic area of Myanmar is about 388 km long (15.5°N–19°N) and comprises all the three stations located in the area. The Central area of Myanmar onset date is on May 20 and model output gave the northern limit of monsoon (NLM) on May 19 and May 21. The reason is that the Central area of Myanmar is about 555 km long (19°–24°N) and comprises seven stations with different onset dates. Unlike the model output that showed different onset dates for different stations and to consider two onset dates for the entire region of Central area of Myanmar in year 2000, while the DMH (Myanmar) gave only 1 onset date. The Northern area of Myanmar onset date is May 25 and model output showed 3 days (May 24, May 26 and May 27). The Northern area of Myanmar is about 555 km long (24°–29°N) and comprises three stations with different onset dates. So, the model advantage can be distinguished the onset dates for the different stations in compare with DMH (Myanmar).

Table 2 Shows 10-day average observed surface winds in the study area (mph)

Station	10-day average winds									
	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Kawthoung										
Speed before onset	1.0	1.9	0.5	1.2	3.2	2.8	1.7	3.0	10.0	2.4
Speed after onset	3.3	0.6	7.0	2.6	2.9	3.1	3.8	3.1	12.1	3.7
Number of S, W, SW before onset	6	3	0	3	3	2	1	3	5	3
Number of S, W, SW after onset	8	4	8	5	7	7	6	7	9	6
Mawlamyine										
Speed before onset	1.8	1.4	4.4	1.1	3.0	1.3	1.7	3.5	1.7	1.5
Speed after onset	4.4	1.4	2.9	1.7	2.0	0.5	2.4	2.4	2.1	1.4
Number of S, W, SW before onset	1	5	2	7	2	4	0	2	1	1
Number of S, W, SW after onset	5	6	6	3	4	3	0	3	5	2
Bassein										
Speed before onset	21	2.8	2.6	3.8	2.3	2.9	2.8	4.3	3.1	1.8
Speed after onset	2.7	1.9	1.9	3.2	3.1	1.9	2.2	3.3	2.1	2.4
Number of S, W, SW before onset	2	6	5	2	1	0	3	0	4	2
Number of S, W, SW after onset	6	6	7	6	9	3	6	3	4	5
Sittwe										
Speed before onset	7.0	7.9	5.8	5.5	4.8	5.5	9.5	6.0	5.5	8.4
Speed after onset	11.6	7.6	8.2	7.0	12.5	6.1	10.1	9.5	7.9	10.0
Number of S, W, SW before onset	0	0	1	0	3	4	1	0	0	3
Number of S, W, SW after onset	6	0	5	1	2	0	4	2	0	0
Kyaukpyu										
Speed before onset	2.9	0.5	0.2	1.7	2.4	4.8	2.6	1.9	3.4	2.8
Speed after onset	3.6	0.5	2.7	2.7	5.9	4.7	2.2	3.6	2.3	1.2
Number of S, W, SW before onset	2	1	1	1	2	3	4	3	1	3
Number of S, W, SW after onset	3	2	1	1	4	3	4	3	5	5
Mandalay										
Speed before onset	2.9	3.7	2.4	1.4	2.7	2.5	0.1	0.8	0.7	1.6
Speed after onset	4.1	2.6	3.7	2.2	0.9	2.5	2.1	1.9	1.6	1.8
Number of S, W, SW before onset	6	4	5	2	7	7	1	4	1	8
Number of S, W, SW after onset	7	5	7	6	5	5	5	6	5	8
Putao										
Speed before onset	1	1.3	1	1.3	1.6	1.1	0.6	0.4	0.6	0.7
Speed after onset	1.2	1.6	1	1.7	1.3	1.4	0.5	0	0.4	0.4
Number of S, W, SW before onset	0	1	0	3	3	6	0	1	3	0
Number of S, W, SW after onset	1	2	2	0	1	7	0	0	2	0

DMH (Myanmar) identified the onset date to occur on May 22 while the model revealed 2 dates for the Southern area of Myanmar: May 9 for Kawthoung and Mergui stations and May 12 for Dawei station (Fig. 11b). May 30 was declared by DMH (Myanmar) to be the onset date in the Deltaic region while the model produced May 12 for Mawlamyine station and May 21 for Bassein and Mingladon stations. The Central area was arrived by the monsoon on June 11 according to the DMH (Myanmar), but the model indicated May 21 to May 23. In the Northern area, the DMH (Myanmar) pronounced on June 15 as the onset date, while May 23 to June 12 were the onset dates as given from the model. The onset dates were earlier using the model is around 10–13 days differences. The difference was less than 3–8 days, when the monsoon progressed to the Northern area of Myanmar.

