WRF Model Simulation of the Active and Break Spells of Summer Monsoon over Bangladesh during 2011 and 2013

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ABSTRACT: In this paper, the weather systems associated with the active and break spells of summer monsoon over Bangladesh have been studied using the WRF model as a regional climate model for two selected years 2011 (excess rainfall year) and 2013 (deficit rainfall year). The active and break spells for two selected years were identified using daily observed rainfall data from Bangladesh Meteorological Department (BMD). The model simulations for each year were made for the period of 1st May to 30th September with a single domain of 30 km resolution and 19 vertical levels. FNL 1°×1° resolution data was used for model simulation. The model-simulated daily rainfall, Sea Level Pressure (SLP), and the wind at 850 hPa, and 200 hPa were compared with TRMM, and ERA-Interim data, respectively. This study reveals that the increase in rainfall is concurrent with a south-westerly wind and the decrease of rainfall simultaneously occurs with a south-easterly wind over the country. A cyclonic circulation (850 hPa) was found over the southwestern part of Bangladesh during active days and the south-easterly wind was found (850 hPa) during break days. The easterly wind was found (200 hPa) during active days and break days. The lowest SLP was found over the southern part during active days (992-995 hPa) compared to break days (998-100 8hPa). Outgoing Longwave Radiation was found high (250-275 W/m^2) during break days compared to Active days (220-270 W/m^2). The WRF model can reasonably capture well the active and break phases of summer monsoon for the years 2011 and 2013.

Keywords: Summer Monsoon; WRF Model; Rainfall; Weather Systems; Active and Break Spells

INTRODUCTION

The summer monsoon in South Asia is distinguished by intraseasonal variability, which can be divided into active and break phases. When the monsoon approaches, South Asia has dry periods termed "breaks phases" in between rainy periods termed "active phases". (Goswami, 2005). As a part of the global circulation system, the southwest summer monsoon has a significant impact on the climate of the Indian subcontinent. Due to its significant impact on the amount of rainfall that falls each year and the significant regional and temporal irregularities in its occurrence, it is crucial to agricultural economy of Bangladesh. The summer monsoon season affects Bangladesh agricultural operations, river drainage systems, and hydrological characteristics, all of which have an impact on the nation economy (Christiansen, 1982). It would be possible to maximize agricultural yields and make preparations for extreme disasters if the monsoon could be accurately predicted. Numerous studies on various summer monsoon-related topics have been published in the past and are nearly always forthcoming in scholarly publications. Sontakke et al., (1992) conducted research on the compilation and analysis of the all-India summer monsoon rainfall series for the longest empirical Period (1813-1991) in 1992. Ahmed and Karmakar, (1993) studied the summer monsoon arrival and departure dates in Bangladesh. Ahasan et al., (2010) have made a study about the trend and variability of summer monsoon rainfall over Bangladesh during 1961-2010. Ohsawa et al., (2000) examined the intra-seasonal fluctuation of monsoon activities while analyzing the rainfall across Bangladesh during the summer monsoon season of 1995. Srinivas et al., (2013) investigated 10 years (2001-2009) of monsoon rainfall by different schemes of the WRF-ARW model. Raju et al., (2014) examined how effectively the Weather Research and Forecasting model works while reproducing the three-dimensional wet and thermodynamic structure of the Indian summer monsoon (ISM) from 2001 to

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2011. Rajeevan et al., (2010) discovered active and break periods using rainfall data collected over the monsoon zone from 1901 to 1989. Srinivas et al., (2015) examined seven representative homogeneous rainfall zone onset phases of monsoon by the WRF-ARW model and reveals model could capture it well. Ahasan et al., (2014) examined an overview of the summer monsoon weather system and its connection to rainfall throughout Bangladesh. Pai et al., (2016) evaluated the active and break phases of the Indian summer monsoon from 1901 to 2014. Taraphdar et al., (2010) found the predictability limit for the active (10 days) and break (10 days) phases over the Indian region by using the WRF model.

This study, which is the first of its sort, did something that none of the earlier studies had properly done: it highlighted the meteorological systems connected to the active and break spells of the summer monsoon over Bangladesh. In this study, two extreme years 2011 and 2013 have been selected based on observed rainfall data of BMD, where 2011 is an excess rainfall year and 2013 is the deficit rainfall year. Identifying active and break spells for 2011 and 2013 is an objective of this study. Investigating the patterns of rainfall, wind circulation, SLP, and OLR in two specifically chosen exceptional years of the summer monsoon over Bangladesh is the main objective of this study.

MODEL SETUP, DATA, AND STRATEGIES

Data Used

BMD Station Data:

The Climate Division of Bangladesh Meteorological Department provided the observed daily rainfall data for 35 rain gauge sites in Bangladesh for 2011 and 2013. The normal value of rainfall (mm) per day was collected from BMD.

NCEP FNL Data

Data from the Global Data Assimilation System is used in the NCEP FNL (Final) Operational Global Analysis (GDAS). Every six hours, operationally prepared NCEP FNL (Final) data resolution on 1°×1° degree is produced. This study uses gridded binary data in the 1°×1° format for 2011 and 2013 (grib2).

