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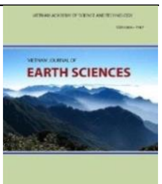

Seasonal variability in climate time series in Rajshahi division, Bangladesh

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ABSTRACT

This work has presented yearly dry and wet seasons in the analysis of 28 years daily recorded temperature, relative humidity and rainfall data from 1988 to 2015 in Rajshahi division, Bangladesh using Hilbert frequency analysis. Analysis has estimated the seasonal boundaries in time according to the instantaneous frequency in cycles/day and the estimations are verified with studying power spectrum of the time series. Two boundaries are obtained in each analysis over the average of yearly analysis of four years. Obtained seasonal boundaries on 16 March and 20 October are indicated as the differentiator of wet season comprises of pre-monsoon and rain in each year. Results have also shown that the length of the wet season is varying ±11days. Estimations have further justified with average rainfall distribution as shown in this work. It is even difficult to differentiate rainy season in rainfall data, however, the estimated wet season using Hilbert analysis well supported the rainy season over temperature and humidity. The presented analysis may assist further to learn more about the seasonal variability in climate dynamics.

Keywords: Hilbert transform; dry season; wet season; seasonal variability; fourier transform; seasonal boundary.

1. Introduction

Seasonal variability is likely to be a natural and continuous process. However, it is being evident that the anthropogenic activities are greatly influencing the climate variables as well as the variation in seasons. In this line, Bangladesh is being attributed as one of the most vulnerable countries to climate change for many years (Karim and Mimura, 2008; World Bank, 2010; Harmeling and Eckstein, 2012; Kreft et al., 2015). Drought, flood, storm, riverbank erosion, sea-level rise, etc. are the effects of climate change resulting in a decline in agricultural production each year (Ayers and Huq, 2008; World Bank, 2010).

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There are diverse threats in different regions, while, Rajshahi division in the northwestern part of Bangladesh is suffering severe to extreme drought and the area has immense contribution to the overall GDP of Bangladesh (Abdullah and Rahman, 2015). The climate in the Rajshahi division is dominated by tropical monsoons. It is categorized by high temperature, modest rainfall with often disproportionate humidity and equally marked seasonal variations (Rashid, 1997). The most striking feature of this climate is the reversal of the wind circulation between dry and wet seasons, which is an integral part of the circulation system of the Indian subcontinent. From the climatic point of view four distinct seasons are recognized in Bangladesh: the dry season from mid-December to February, the pre-monsoon summer from March to May, the wet season from June to August, post-monsoon September to November and winter or dry from December to February (Syed and Amin, 2016). However, the real-life observations speculated that the seasons and/or the seasonal lengths are varying. For instance, the area is largely dependent on rain-fed agriculture, while the rainfall pattern is abnormal and so far, creating devastating droughts. Therefore, it is essential to inspect the changes in rainfall patterns along with other climate variables with time and space. Hence, this research work intends to investigate the seasonal variability in the northwestern part of Bangladesh over climate time series data.

A number of investigations about climate change for the area have been contributed (Rashid, 1997; Ayers and Huq, 2008; Asib and Jakir, 2017). Rajshahi has been described as an area of extreme weather and showed in summer, the highest maximum temperature to be well above 40°C, whereas in winter the lowest minimum to be below 5°C. Ayers and Huq (2008) have reported the climate of Barind region that the mean annual rainfall of this region to be lower even below 2000 mm. The temperatures in this region have increased by about 1°C in May and 0.5°C in November between 1985 and 1998. It is also speculated that maximum temperature has been increased dramatically over the last 40 years period, while the highest temperature of 44°C was recorded at Bogura and Ishwardi in April 1956 and May 1970 respectively, the lowest temperature of 3.2°C was recorded at Rajshahi in January 2003 and the maximum rate of decrease in rainfall at Ishwardi -0.455 mm/year (Asib and Jakir, 2017). The climate dynamics of the region are getting more attention. Therefore, this work likes to investigate the climate of the area with Hilbert analysis as the technique can estimate the different properties of time series as instantaneous amplitude, phase and frequency.

In the wide diversity of applications, the Hilbert analysis may play an important role to study climate change. The technique is found employed to investigate atmospheric data like rainfall, temperature, relative humidity, pressure, etc. to observe the climate variability (Xie et al., 2002; Salisbury and Wimbush, 2002; Pan et al., 2003; Wu et al., 2005;). Iyengar and Kanth (2005, 2006) used in predictions for the seasonal monsoon in India. Hence, this work intends to study the useful application of Hilbert transformation along with Fourier transformation over climate to estimate the seasonal variability in Rajshahi, Bangladesh.

2. Data and Methods

2.1. Data

Daily minimum temperature, maximum temperature, humidity, and rainfall data, recorded at three stations named Rajshahi, Bogura, and Ishwardi under Rajshahi division for a period of 28 years from January 1988 to December 2015, have obtained from the Bangladesh Meteorological Department (BMD). The area is mostly Barind region located in the northwestern part of Bangladesh as shown in Fig. 1. This study region is surrounded by Jamuna River in the east and Padma River in the south.

