Study of Arrival and Withdrawal of Southwest Summer Monsoon over Bangladesh and Analysis of Extreme Early and Late Arrival Events Using RegCM

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ABSTRACT: This research attempts to identify the dates of arrival and withdrawal for the southwest summer monsoon over Bangladesh using observed data. In addition, both the extremely early and late arrival of summer monsoon are studied using the RegCM. - Rainfall, wind direction, wind speed, maximum temperature, minimum temperature, and relative humidity of 11 stations in Bangladesh for the months of May to October, for the years between 1990 to 2019, have been analyzed statistically. Secondly, two anomaly events were simulated using the Regional Climate Model (RegCM). This analysis is done for determining various spatial and temporal patterns during the arrival and withdrawal dates for the summer monsoon. It is found from this research that the arrival of the summer monsoon in the extreme south-eastern region of the country is around 10 June. After covering the entire country by just 14 days, the summer monsoon completes its journey from Teknaf to the northwestern tip of the country via Sylhet. The summer monsoon begins to depart from extreme north-western Bangladesh on 4 October. It takes about 16 days to complete the withdrawal from Bangladesh via the southeastern route, with the average date being 20 October. Both the arrival and withdrawal dates have standard deviations ranging from 7 to 8 days and 5 to 7 days respectively. From the analysis of 30 years of data, the summer monsoon season lasts from 102 to 132 days.

Keywords: Southwest Monsoon; Arrival; Withdrawal; RegCM Simulations

INTRODUCTION

The word – Monsoon – has an Arabic descent, arriving from the word - "Mausoom" - which means 'season', and it is mainly referred to the winds of the Arabian Sea (Huq, 1978). Etymologically, it was first coined by sailors to describe a system of alternating winds over the Arabian Sea and the Bay of Bengal. Monsoon is now connected with a reversal of winds and their persistence for a lengthy period, mostly from June to September, accompanied by rain. The climate of Bangladesh is such that the country receives seasonal rainfall each year (Rasheed, 2006). This rain is very crucial for the agriculture of the country as the cultivation system is more akin to a primitive system (Rahman et al., 2012), whereby the farmers and peasants depend on rainwater for irrigation (Guimberteau et al., 2012). Maximum rainfall occurs during the monsoon period. So, the timely arrival of monsoon is a must for the farmers (Ahasan et al., 2010). Again, timely withdrawal is required for some crops that need less irrigation (Mahmood et al., 2003). Therefore, it is quite understandable that both of these activities are heavily influential on agricultural productivity in Bangladesh (Rahman et al., 2016). But this needs a structured assessment with essential tools so that it becomes easier to explain (Peiris et al., 2000). Therefore, this research is important in the context of our country.

The idea of this research is to analyze the monsoonal effect on agriculture. It is very important to know the timing of monsoon arrival and withdrawal so that we can know the trend of rainfall, humidity, temperature, wind component, etc. According to some reports, the arrival of the southwest monsoon has been delayed in recent years. Besides, knowledge about the arrival and withdrawal of monsoon has great importance from an agronomic standpoint. The late arrival of the monsoon affects Kharif crops. A 10-day delay in the arrival of the monsoon decreases the yield of Rice and Pearl millet (Peiris et al., 2000). So that's the reason for choosing the topic for research.

The monsoon is a vast phenomenon that encompasses not only precipitation but also other different factors that make up the monsoonal system. However, significant precipitation and wind direction are required to make any conclusions about the monsoon. In the summer monsoon, winds are mainly southwesterly over the Bay of Bengal (Ahasan et al., 2014; Karmakar, 2007). A

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southerly component is a must for determining the onset of the southwest summer monsoon (Karmakar, 2007). Southwest monsoon persists from June to September mainly (Ahasan et al., 2014; Rahman, 2013; Huq, 1978). The monsoon trough is another factor that influences monsoonal activity. It's a low-pressure zone that covers a broad area. The monsoon trough is the name given to this trough when it is spotted during the monsoon season. On the eastern coast of the Bay of Bengal, a low is formed, and then it heads toward the northwest. In the southwest, it follows the direction of the monsoon trough line, resulting in a significant amount of rainfall. (Ahasan et al., 2014).

Summer monsoon arrival in India from 2001-2005 is modeled using the Regional Climate Model (version 4.9), which is also known as RegCM. RegCM utilizes many cumulus convection schemes, such as - Kuo, Mix98, Mix99, Emanuel, Grell, and Tiedtke. They are tested at 50 km horizontal resolution. The Mix98 scheme (Grell over land and Emanuel over the Ocean) has previously performed well among the six convective schemes tested in this research (Bhatla et al., 2015). The Emanuel scheme has produced better signatures for the rainfall at the Arabian Ocean and Bay of Bengal branches of the Indian Summer Monsoon (Bhatla et al., 2020). In consequence, we have used Emanuel for both land and ocean.

The summer monsoon enters in South Asia through Kerala (India). This is specifically defined by the first day of a period of five or more successive days of rainfall when the daily rainfall is at least 10 mm on all days (Ananthakrisnan and Soman, 1988; Karmakar, 1993). Beginning on 1 May, data of daily rainfall and the predominant wind vector (direction and speed) are analyzed by operational meteorological agencies to forecast the arrival of summer monsoon. In addition to that, mean daily temperature and mean daily relative humidity are used in the early stages of analysis.

DATA SOURCES, METHODOLOGY AND MODEL SETUP

Observational Data

We have used several types of observational data from the sources of the Bangladesh Meteorological Department (BMD). From BMD - rainfall, wind speed and wind direction, relative humidity, minimum temperature, maximum temperature and mean sea level pressure data are collected for analyzing the dates of arrival and withdrawal for Southwest Monsoon in Bangladesh. The data has been analyzed for the years from 1990 to 2019 in this research. Daily precipitation data was collected for 11 stations of the BMD. Those 11 stations are selected randomly that cover the whole of Bangladesh widely (Fig. 1).