TRMM Data

Tropical Rainfall Measuring Mission (TRMM), daily precipitation (TRMM_3B42_daily7) 0.25°×0.25° resolution data available over the study area. 3B42 Research Version provides total daily precipitation data. TRMM Multi-Satellite Precipitation Analysis is applied as an algorithm in the 3B42_daily 7 versions.

ERA-Interim Data

The ERA-Interim data, which is also worldwide atmospheric reanalysis data, is provided by the European Centre for Medium-Range Weather Forecasts (ECMWF). ERA-Interim data assimilation is based on an IFS release from 2006. (Cy31r2). In this study, ERA-Interim 6-hour interval daily data (0.25° × 0.25°) are used.

METHODOLOGY

Statistical Analysis

1. For the identification of active and break spells, firstly the anomaly was calculated by normal rainfall per day (June to Sep) by subtracting it from the daily average rainfall for a particular year (June to Sep).

2. Secondly, for calculating the standardized rainfall anomaly of a particular year, rainfall anomaly was divided by the standard deviation for a particular year. The paper ″Intraseasonal variation of monsoon activities associated with the rainfall over Bangladesh during the 1995 summer monsoon season" by Oshawa et al. (2000) is used as a reference for the threshold value +0.5 to -0.5 of standardized rainfall over Bangladesh to identify the active day and break days.

Standardized Rainfall anomaly:

$$\frac{X-\bar{X}}{\sigma}$$

X=Daily average rainfall (mm) for a particular year.

$\bar{X}$ =Normal daily average rainfall (mm).

Equation of Standard deviation:

$$\sigma = \sqrt{\frac{\Sigma\ (x-\bar{x})^2}{n}}$$

σ = Sign of Standard deviation.

n =Number of days.

Model Experimental Setup

For this study, simulations were conducted using the WRF-ARW model, version 4.0. The WRF model is carried out on a single domain with a horizontal resolution of 30 km and 19 vertical layers with a model top at 100 hPa. For seasonal scale simulations, the model resolution of 30 km is considered to be sufficient for resolving

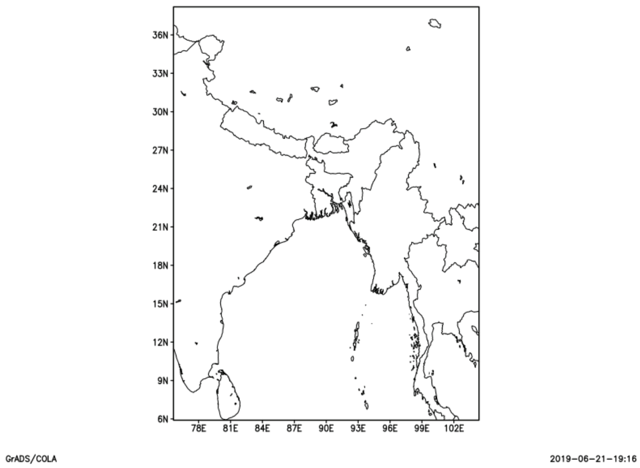

Figure 1: Domain for the WRF Model

hydrology-related processes and capturing key synoptic scale events (Srinivas et al., 2013). The model was incorporated starting on May, 1 and running through September, 30 each year. The lateral force and internal physical dynamics of this simulation process can be dynamically balanced after one month (May) of spin-up time (Anthes et al., 1989). The model output was collected once every day, which corresponds to 00 UTC. Figure 1 depicts the WRF model domain for this study. The model was run using the WSM 6 class graupel schemes for cloud microphysics (Hong, 2006), Kain-Fritsch (new Eta) scheme for cumulus parameterization (Kain, 2004), Mellor-Yamada Nakanishi and Niino Level 2.5 PBL (MYNN2) scheme for the boundary layer parameterization, Rapid Radiative Transfer Model (RRTM) for longwave (Mlawer et al., 1997), and Dudhi for short wave radiation scheme (Dudhia, 1989) for the selected case.