Fig. 10 Onset dates between
the model vs DMH (Myanmar).
The *red line* shows linear
correlation between DMH and
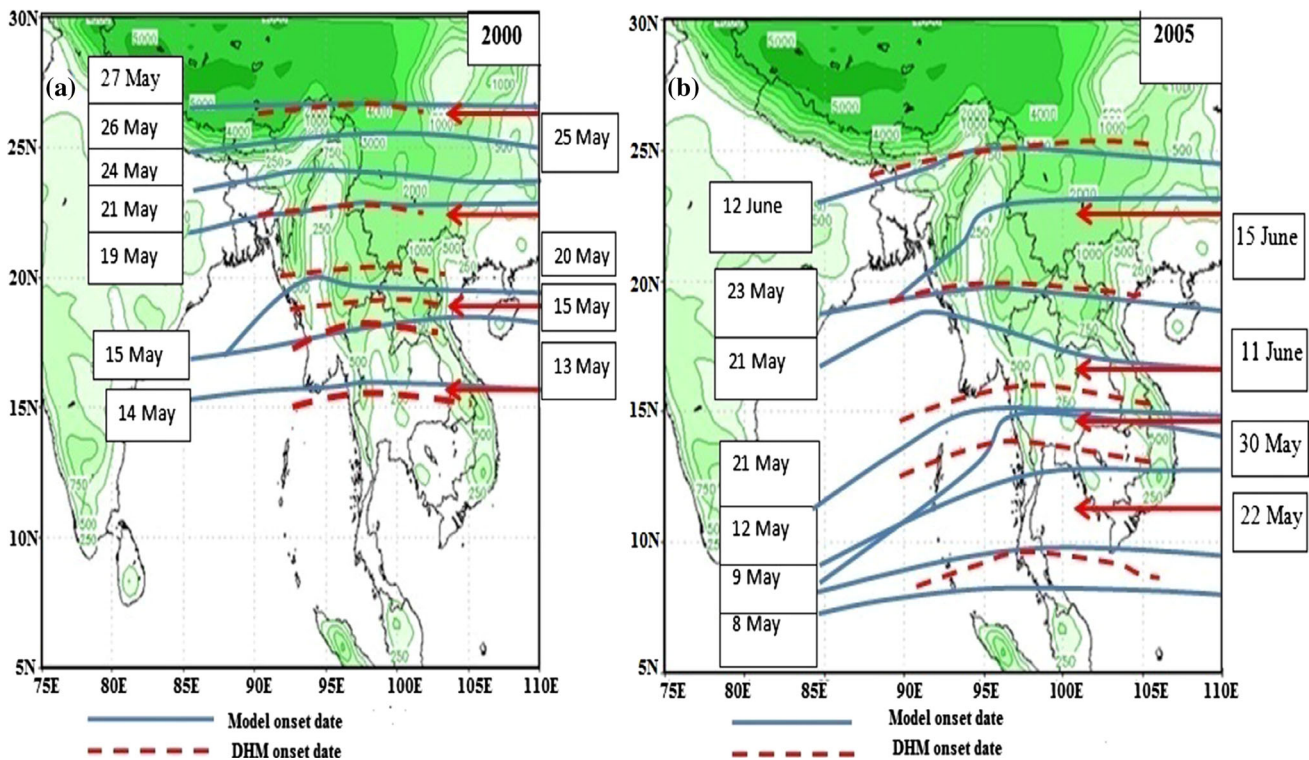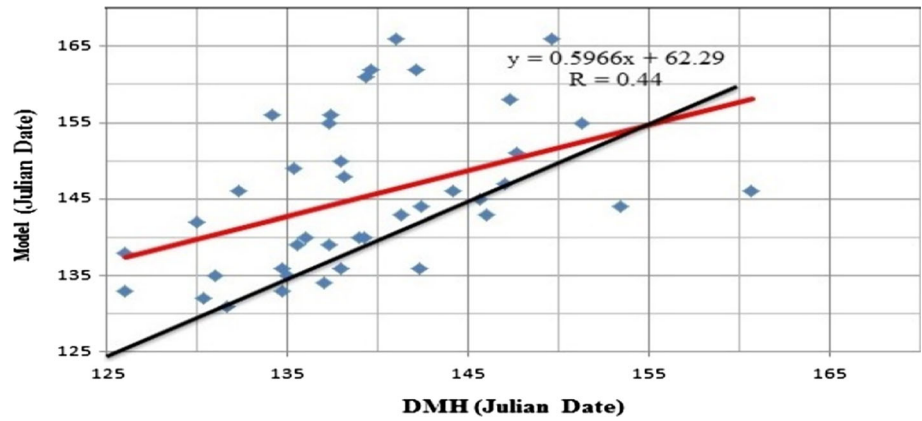the model; *black line*
corresponds to a 1 to 1
correlation