Study Area

The study area, Bangladesh, is located in South Asia (latitudes between 20°34'N-26°38' N and longitudes between 88°01'E-92°42' E). The country is surrounded by India and Myanmar; with the Bay of Bengal to her south. The physiography of Bangladesh has two distinctive features: the world's largest deltaic plain and other is the flowing rivers with small hilly regions (Rashid, 2019).

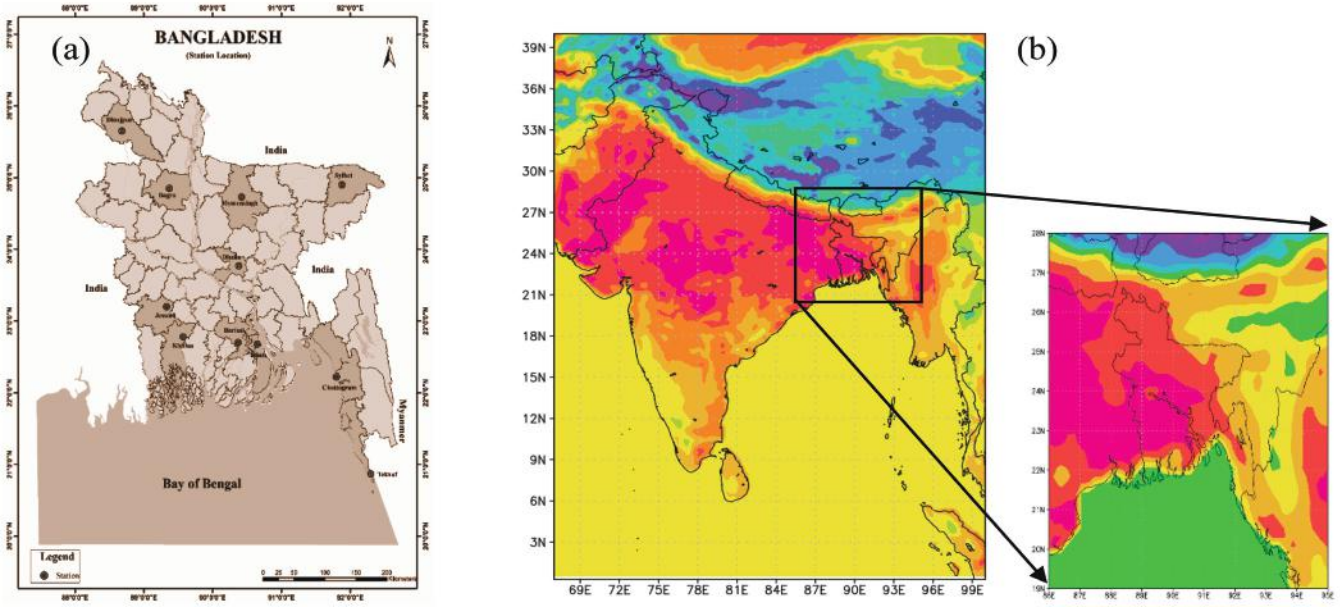

Figure 1: (a) Location of BMD Stations used in This Research; and (b) Domain used for RegCM

Model Domain

This research is for analyzing the arrival and withdrawal of summer monsoon over Bangladesh, so a nested domain over the Bangladesh region is selected for getting better results. The domain has a horizontal resolution of 25 km, and the data used for simulations - Era interim 75 - has a resolution of approximately 75 km (0.75°).

The model has been simulated with a parent domain of 69.04°E to 112.16°E and 2.73°N to 41.45°N for the analysis of the monsoonal system, and the nested domain is located between 86°E to 96°E and 18°N to 27°N.

Criteria for Arrival and Withdrawal of Southwest Monsoon over Bangladesh

The summer monsoon arrives first in the southeastern coastal area of Bangladesh. So, the necessary factors for coastal stations were examined first to determine the summer monsoon's arrival dates at those locations. After that, the variables for the inland stations were analyzed. Similarly, because the withdrawal of summer monsoon begins in the northwestern region of the country. Climatological data from stations in that region were analyzed to determine the start of the withdrawal episode. The number of days elapsed since 30 April was used to calculate the arrival and departure dates of the summer monsoon each year. For example, 01 denotes 1 May, 61 denotes 30 June, and so on. Ananthakrisnan and Soman utilized this method to determine the arrival date of the summer monsoon in Kerala, India (Ananthakrisnan and Soman, 1988).

In this research - mean daily temperature and mean daily relative humidity were used as additional criteria in the early stages of the analysis. If there was an event of continuous rain for three or more days, with daily rainfall of at least 5 millimeters and winds blowing from the south or south-east, the initial date is then used as the date for this study to determine when summer monsoon would arrive in Bangladesh.

In this research, the criteria for the withdrawal of monsoon have been defined as the last spell of three or more consecutive days of rain, when the wind direction has changed from southerly to northerly or northwesterly, and the temperature going down, as well as a downward tendency of humidity.

Methodology for Analyzing Model-Simulated Results

At first, the selection of domain and parameterization schemes are done for the study. Then, model simulation is done for several years with the EIN75 data through RegCM. Two anomaly events have been simulated for further analysis and compared to the observed data. For determining the arrival and withdrawal of southwest monsoon through the analyses of several variables like precipitation, humidity, pressure, temperature, etc., the location of Teknaf station is being selected. This location has been utilized for other analyses of this research.