RESULT AND DISCUSSION

Analysis of Active and Break Spells for the Excessive Rainfall Year 2011

Identification of Active and Break Spells for the Year 2011

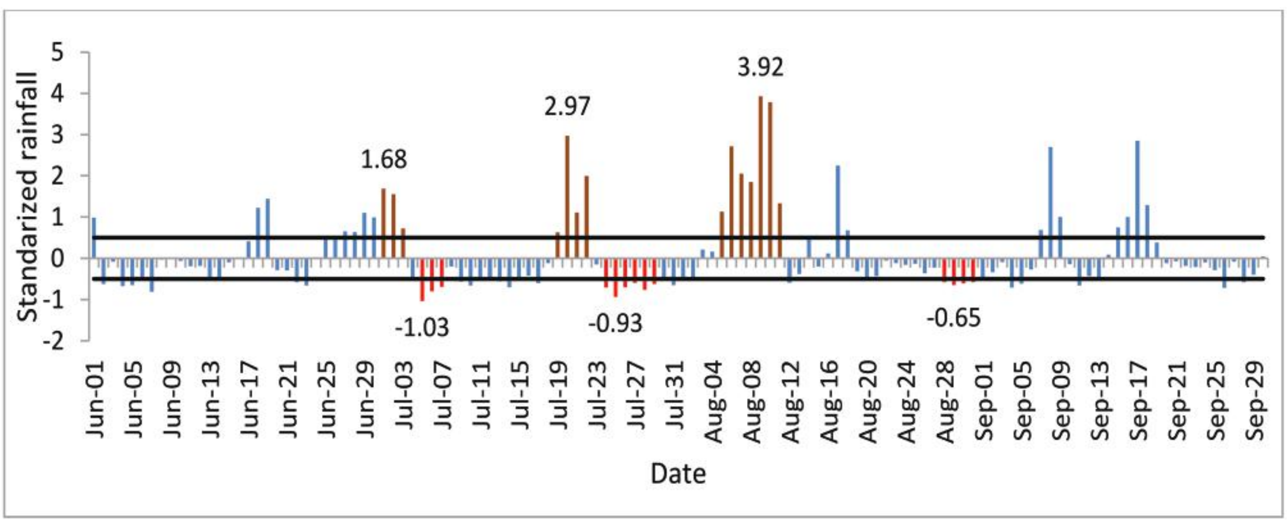

Figure 2: Standardized Rainfall of Monsoon 2011 Over Bangladesh

The peak monsoon season is July and August in Bangladesh, and for this reason, identification of active and break spells of monsoon for this study is selected within the duration of July 1 to August 31. Break and active days, respectively, are defined as when the threshold value has been taken as less than -0.5 or greater than 0.5 and has existed for at least three consecutive days. From the figure the active and break phases are-

Table 1: Active and Break Spells of Monsoon in 2011

Active	1-3July, 19-22 July, 5-11Aug
Break	5-7July, 24-29July, 28-31Aug

Rainfall Pattern

Figures 3 (a) and 3 (b) show the active day of monsoon rainfall in 2011 from WRF simulation and TRMM.

The southern part of Bangladesh received an estimated accumulated rainfall of approximately 20-90 mm according to the WRF model, while the TRMM model indicates a slightly higher estimated accumulated rainfall of approximately 30-100 mm for the same region. WRF shows the lowest rainfall of less than 10 mm over the northwestern part. Meanwhile, TRMM indicates that the eastern part of the country experienced the lowest precipitation, also measuring less than 10 mm. WRF shows rainfall over the central part was 10-20 mm but TRMM shows 20-30 mm.

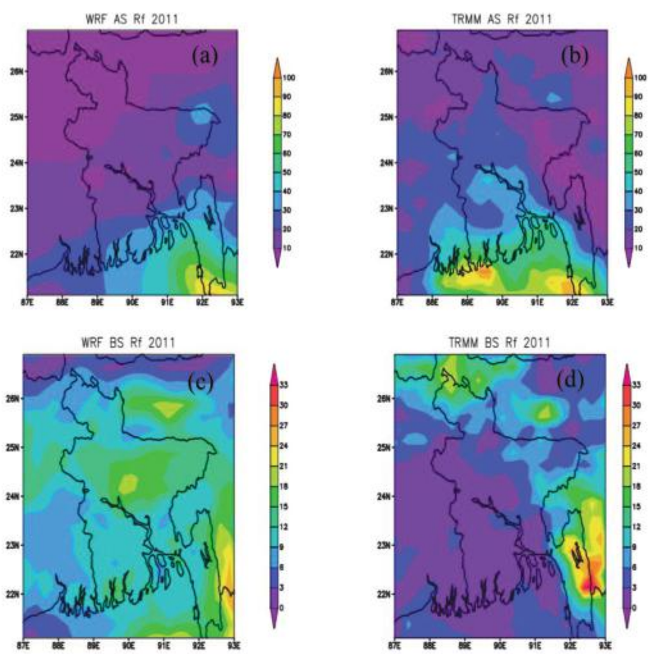

Figure 3: Active (a, b) and Break (c, d) Day Monsoon (2011) Rainfall Derived from WRF and TRMM Respectively

The highest difference between TRMM and WRF shows over the southwest part (20-70 mm). The lowest difference between TRMM and WRF shows over the eastern part (-20 to 0 mm). Both the model and the observation indicate that most of the rainfall occurs in the northeastern and southeastern regions of the country. The Shillong Plateau and the Chittagong Hill Tracts, which operate as barriers to the southerly or southwesterly monsoon wind, are said to have an impact on these regions to initiate rainfall.

Figures 3 (c) and 3 (d) show the rainfall of break day over Bangladesh in 2011. The WRF simulation indicates that the central region of Bangladesh received between 12-24 mm of rainfall, while the TRMM data suggests a lower amount of precipitation ranging from 0-15 mm in the same area. According to TRMM, the southeastern region experiences rainfall ranging from 9-33 mm, whereas WRF indicates a rainfall range of 15-27 mm in the same area. The highest discrepancy between TRMM and WRF occurred in the northern region of Bangladesh, with a range of -3 to 15 mm. The central region of Bangladesh exhibits a minimum difference of -18 to -12 m/s.