Fig. 11 **a** The model vs DMH (Myanmar) onset dates of southwest monsoon for 2000; **b** the model vs DMH (Myanmar) onset dates of
southwest monsoon for 2005

3.5 Outgoing longwave radiation (OLR) and southwest monsoon onset

A low outgoing longwave radiation (OLR) is most likely to
occur due to enhanced convective activity over the area.
The same area exhibits OLR during the clear sky and
heated surface. The cloud cover increases up to 6–8 octas
during the southwest monsoon onset date. Thus, it is
expected that there would be a decrease of OLR with the
southwest monsoon onset. From May 17, 2009 to May 24,
2009; the OLR is quite high then decreased after May 20,
2009 (Fig. 3b). This observation supports further in

establishing May 20 as the onset date for Kawthoung sta-
tion. So, the decreased of OLR is observed in other years
during the onset by using the meteograms.

3.6 Rainfall and southwest monsoon onset

Rainfall is the one of the most significant features of the
southwest monsoon onset. Southwest monsoon rainfall over
Myanmar during 1981–2010 shows that Central Myanmar
area (dry zone) has less amount of rainfall. This observation
can be attributed to the topography, the region is located
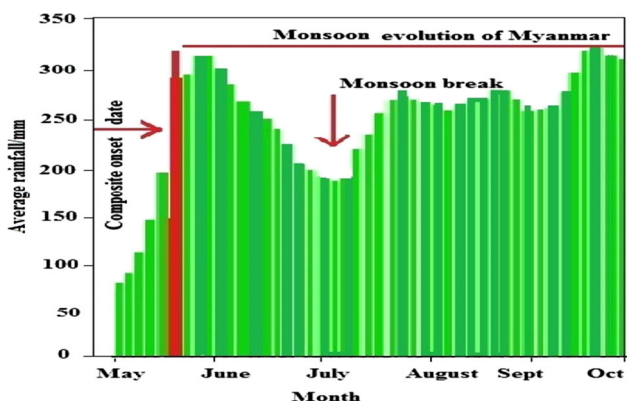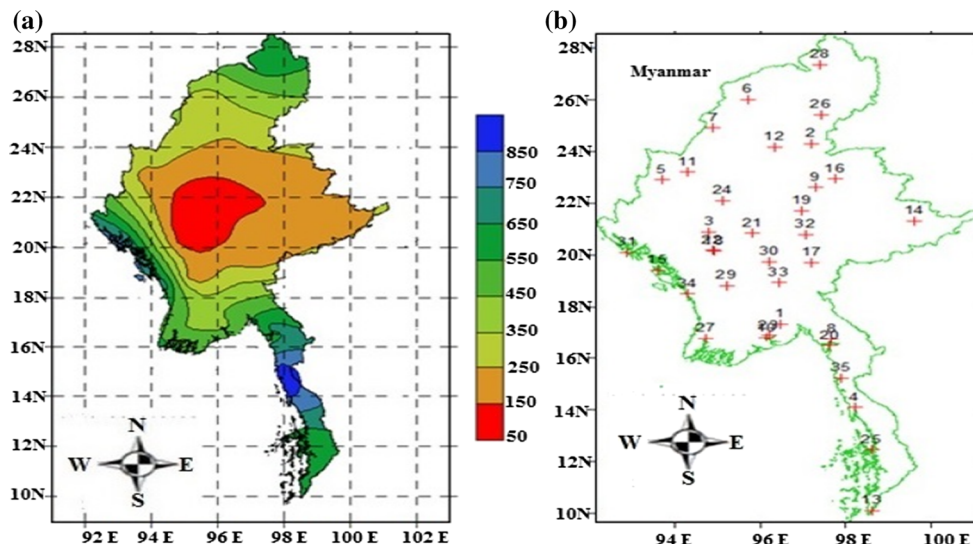between running mountain chains of Rakhine-Yoma