Model Configuration for the Study

Model configuration is an integral part of this research. The model configuration for this research has been listed below -

Table 1: Model Configuration for RegCM in this Research

Model features	Scheme Selection
Model domain	69.04°E to 112.16°E and 2.73°N to 41.45°N (Nested domain: 86°E to 96°E and 18°N to 27°N).
Dynamics	MM4 Hydrostatical core
Resolution	25 km (horizontally)
ICBC	Era Interim 75
SST	NOAA Optimum Interpolation (OI) Sea Surface Temperature V2 data
PBL	Holtslag 1990
Cumulus Convection Scheme	MIT-Emanuel over land and ocean
Land Surface	BATS
Ocean Surface Flux	Zeng 1998
Moisture	SUBEX

MAJOR FINDINGS

Using the selected criteria, the arrival and withdrawal dates of the summer monsoon in Bangladesh were calculated for each year from 1990 to 2019. Firstly, characteristics related to coastal stations were examined

to establish the arrival dates of the summer monsoon at those locations, for the summer monsoon comes in southern coastal areas at first (Karmakar et al, 1993). As a result, Teknaf station is selected for analyzing the arrival and withdrawal dates of Bangladesh. The stations that are located elsewhere (except the coast) were analyzed afterward.

The following tables contain information regarding the duration of summer monsoon in Bangladesh from 1990 to 2019. Please note that; here 'A' denotes the arrival date of the summer monsoon; 'W' means the withdrawal date of the summer monsoon; 'M' is for missing data; 'I' stands for inconclusive arrival or withdrawal date. The dates are given sequentially as follows: 01 for 1 May 32 for 1 June, etc. Furthermore, 'n' means the number of observations; '$\bar{x}$' is the mean date of arrival or withdrawal of the summer monsoon; and 'σ' is the standard deviation of arrival or withdrawal date.

Table 2: The Arrival and Withdrawal Dates of the Summer Monsoon at Different Stations in Bangladesh for the Period of 1990-2006

Stations	A or W	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
Teknaf	A	48	39	48	29	45	42	48	50	50	28	41	33	41	39	43	54	28
	W	166	169	176	179	172	173	184	163	175	177	168	184	170	171	171	184	167
Chattogram	A	49	39	53	29	45	43	50	50	50	28	46	34	43	39	M	M	M
	W	165	169	175	178	160	163	184	162	174	177	163	184	169	169	M	M	M
Bhola	A	50	41	54	33	48	43	50	57	53	28	50	37	43	47	45	59	37
	W	164	167	175	176	162	172	183	162	174	176	I	184	169	164	I	177	I
Barishal	A	52	41	54	33	48	43	50	55	55	28	50	37	43	49	45	59	37
	W	164	168	175	175	160	173	183	162	174	176	I	I	184	168	164	177	164
Sylhet	A	52	41	54	32	48	44	52	58	55	30	52	37	43	51	45	60	37
	W	163	169	175	172	I	173	171	157	174	176	164	184	169	164	169	177	164
Dhaka	A	54	43	54	33	48	43	52	58	56	41	53	37	44	52	50	63	40
	W	164	168	170	174	163	I	165	157	175	175	164	172	165	164	161	170	159
Mymensingh	A	54	42	55	32	47	I	53	58	56	41	54	37	43	52	49	62	40
	W	165	169	170	174	164	172	163	157	173	174	166	172	I	163	169	164	161
Khulna	A	55	43	55	33	48	52	58	56	41	53	53	37	44	51	50	65	37
	W	163	167	169	174	163	172	163	155	172	176	165	I	168	163	166	156	161
Jessore	A	54	42	55	33	47	43	52	39	56	42	53	37	43	51	50	61	40
	W	163	163	169	172	163	174	165	154	173	176	163	163	I	163	163	157	164
Bogura	A	60	44	56	37	50	48	53	59	58	41	55	39	45	53	53	65	40
	W	157	159	152	157	163	162	163	151	171	161	158	164	156	165	163	156	160
Dinajpur	A	60	48	59	39	54	48	61	59	42	58	58	48	49	54	55	65	52
	W	147	156	152	155	163	162	160	151	159	160	148	163	156	164	161	154	151

Table 3: The Arrival and Withdrawal Dates of the Summer Monsoon at Different Stations in Bangladesh for the Period of 2007-2019

Stations	A or W	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	n	$\bar{x}$	Σ
Teknaf	**A**	39	38	24	43	39	46	38	49	36	39	42	40	44	30	40.77	7.19
	W	171	181	173	179	174	167	182	170	169	167	176	167	164	30	172.97	6.11
Chattogram	**A**	M	40	24	43	39	47	39	49	36	39	42	40	44	26	41.54	7.22
	W	M	181	172	179	173	166	181	170	168	167	175	167	164	26	171.35	7.00
Bhola	**A**	46	48	25	50	48	51	38	49	I	44	42	40	51	29	45.07	7.96
	W	169	169	163	168	171	166	180	I	165	165	175	166	163	26	170.19	6.49
Barishal	**A**	46	48	25	50	48	52	38	50	44	44	43	41	51	30	45.30	7.90
	W	168	168	164	167	172	167	164	I	I	165	175	175	166	26	169.72	6.66
Sylhet	**A**	47	51	26	49	49	52	37	49	45	45	44	42	50	30	45.90	8.06
	W	168	168	164	167	172	167	172	I	165	166	176	166	163	29	169.11	5.63
Dhaka	**A**	47	50	25	50	48	55	38	53	45	49	46	41	51	30	47.30	7.91
	W	170	167	162	162	164	167	176	166	I	167	175	166	163	28	166.82	5.10
Meymensingh	**A**	47	50	25	51	49	55	38	53	45	48	46	41	50	29	47.34	8.12
	W	169	166	170	162	151	166	176	170	I	166	175	166	163	28	167.00	5.64
Khulna	**A**	47	51	25	50	52	56	45	52	45	49	47	41	52	30	48.10	8.12
	W	164	163	162	162	147	163	176	167	I	I	175	166	163	27	165.22	6.57
Jessore	**A**	47	50	25	49	51	55	45	51	45	50	47	40	52	30	47.50	7.71
	W	164	162	162	162	150	165	176	167	156	164	175	166	I	28	164.79	6.40
Bogura	**A**	47	50	41	I	54	65	57	59	54	64	63	55	57	29	52.48	8.09
	W	158	162	162	166	165	161	172	153	152	157	169	155	162	30	160.40	5.38
Dinajpur	**A**	47	52	44	55	55	65	58	59	54	62	62	57	59	30	54.60	6.60
	W	156	160	162	166	162	148	171	150	147	151	164	150	150	30	156.63	6.49