Wind Pattern

Figures 4 (a) and 4 (b) show the wind distribution pattern (850 hPa) during the active day of monsoon 2011. According to WRF, the wind was coming from the southwest, and ERA-Interim confirms this direction as well. WRF indicated the presence of cyclonic circulation in the central region of Bangladesh, while ERA-Interim shows it in the northwestern part of the country. The wind speed range in the southern region was shown as 7-13 m/s by WRF, while ERA-Interim indicated a range of 7-11 m/s at the same location. The WRF model detected wind speeds of 7-12 m/s in the northern region, whereas the ERA-Interim detected lower speeds of less than 2-5 m/s in the same location.

Figures 4 (c) and 4 (d) show the wind circulation pattern (850 hPa) during the break day of monsoon 2011. WRF shows the wind was flowing from a southeasterly direction but ERA-Interim shows two directions, southwest direction over the western part and southeast direction over the eastern part. As per the analysis of WRF and ERA-Interim models, the highest wind speeds in the country are recorded in the northwest at 7-12 m/s and in the south at 6-10 m/s, respectively. While the ERA-Interim model shows the minimum wind speed ranging between 1-3 m/s in the northernmost part of the country, the WRF model indicated a slightly higher minimum wind speed of 2-4 m/s in the southwest region. Rainfall over Bangladesh increases when the monsoon trough is at the foot of the Himalayas and the southwesterly wind is enhanced to the south of the trough axis.

Figures 4 (e) and 4 (f) show the wind distribution pattern (200 hPa) during the active day of monsoon 2011. WRF shows the wind was flowing from an easterly direction and ERA-Interim shows a northeasterly direction.

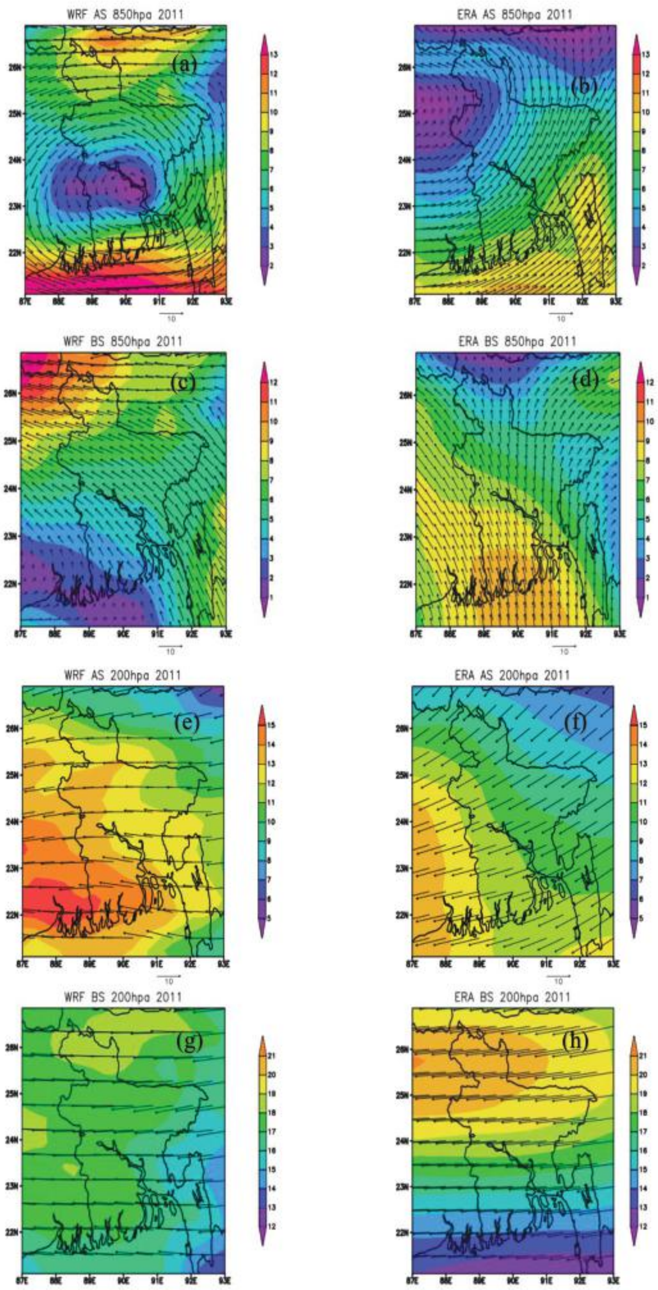

Figure 4: 850 hPa Height Winds during Active (a, b) and Break (c, d) Day of Monsoon (2011), and 200 hPa Height Winds during Active (e, f), and Break (g, h) Day of Monsoon (2011)

WRF and ERA-Interim show the wind speed was increasing from the eastern part to the western part. According to WRF, the highest wind speed in the southwest region ranges from 13-15 m/s, whereas as per ERA-Interim, the highest wind speed in the same area ranges from 11-13 m/s. According to both WRF and ERA-Interim, the lowest wind speeds are observed in the northeastern areas of Bangladesh, with WRF reported speeds of 10-12 m/s and ERA-Interim reported speeds of 8-10 m/s.