Fig. 13 Composite average rainfall shows monsoon evolution over Myanmar from 1981 to 2010; May 20 is the average composite onset date (day 0, *red line*)

mountains (mean elevation 1800 m, peaks 3000 m) to its right north–south and Shan Plateau (mean elevation 1000–2000 m) on left. The coastal area is located beside the Bay of Bengal (BoB) and Andaman Sea has the maximal rainfall (Fig. 12). The observation is in agreement with Kumar et al. (2013) and Roy Bhowmik and Durai (2008) that Myanmar coast experiences heavy rains that contribute more to the total rains in the Western Ghats as compared to the Central and Northern regions. According to the study, the differences features between the south and other parts of the country could be explained by linkages between cloud microphysics and large-scale dynamics. Composite rainfall shows monsoon evolution over Myanmar and May 20 is the average composite onset date which is indicated by red line (Fig. 13). Rainfall is usually weak before the onset begin until May 20 when sudden increase in rainfall happens and after the onset date, a considerable decrease in rainfall is

known as monsoon break. Moreover, monsoon rainfall over Myanmar is very sensitive to the seasonal annual cycle. The study suggests that the large-scale weather circulation patterns modulate the onset and monsoon break in Myanmar. This finding is consistent with Fosu and Wang (2014) study in Bay of Bengal coupling of pre-monsoon tropical cyclones with the monsoon onset in Myanmar. The heavy rainfall on May 20 further confirmed the onset as deducted from the model (Fig. 14a). Although rainfall occurred before this date, there was no marked shifting of winds in the upper levels which was the main criterion used by this study in identifying the southwest monsoon onset. The amount is overestimated using the model rainfall, but temporally it is almost correct. It is interesting to note that the DMH (Myanmar) identified May 16 as onset date in 2009, and yet there was not much rainfall in Kawthoung station on this date. In the case of Putao station, the northernmost station included in this study, the heavy rainfall occurred on June 12, 2009 (Fig. 14b). The study is in agreement with the observations of Fosu and Wang (2014), although the model rainfall is overestimated. Bhaskar et al. (2008) indicated that predictability up to 5–10 days, of the rainfall during the onset phases of the monsoon over southeast Asia.