As the monsoon withdrawal begins in northwestern India, the climatological data of that region was initially analyzed to pinpoint the commencement of the withdrawal event, and hence the following analyses were done for other stations. Table 2 and 3 list those dates for each year from 1990 to 2019 for the stations of Bangladesh. There have been some cases where the arrival of the summer monsoon at particular stations has not been established over the years. Sometimes rainfall was shorter than 3 consecutive days, the wind direction was not prominent, and temperature, as well as humidity, had not enough match. Therefore, those cases were therefore classified as inconclusive (in Tables 2 and 3). Only 2.1% of the total 330 observations have uncertain arrival dates. Similarly, for withdrawal some years had haphazard rainfall patterns and uneven wind patterns, so it was so much problematic for analyzing withdrawal dates for some years. This has been also denoted as inconclusive Around

5.5% of the 330 total observations are found to be inconclusive. Some stations didn't have data for either the arrival or withdrawal period or both Tables (Table 2 and 3) show those data as missing (M), and they were not analyzed (e.g., Chattogram from 2004 to 2007).

In addition, Table 2 and 3 show the average arrival and withdrawal dates for all 11 stations all over Bangladesh, and also standard deviation of dates is shown for those 11 stations. In calculating the total number of observations, means, and standard deviations of the arrival and withdrawal dates, data designated by I, and M in Table 2 and 3 were omitted. To accommodate for all of the differences in geography, these stations were chosen from all over the country. Arrival and withdrawal dates were found to be reasonably distributed across all locations.

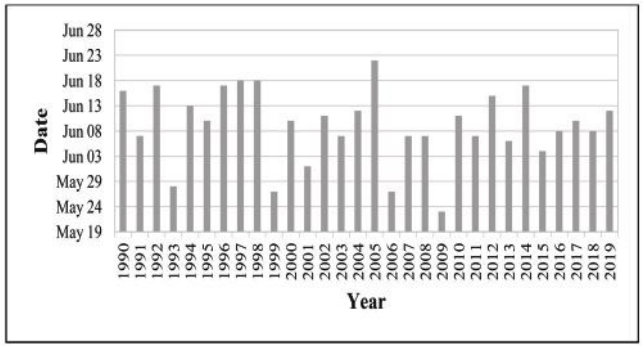

Figure 2: Analysis of Arrival Dates of Southwest Monsoon over Bangladesh from 1990 to 2019

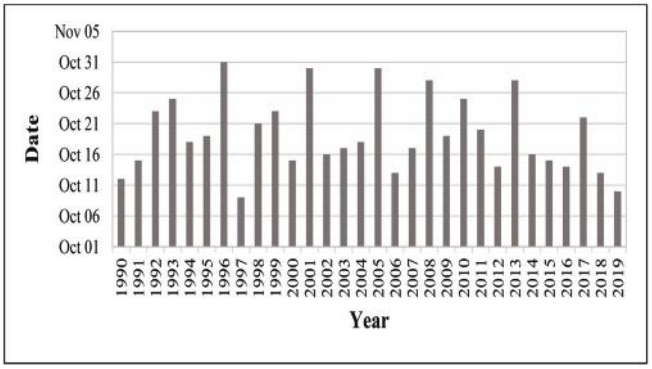

Figure 3: Analysis of Withdrawal Dates of Southwest Monsoon over Bangladesh from 1990 to 2019

Figures 2 and 3 show the graphical representation of the arrival and withdrawal dates of the southwest summer monsoon from 1990 to 2019. Here, annual arrival and withdrawal dates have been given in column diagrams.

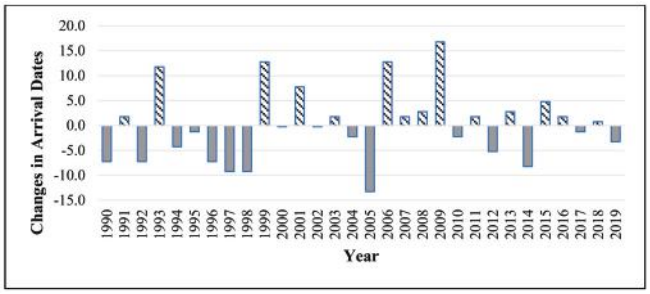

Figure 4: Analysis of Anomaly for Arrival Dates of Southwest Monsoon over Bangladesh from 1990 to 2019