Figures 4 (g) and 4 (h) show the wind pattern (200 hPa) during the break day of monsoon 2011. The WRF and ERA-Interim both showed that the wind was coming from the east. WRF and ERA-Interim data indicated that the maximum wind speed in the northern region was around 19-20 m/s, while in the southern region, it was approximately 20-21 m/s. According to WRF data, the minimum wind speed in the southeast part of Bangladesh ranged from 13-17 m/s, whereas ERA-Interim data indicated that the lowest wind speed in the southern region of Bangladesh was between 12-16 m/s.

Sea Level Pressure (SlP) Pattern

Figures 5 (a) and 5 (b) show the SLP pattern during an active day of monsoon (2011). According to WRF, the sea level pressure over Bangladesh ranged between 992-996 hPa, whereas ERA-Interim indicated a range of 997-1003 hPa. Both WRF and ERA-Interim indicated that the highest SLP was located in the eastern region of Bangladesh. A significant disparity of 5.5-6.5 hPa between ERA-Interim and WRF was detected in the southern area. Over the western part of Bangladesh, SLP was found less than 992 to 993 hPa from WRF but ERA-Interim was found 997 to 1000 hPa.

Figures 5 (c) and 5 (d) show the SLP pattern during the break (monsoon) day of 2011. As per WRF, the sea level pressure over Bangladesh ranged between 998-1004 hPa, while ERA-Interim indicated a range of 1003-1007 hPa. WRF and ERA-Interim show the highest SLP over the northeastern part of Bangladesh. The highest difference between ERA-Interim and WRF was found over the southern part i.e. 4 to 5 hPa. The lowest difference between ERA-Interim and WRF was found over the northeast part i.e. less than 0.5 hPa. Over the western part of Bangladesh; SLP was found less than 999 to 1001 hPa from WRF but ERA-Interim was found 1003 to 1004 hPa. During active and break monsoons, the value of the lowest and highest range of SLP is nearly similar. But the spatial distribution is found in a different pattern. Compared to the break (monsoon) days, most of the areas of the country experience the lowest SLP during active (monsoon) days.

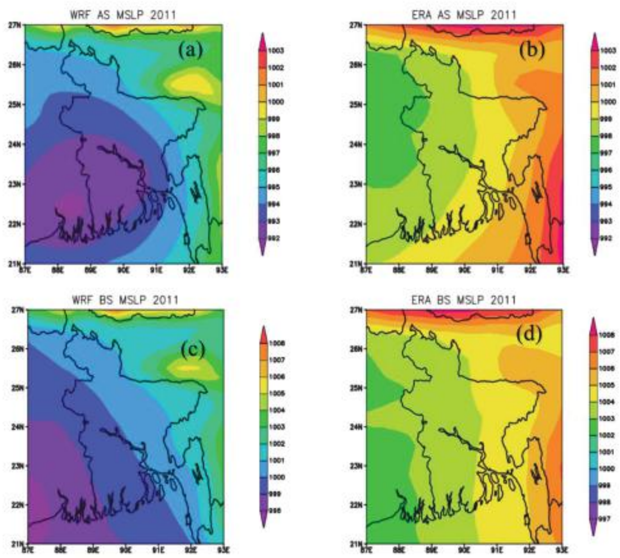

Figure 5: Active (a, b) and Break (c, d) Day of Monsoon (2011) Mean (Average) SLP Derived from WRF and ERA-Intrim Respectively

Outgoing Longwave Radiation Pattern

Figure 6 (a) shows the OLR value on an active day in 2011 on the left side and figure 6 (b) shows the OLR value on a break day in 2011 on the right side. From figures 6 (a) and 6 (b), it is evident that the active days OLR value is lower than the break days OLR value. On the active days, the OLR value varied from 200 to 270 W/m² and on the break days OLR value started from 240 up to 275 W/m². Over the northwestern side of Bangladesh, the highest OLR value was found i.e. 260 to 270 W/m² during the active day whereas during break day the highest OLR value was found up to 275W/m² over the central part of this country. During active days the lowest value found over the southeast part was 200-220 W/m² and during break days the lowest value was found at the same place but the value was 230-250 W/m².

Over Bangladesh, the OLR pattern of an active day is different from that of a break day. On active days, the sky is typically cloudy and clouds absorb radiation, lowering the rate of OLR. The opposite of active days was identified through the process on the break day. As the sky is clear on break days, the OLR rate is higher than it is on active days.

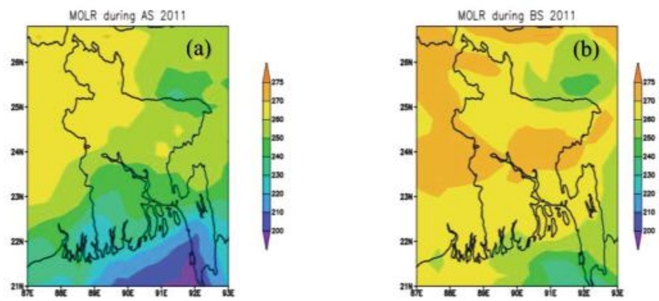

Figure 6: OLR during Active (a) and Break (b) Day of Monsoon (2011) Derived from WRF

Analysis of Active and Break Spells for the Deficit Rainfall Year 2013

Identification of Active and Break Spells for the Year 2013

The peak monsoon seasons are July and August in Bangladesh and for this reason identification of active and break monsoons for this study is selected within the duration of July 1 to August 31.