3.7 Weather systems affecting monsoon onset

The Intertropical Convergence Zone (ITCZ), jet streams and 500 hPa ridge were studied in order to find the relationship about the southwest monsoon onset. The position of the ITCZ was examined using the 10 m winds starting 10 days before the onset until the onset occurs. The ITCZ is located around 25°N over the Northern Myanmar and indicated by blue line in the study (Fig. 15a, b). The path of ITCZ indicates the southwest monsoon onset, but it may
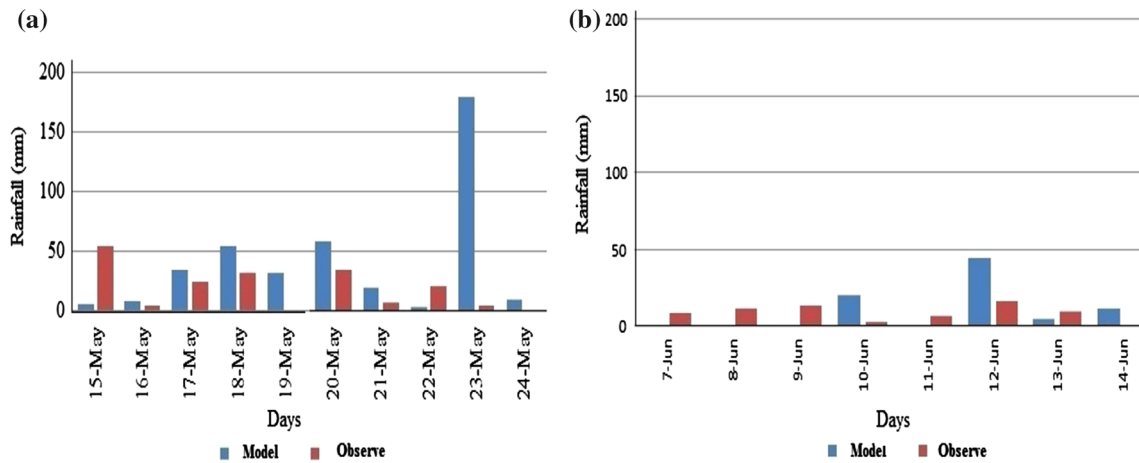
Fig. 14 a The model vs observed daily rainfall (mm/day) in 2009 over Kawthong station; b the model vs observed daily rainfall (mm/day) in 2009 over Putao station
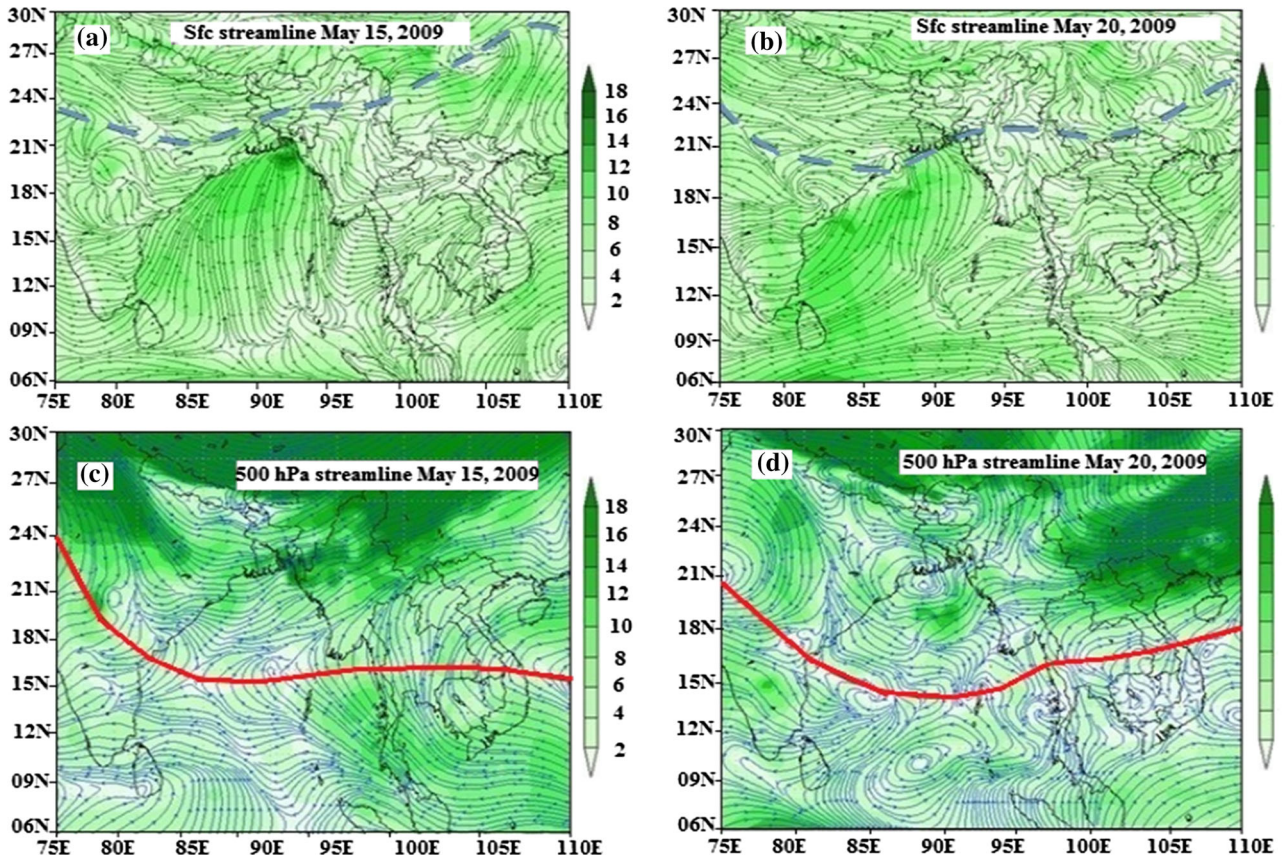