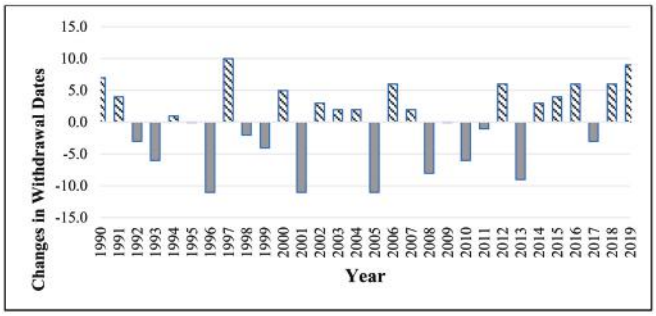

Figure 5: Analysis of Anomaly for Withdrawal Dates of Southwest Monsoon over Bangladesh from 1990 to 2019

The outlier years of 30 years for both arrival and withdrawal are shown in Figures 4 and 5. Positive values indicate an early arrival and an early retreat in this case, respectively. A late arrival or withdrawal is indicated by a negative value. In this scenario, there were 14 years of early arrival, 14 years of late arrival, and 2 years of regular arrival based on a 30-year analysis. Again, out of the investigated period, there were 16 years with early withdrawal, 12 years with late withdrawal, and 2 years with normal withdrawal. Extremely early arrival occurs in 4 years, while extremely late arrival occurs in 1. Additionally, 3 separate years had excessive late withdrawal, whereas 1 year has extreme early withdrawal. Extreme year in this context refers to an early or late arrival or withdrawal of 10 days.

Mean Arrival Date for Bangladesh

Initially moving in from the extreme southeast, the summer monsoon arrives in Bangladesh and then travels inward. Summer monsoon in Bangladesh arrives at various times throughout the year. According to the statistics in Table 2 and 3, the arrival of the summer monsoon in the extreme south-eastern region

of the country is on the 10th of June on average. The arrival dates of the summer monsoon in Kerala are used as a starting point for comparison. After covering the entire country in just 14 days, the summer monsoon completes the journey from Teknaf to the northwestern tip of the country via Sylhet. Sometimes summer monsoon may arrive later than usual in the north-western portion of the country due to the convergence of the Arabian Sea branch and the Indian Ocean branch of monsoonal wind.

Mean Withdrawal Date for Bangladesh

Figure 6 illustrates that the summer monsoon begins to depart from extreme north-western Bangladesh on 4 October on average, with the departure beginning from extreme north-western region of Bangladesh. The summer monsoon retreats slowly in the northern half of the country, whereas it disappears swiftly in the eastern half of the country. In response to the increasing strength of the subtropical high, the summer monsoon retreats at a faster rate as time progresses, causing a flood. It takes 16 days on average to complete the withdrawal from Bangladesh via the southeastern route, with the average date being on 20 October.