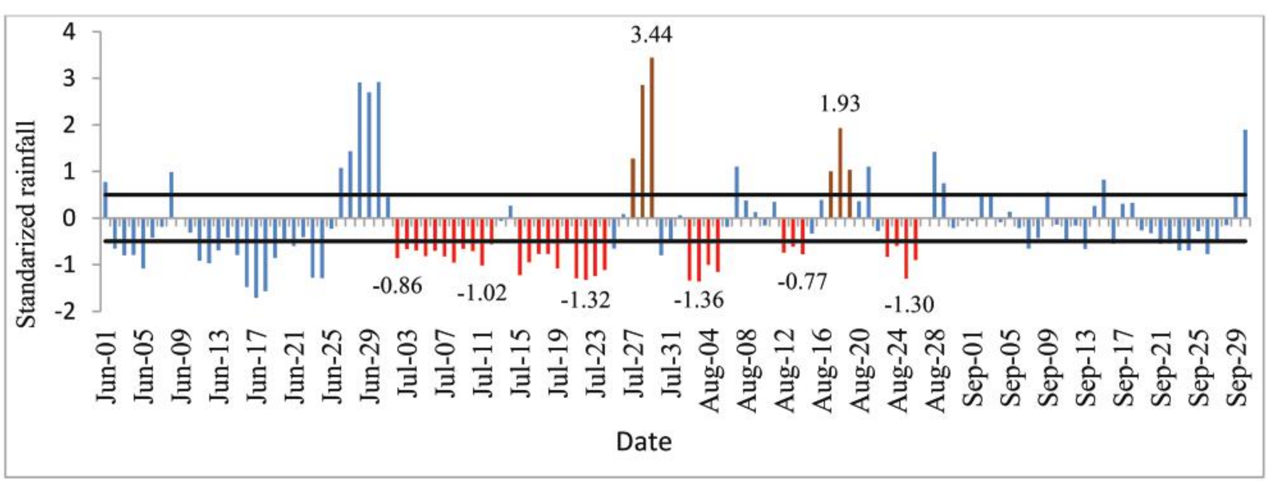

Figure 7: Standardized Rainfall of Monsoon 2013 Over Bangladesh

Break and active days, respectively, are defined as when the threshold value has been taken as less than -0.5 or greater than 0.5 and has existed for at least three consecutive days. From the figure the active and break phases are

Table 2: Active and Break Spells of Monsoon in 2013

Active	26-29July, 17-19Aug
Break	2-12July, 15-25July, 2-5Aug, 12-14Aug, 23-26Aug

Rainfall Pattern

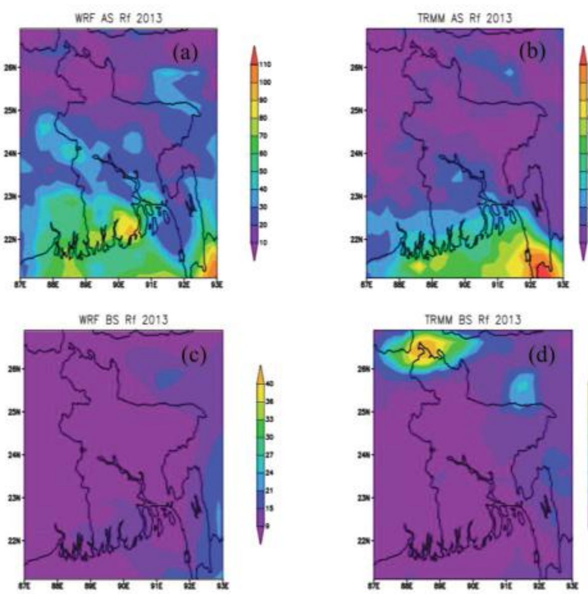

Figure 8: Active (a, b) and Break (c, d) Day Monsoon Rainfall for 2013 Derived from WRF and TRMM Respectively

Figures 8 (a) and 8 (b) show the active day of monsoon rainfall in 2013 from WRF simulation and TRMM respectively. The southern region of Bangladesh recorded the highest rainfall, with WRF indicating a range of 20-110 mm and TRMM indicating a range of 60-110 mm. In the north-western part of the country, WRF indicated the lowest rainfall of less than 10 mm, while TRMM suggested that the eastern part of the country records the least amount of rainfall, also less than 10 mm. WRF was found over the central part rainfall was 10-50 mm but TRMM shows it was less than 10-20 mm. Figures 8 (c) and 8 (d) show the break day of monsoon rainfall in 2013 in Bangladesh. WRF and TRMM both show that rainfall was less than 9 mm over the central part of Bangladesh. TRMM shows the highest rainfall over the northeastern part was 15 to greater than 40 mm but WRF shows the highest rainfall was 9-24 mm over the southeastern part.