Fig. 15 a Surface streamlines on May 15, 2009; b surface streamlines on May 20, 2009; c 500 hPa streamlines on May 15, 2009; d 500 hPa streamlines on May 20, 2009. *Thick dashed blue line* indicates ITCZ position and *thick red line* shows the 500 hPa ridge line position

change from season to season by the interaction between ITCZ, jet stream and 500 hPa ridge as well as changes in local circulation patterns of weather systems. The average position of ITCZ over Northern Myanmar 6–10 days before the southwest monsoon onset was 23°N–28°N latitudes. This condition signifies that the monsoon follows the ITCZ which is related to the Mascarenes high and the southwesterly pressure gradients. Yin (1949) showed that trough movement was the reason behind with burst of monsoon over the India and Myanmar.

Findlater ([1969]) found that the monsoon low level jet (MLLJ), which has its origin in the south Indian Ocean north of the Mascerene high as an easterly current, crosses the equator as narrow current of air close to the East African coast, turns into westerly current over Arabian Sea, and enters to the Indian regions as strong south westerly jet. The study tried to find out the two jet streams were associated with monsoon onset: (a) upper level subtropical easterlies jet stream which is around the 100 hPa level, and (b) low level tropical westerly's jet stream in 1000 m thickness layer. The Findlater jet, known as the low level jet (LLJ) stream near the equator was traced by Bunker ([1965]) off Somalia and then across the central parts of the Arabian sea to the coast of India, decreasing in speed progressively eastward. A maximum speed of about 50 knot is attained at the top of a 1000 m thick layer of air. The LLJ was not found in May and June over the study domain. So, there was no evidence of the presence of the above two jet streams in the study area which focused on the southwest monsoon onset. Some of the monsoon-influenced countries are closely linked with two jet streams for the monsoon onset. However, Myanmar monsoon onset was earlier than two jet streams appeared usually in July and August. In fact, the model was run in April to July to find out the monsoon onset date. Therefore, out of the model simulation period over Myanmar, those two jet streams already established in July and August. Near 100 hPa level strong easterlies blow to the south of 25°N in the southwest monsoon period, which concentrate into a core of high winds known as easterly jet stream (EJS). Rao ([1976]) pointed out easterly winds of 50 m s^{-1} at about 75 hPa (19 km) over Nagercoil in India which constitute a part of the easterly jet stream (EJS) over the South India between 7°–18°N latitudes. Koteswaram ([1950]) first studied the easterly jet stream (EJS) over the India in a short note about upper level (700 mb) lows in low latitude 8°N during southwest monsoon onset and breaks in the monsoon.