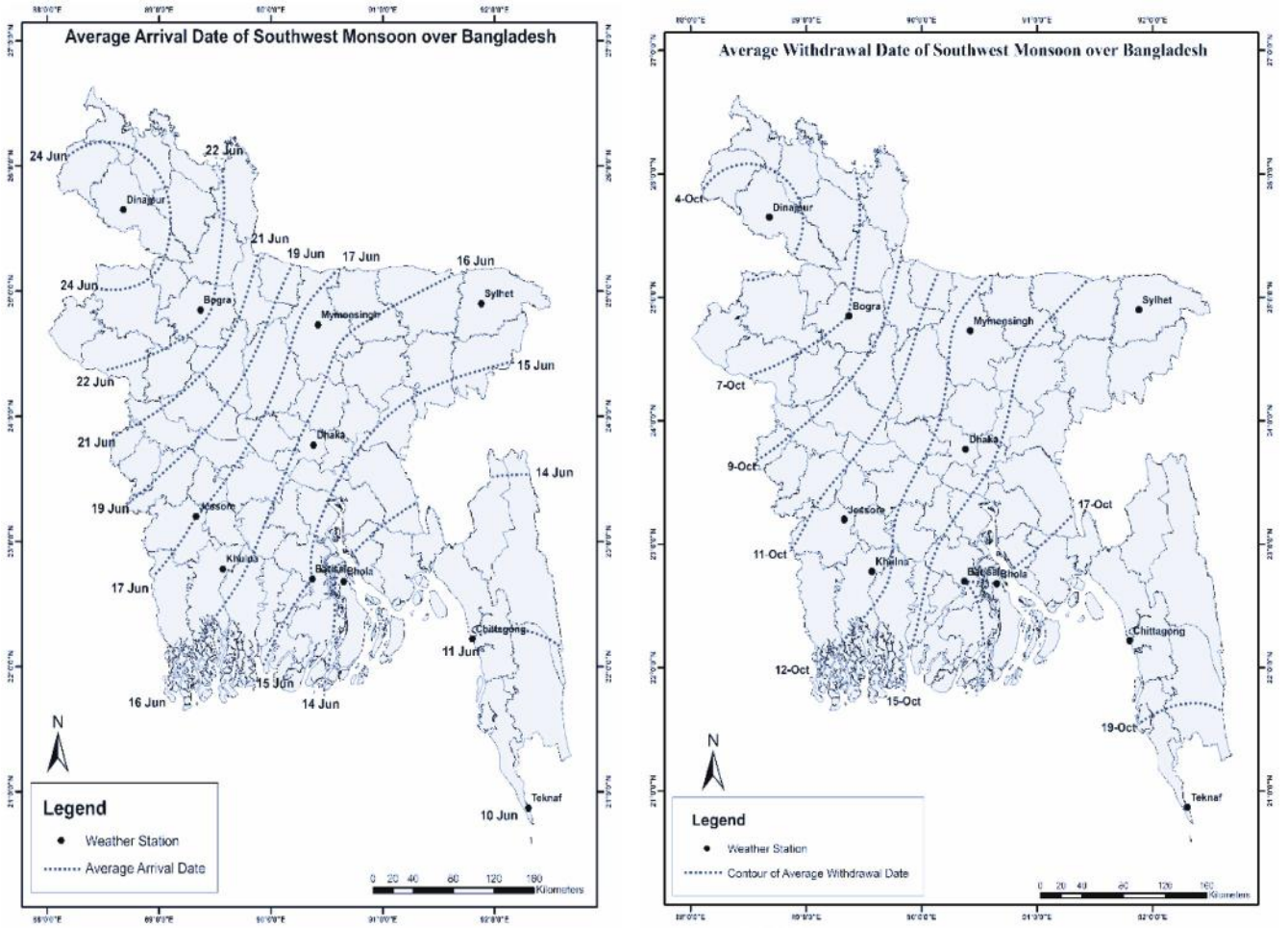

Figure 6: Analysis of Average Arrival and Withdrawal Dates of Southwest Monsoon over Bangladesh

Variability in the dates for Arrival and Withdrawal of Summer Monsoon

When it comes to the arrival and withdrawal dates of the summer monsoon, there is a considerable occurrence of variety, as illustrated in Figure 6. In these two maps, the patterns of their geographic distributions appear to be comparable to one another. Both the arrival and withdrawal dates have standard deviations ranging from 7 to 8 days and 5 to 7 days respectively, depending on the month. The standard deviation of those arrivals

and withdrawals is shown in Figure 7. There is a wide area of the country where arrival and withdrawal dates are highly unpredictable, ranging from the southwest to the northeast, and this is especially true in the winter. Similarly, as the monsoon moves ahead in some places, it also moves backward. As a result, the paths of arrival and withdrawal have more or less the same length. From the analysis of 30 years of data, the summer monsoon season lasts from 102 to 132 days.

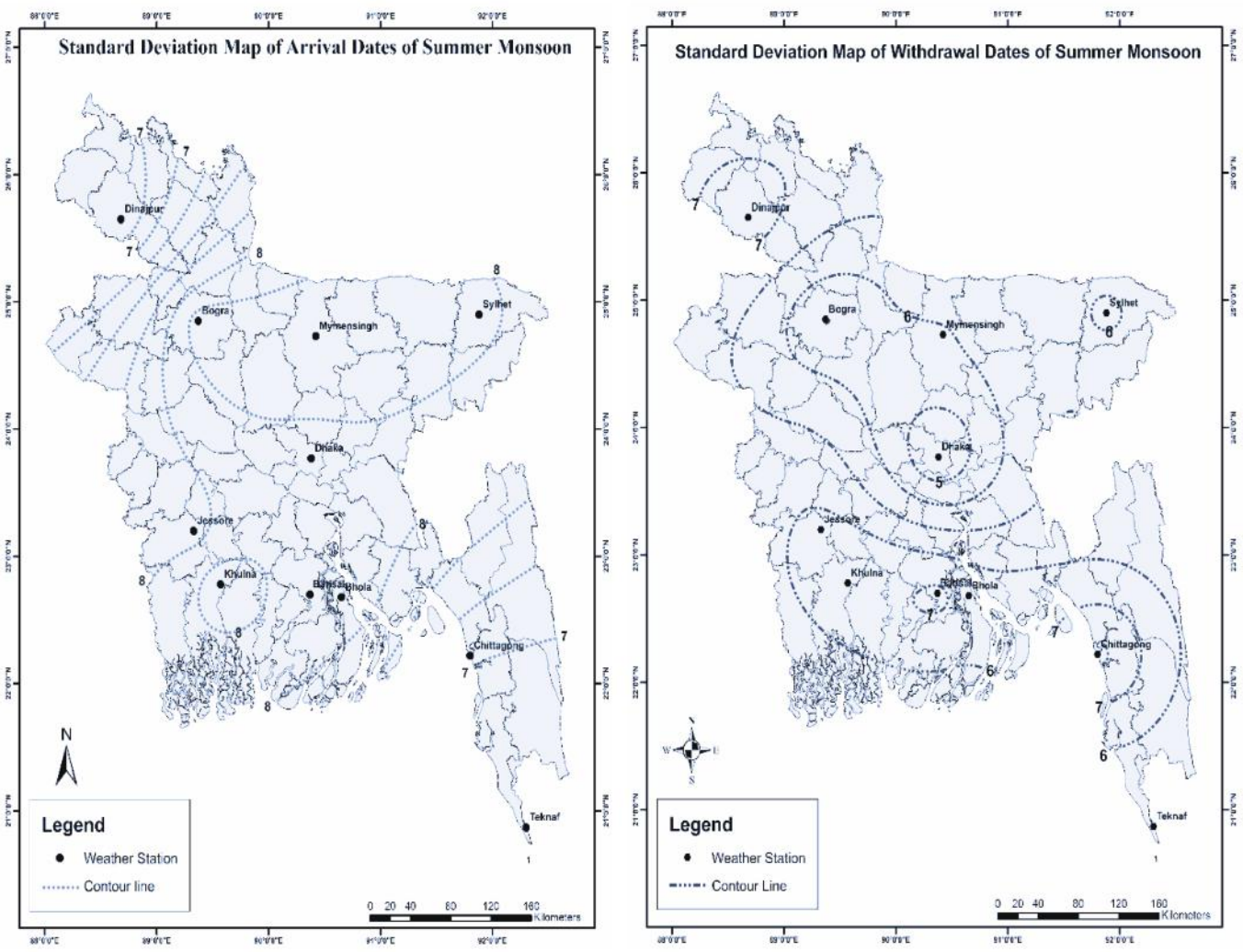

Figure 7: Analysis of Standard Deviations for Arrival and Withdrawal Dates for Southwest Monsoon over Bangladesh

Analysis of Simulations from Regcm

Anomaly Event - 1: Late Arrival of Monsoon in 2005

For the first anomaly case, we look into the arrival of the summer monsoon in 2005. On 22 June, precipitation occurs in Teknaf station, and day by day it spreads throughout its region. So, on June 22 monsoon theoretically reached the region of Teknaf. In Teknaf, rainfall was between 15 to 40 mm, and in the northeast of the country, it was more than 170 mm.