Wind Pattern

Figures 9 (a) and 9 (b) show the wind pattern (850 hPa) during an active day of monsoon in 2013. WRF shows the wind was flowing from the south-easterly direction and ERA-Interim shows the south-westerly direction. WRF showed cyclonic circulation over the southeastern part of Bangladesh but ERA-Interim showed cyclonic circulation over the

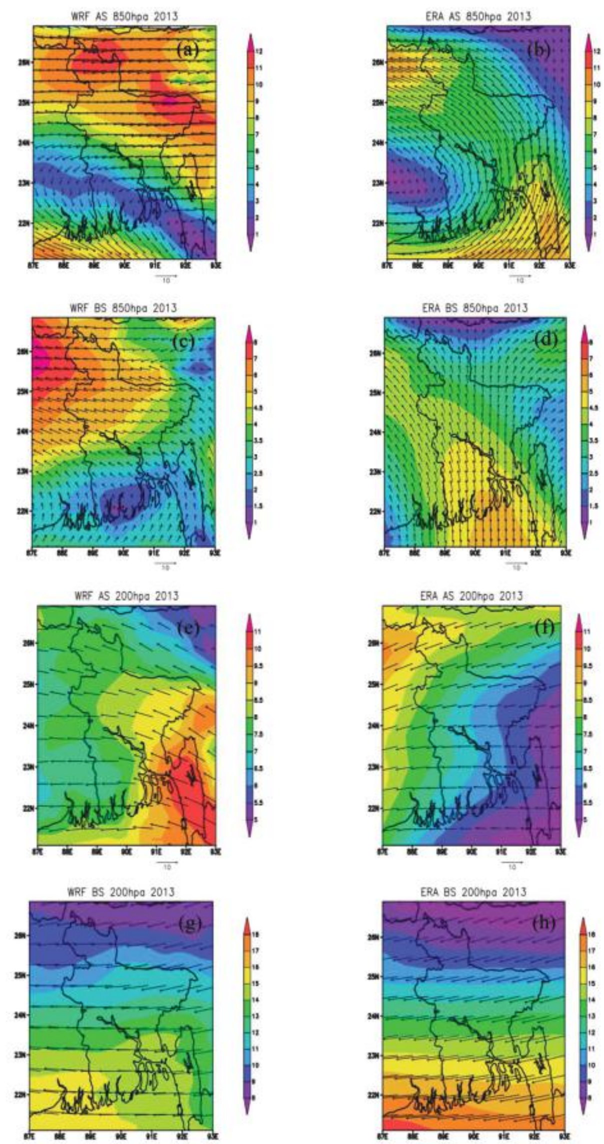

Figure 9: 850 hPa Height Winds during Active (a, b) and Break (c, d) Day of Monsoon for 2013, and 200 hPa Height Winds during Active (e, f), and Break (g, h) Day of Monsoon for 2013

southwestern part of this country. WRF showed the maximum wind speed is 8-12 m/s over the northern part but ERA-Interim showed the maximum wind speed over the north-western and south-eastern parts which speed was 6-10 m/s.

Figures 9 (c) and 9 (d) showed the wind pattern (850 hPa) during the break day of the monsoon in 2013. WRF shows the wind was flowing south-easterly direction but ERA-Interim shows two directions, southwest direction over the western part and southeast direction over the eastern Part. The maximum wind speed found in the northern part was 3.5-8 m/s according to WRF, and 3.5-6 m/s according to ERA-Interim over the southern part of this country. WRF shows the lowest wind speed was 1.5- 2.5 m/s in the southern part but ERA-Interim shows the lowest wind speed is 2-3 m/s over the northeastern part of this country.

Figures 9 (e) and 9 (f) showed the wind pattern (200 hPa) during an active day of monsoon in 2013.WRF shows the wind was flowing from the south-easterly direction but ERA-Interim shows the easterly direction. WRF shows the highest wind speed was 8 m/s to 11 m/s over the south-eastern part of this country but ERA-Interim shows the highest wind speed was 7.5-9 m/s over the north-western part. WRF shows the wind speed was increasing from the northwestern part to the southeastern part but ERA-Interim shows a different pattern i.e. the wind speed was increasing from the southeastern part to the northwestern. ERA-Interim shows the lowest wind speed was less than 5-6 m/s over the southeastern part of this country.

Figures 9 (g) and 9 (h) showed the wind pattern (200 hPa) during the break day of the monsoon in 2013. The wind was flowing from the east according to WRF and ERA-Interim. WRF indicates that the southern region highest wind speed was 13–16 m/s, whereas ERA-Interim indicates the same location highest wind speed was 13–18 m/s. The northern region of Bangladesh is where the lowest wind speed, as indicated by WRF and ERA-Interim, is between 8 and 12 m/s. Both WRF and ERA-Interim indicate that the wind speed was rising from northern part to the southern part of Bangladesh.

Sea Level Pressure (SLP) Pattern

Figure 10 (a) and 10 (b) showed the SLP pattern during active (monsoon) day in 2013. WRF shows the sea level pressure was 994-1000 hPa over Bangladesh but ERA-Interim shows it was 998-1003 hPa. WRF showed the highest SLP over the northern part but ERA-Interim showed the highest SLP the over eastern part. The highest difference between ERA-Interim and WRF was found in the south-eastern part i.e. 5-8 hPa. The lowest difference between ERA-Interim and WRF was found over the northeast part i.e. less than 1-2 hPa.