One of the criteria of DMH (Myanmar), 500 hPa ridge, moved from south to north over the Myanmar. The study was an attempt to find the position of 500 hPa ridge axis before the onset which was analyzed from 10 days prior and until the onset the 500 hPa streamlines over the domain. The upper panel shows the streamlines on May 15, 2009 while the lower panel shows the streamlines on May 20, 2009 indicated by the solid red line (Fig. [15]c, d). The 500 hPa ridge was located around 16°N over the Deltaic area of Myanmar. The ridge axis appeared over the Deltaic area of Myanmar 6–10 days before the southwest monsoon onset. The study suggests that the ITCZ and 500 hPa ridge appeared before the summer monsoon onset, but the jet streams occurred in July and August after southwest monsoon onset over the Myanmar. The study also depicts that ITCZ occurred in Northern region of Myanmar, whereas 500 hPa ridge appeared in Deltaic area of Myanmar.

4 Summary and conclusions

The present study characterizes the inception, northern limit and progression of southwest monsoon in Myanmar using synoptic maps generated through a 10-year simulation by using the model. The southwest monsoon onset dates had occurred in Myanmar when the direction of prevailing wind, up to 600 hPa levels, shifted to westerly or southwesterly direction. The model synoptic maps were employed to detect the arrival dates of the southwest monsoon for each of the 16 stations in the 2000–2009 periods. The key criterion used to distinguish the arrival of southwest monsoon onset in Myanmar was the shifting of direction of the prevailing winds from the surface up to 600 hPa levels onto westerlies or southwesterlies direction with a speed of more than 5 m s^{-1} or 5–10 knots in 700 and 850 hPa levels. Coincident with this occurrence were observed winds with average speed greater than 5 m s^{-1} or 5–10 knots 10 days before and after the onset. The results indicated that the number of occurrences of westerly, southwesterly and southerly winds also increased over the Myanmar. Furthermore, the arrival dates of monsoon were also accompanied by rainfall increases, not only by the model but also from the observations, and a decrease in OLR. The northern limit of southwest monsoon (NLM) for a given day was also identified and found out to be one of the most important features in the weather patterns and update in meteorology as it presented the accuracy of the wind direction and wind speed over a particular place and time. The vertical wind profile from 5° to 15°N latitudes and 85°–105°E longitudes were generated daily using the 0000Z hour. The delineation of the onset dates over the domain, which was found to progress northward in this study.

The beginning dates of the southwest monsoon onset in the 16 stations in Myanmar vary year to year, thus causing different onset dates. The arrival of monsoon from the Southern to Northern part of the country was quite variable, but on the average it took 19 ± 10 days to traverse from south to north for the whole Myanmar. During the 10-year period (2000–2009), the earliest monsoon arrived on May 6, 2007 while the latest came on May 20, 2009. The delay in the onset dates of southwest monsoon are due to weak monsoon intensity while the early arrival is due to strong monsoon intensity. The southwest monsoon onset dates were predicted by the model which is likely to occur later than the onset dates declared by the DMH (Myanmar). For 6 years, the onset dates of model and DMH (Myanmar)

coincided within 3 days in the Southern Myanmar region. The ITCZ and 500 hPa ridge were indicated to influence the arrival and progression of monsoon in Myanmar. With regard to ITCZ, its average position was 23°–28°N latitudes 6–10 days before the onset. The 500 hPa ridge appeared consistently over the Deltaic area of Myanmar 6–10 days before the monsoon onset. Its position is about 6° to the south of the ITCZ. There was no symptom of the presence of upper level easterly jet streams (EJS) and low level westerly jet streams (WJS) during the pre-monsoon and start of monsoon period. The jet streams were observed to appear in July and August when monsoon already progressed from the southernmost to the northernmost tips of the country.

The study depicts that the onset dates, northern limit and progression of southwest monsoon can be predicted more accurately by using synoptic maps while the DMH (Myanmar) had followed the guidelines for declaring the arrival of monsoon at a specific weather stations based only on rainfall. The study has characterized the southwest monsoon onset over Myanmar using the model and accompanying important weather elements using the boundary conditions generated by any global model instead of the reanalyzed datasets. The findings may encourage researchers and modeling hubs to further improve the performance of the model over Myanmar.

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