It is known that if rainfall occurs then relative humidity increases. In monsoon, rainfall is prominent. That means in monsoon relative humidity is very high. From the above images, it is noticeable that Relative Humidity is high, more than 90%, in Bangladesh.

According to Karmakar et al. (1993), the temperature goes down when the monsoon arrives. The above maps show the temperature of the study area, which is between 30 to 40°C.

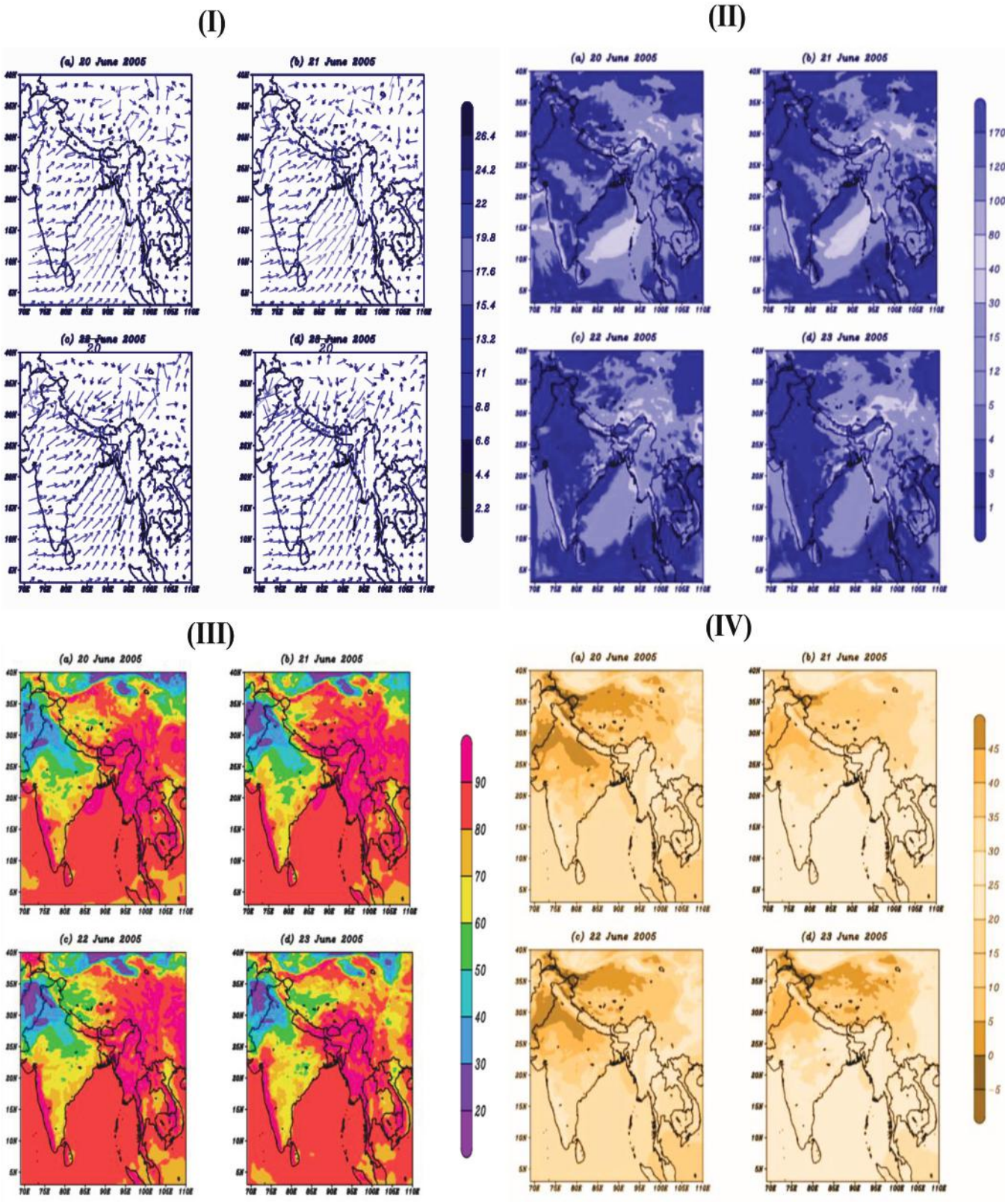

Figure 8: Analysis of (I) Wind Speed and Direction; (II) Precipitation; (III) Relative Humidity; and (IV) Temperature from 20th June to 23rd June of 2005