Figures 10 (c) and 10 (d) showed the SLP pattern during the break (monsoon) day in 2013. WRF shows the sea level pressure was less than 998-

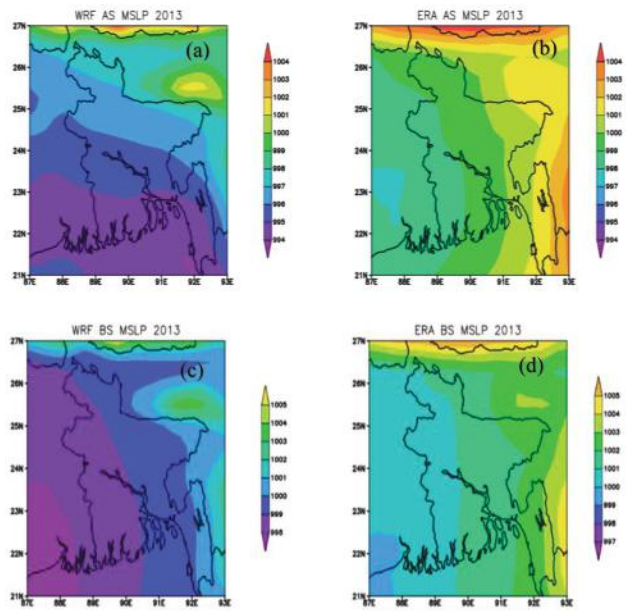

Figure 10: Active (a, b) and Break (c, d) Day of Monsoon (2013) Mean (average) SLP Derived from WRF and ERA-Intrim Respectively

1004 hPa but ERA-Interim shows it was 997-1004 hPa over Bangladesh. The highest difference between ERA-Interim and WRF was found over the south-eastern part i.e. 2.2 to 3 hPa. Over the western part of Bangladesh SLP was found less than 998 to 999 hPa from WRF but ERA-Interim was found 1000 to 1002 hPa.

Outgoing Longwave Radiation Pattern

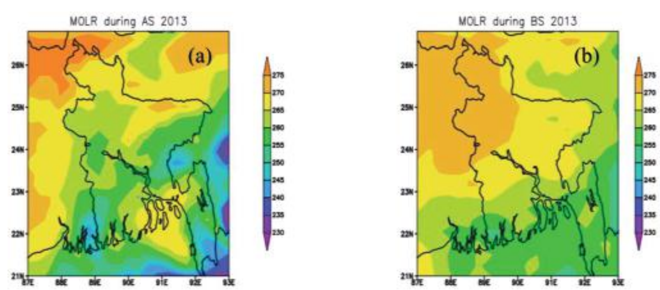

Figure 11: OLR during Active (a) and Break (b) Day of Monsoon (2013) Derived from WRF

Figures 11 (a) and 11 (b) showed the OLR value on an active day in 2013 on the left side and the right side shows the OLR value on a break day in 2013 respectively. From the figure, it is evident that an active day OLR value is lower than the break day OLR value. On an active day, the OLR value was varying from 240 to 275 W/m², and on the break day OLR value starts from 255 up to 275W/m². Over the north-western side of Bangladesh, the highest OLR value was found at 260-275 W/m² during active days but during break days the highest OLR value was found at 265-275 W/m² over the western part of this country. During active days the lowest value was found over the southeastern part which was 240-260 W/m² and during break days the lowest value was found over the southern part which was 255-265 W/m².

CONCLUSIONS

The WRF Model was used in this work to look into the weather patterns connected to active and break periods of the summer monsoon over Bangladesh in 2011 and 2013. The results of the study are summarised in the following parts in detail:

2011 is an excess rainfall year in which the total active periods are three, among which two occurred in July and one occurred in August. From the WRF simulation of the 2011 intra-seasonal variability of the southwest monsoon, a cyclonic circulation (850 hPa) was found over the central part of Bangladesh during an active day and the south-easterly wind was found (850 hPa) during break day. The easterly wind was found (200 hPa) both on active and break days. SLP and OLR patterns were found lower on an active day compared to a break day.

2013 is a deficit rainfall year in which total active periods are two, one found in July and another in August. From WRF simulation of the 2013 intraseasonal variability of the southwest monsoon, a cyclonic circulation (850 hPa) was found over the south-eastern part of Bangladesh during an active day and the south-easterly wind was found (850 hPa) during break day. The south-easterly wind was found (200 hPa) during the active day and the easterly wind was found during break day. The lowest SLP was found over the southern part during an active day and the lowest SLP was found over the western part during a break day. The OLR pattern was found lowest on an active day in the southern part compared to a break day.

This study finds that the increase of rainfall is concurrent with a south-westerly wind and the decrease of rainfall simultaneously occurs with a south-easterly wind. It can finally be said that the WRF model can reasonably capture well the active and break spell of summer monsoon for the years 2011 and 2013.

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