Anomaly Event - 2: Early Arrival of Monsoon in 1993

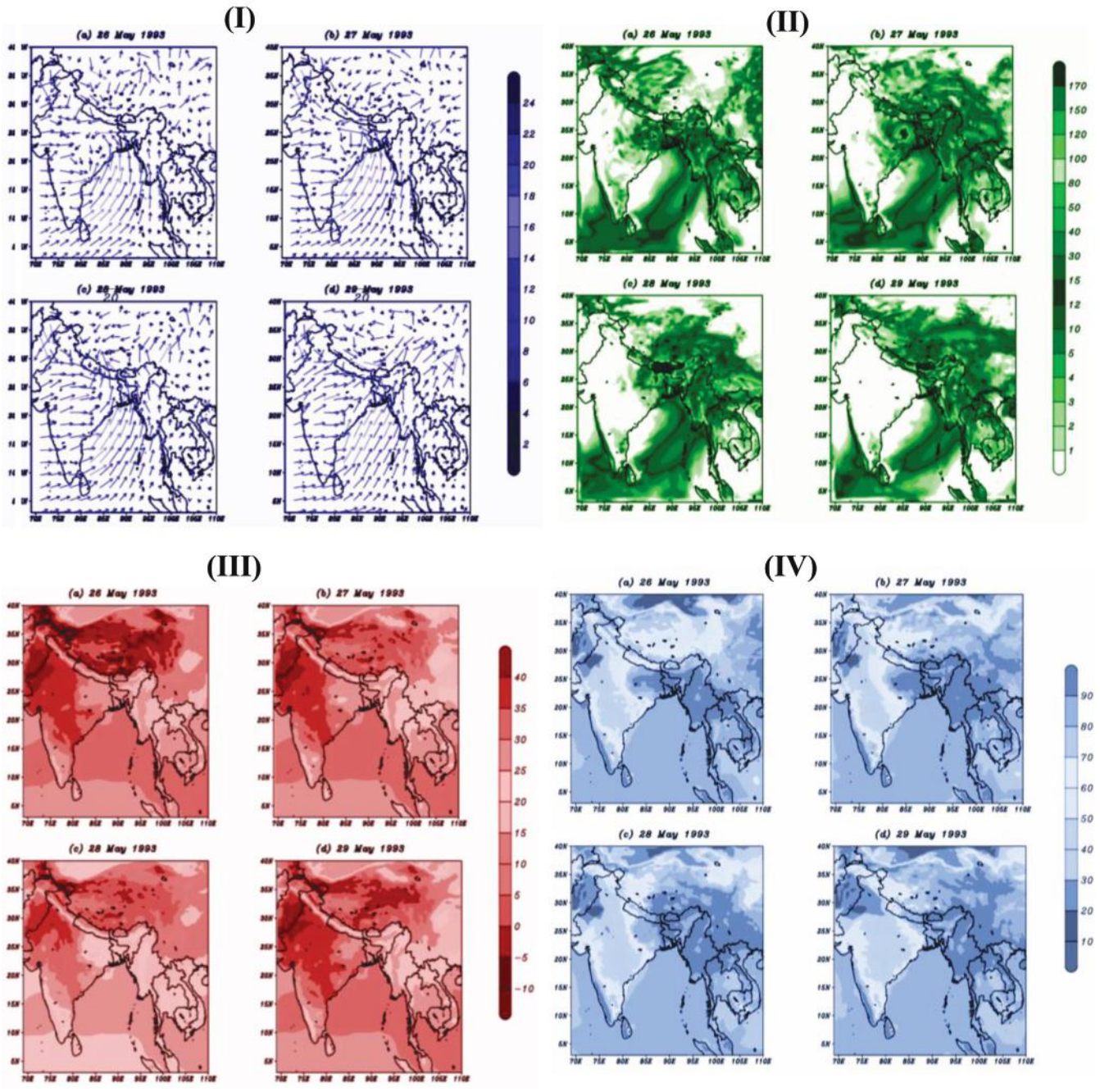

Figure 9: Analysis of (I) Wind Speed and Direction, (II) Precipitation, (III) Temperature, and (IV) Relative Humidity from 26th May to 29th May of 1993

Figure 9 (I) shows the wind direction and its magnitude. When monsoon arrives, wind direction must have a southerly component. It is either south-easterly or south-westerly. From the above maps, we find that there is a south-westerly direction of the wind. For India, it is blown from the southwest direction of the region of the Arabian Sea. And in Bangladesh, the direction of the wind is south-easterly. Also, wind speed remains high when the monsoon arrives in the region. The above maps show this also through a color bar.

In Figure 9 (II), it is shown that most of the precipitation occurs in the monsoon season and there is a remarkable difference before the onset of the monsoon and during the monsoon. On 28 May, rainfall occurs in Teknaf station and that spreads increasingly along with its region. Again, by 29 May, the monsoon has reached the region of Teknaf. In

Teknaf, rainfall was between 12 to 40 mm and it was more than 150 mm in the northeast of the country.

According to Karmakar et al. (1993), the temperature is low when the monsoon arrives. In Figure 10 (III), we see that the temperature went down when the monsoon arrived in the study region. The above maps show that the temperature of the study area is between 25 to 35°C**.**

Table 4: Comparison between Observed Data and RegCM Simulations

Station	Year	Observed Data	RegCM Simulation	Comparison
Teknaf	1993	29 May	29 May	Normal
	2005	23 June	22 June	Underestimating

CONCLUSIONS

From the observed data of BMD, the average arrival date is 10 June and the average withdrawal date is 20 October. The standard deviation values for both arrival and withdrawal dates of the summer monsoon in Bangladesh vary from 6 to 8 days in various parts of the country. The average duration of the summer monsoon in the country varies from 102 days in the extreme northwestern part to 132 days in the extreme southeastern. According to RegCM simulations, the arrival of monsoon for the years between 1993 and 2005 was 29th May and 22nd June respectively. And from our observed data, the arrival of summer monsoon for the years between 1993 and 2005 was 29th May and 23 June respectively. From the RegCM, we further analyzed two anomaly events (Table 4). The spatial comparison has been done for comparing BMD station data and RegCM simulations. For the comparison, the absolute location of the Teknaf station has been used. From the comparison, it has been found that the model underestimates the southeast corner of Bangladesh for a late arrival of the monsoon. But, for the early arrival of the summer monsoon in Teknaf station, RegCM performs similarly to the information given in the observed data.

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