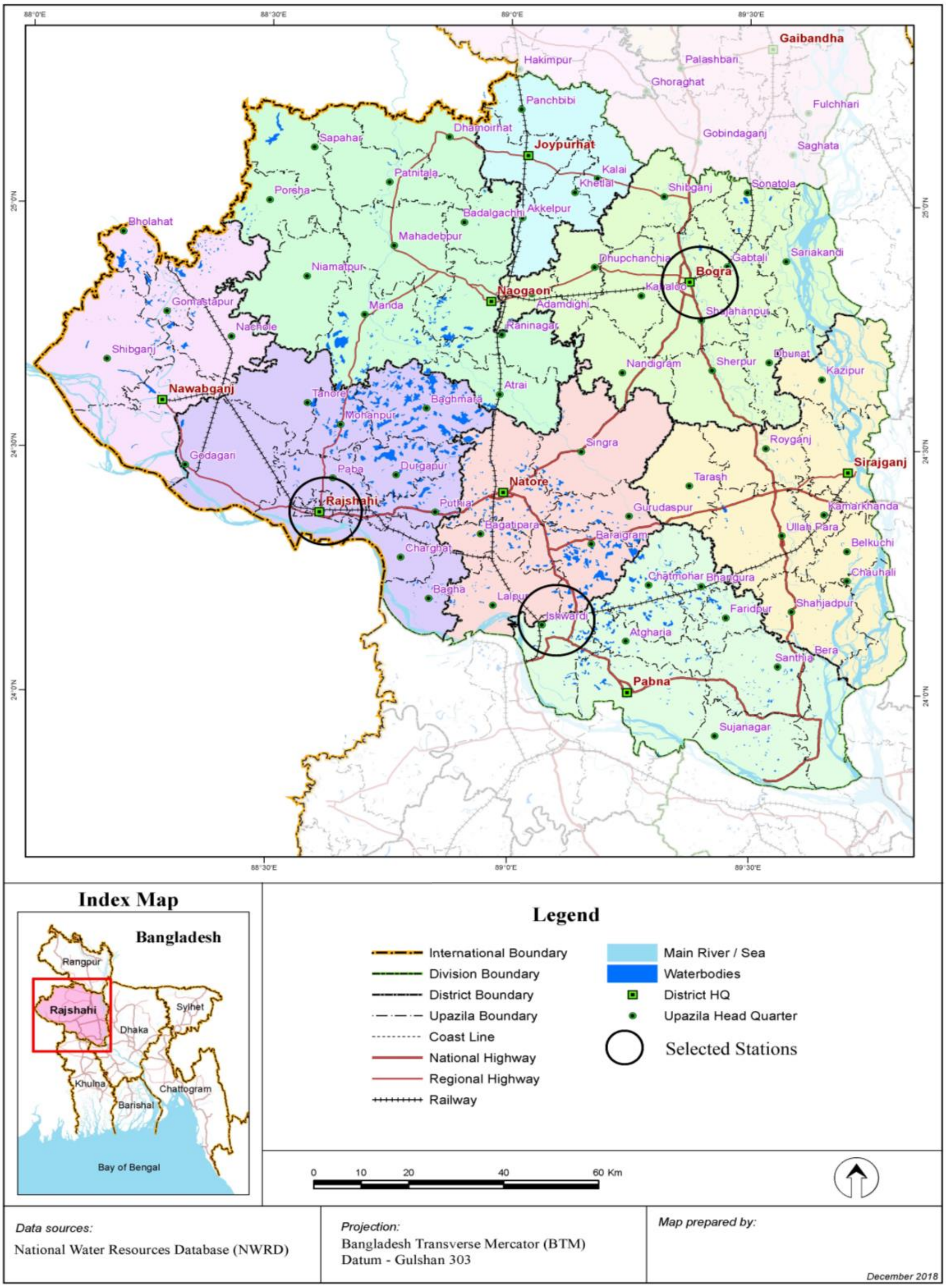

Figure 1. Map of the Study Area Rajshahi division in Bangladesh

2.2. Methods

2.2.1. Hilbert Frequency Analysis

Hilbert transform, basically a spectral technique for the analysis of periodic signals can be used to realize synoptic and climatic features. The technique can estimate instantaneous amplitude, phase, period or frequency of a function of time that is useful to locate significant events in the original data (Duffy, 2004). The Hilbert Transform of a time function x(t) can be written as (Toodoran et al., 2008):

$$\hat{x}(t)=H\{x(t)\}=\frac{1}{\pi}v.p.\int_{-\infty}^{\infty}\frac{x(\tau)}{t-\tau}d\tau \qquad (1)$$

Using $\hat{x}(t)$ complex analytic signal $z(t)$ build as:

$$z(t)=x(t)+j\hat{x}(t) \qquad (2)$$

Further relations can be deduced as:

$$a(t)=|z|=\sqrt{x^2(t)+\hat{x}^2(t)},$$

$$\varphi(t)=\arctan\frac{\hat{x}(t)}{x(t)},$$

$$\text{and } \omega(t)=\frac{d\varphi(t)}{dt}=\varphi'(t) \qquad (3)$$

2.2.2. Power spectrum

Fourier transform is a mathematical tool through which any waveform can be decomposed into individual component sine waves at different frequencies and amplitudes. Individual components can be represented by peaks in a frequency spectrum, the process is known to be spectral analysis or power spectrum. The power spectrum can be estimated using the Fourier transform of a time function *x(t)* can be written below.

$$X(\omega)=\int_{-\propto}^{\propto}x(t)e^{-i\omega t}dt, \qquad x(t)=\frac{1}{2\pi}\int_{-\propto}^{\propto}X(\omega)e^{-i\omega t}d\omega \text{ and } PS(f)=|X(f)|^2 \quad (4)$$

3. Example: hilbert analysis of climate time series

In this section, Hilbert transform was applied over synthetic daily climate time series constructed using the Equations 5-12 of known amplitude and frequency are given below for a defined time span to show how well this approach can identify the changes of amplitude and frequency with time. Figure 2a shows the known or synthetic daily minimum temperature climate time series, where, the function of time and frequency is as defined below.

$$y=y_1+y_2+y_3+y_4+y_5+y_6 \qquad (5)$$

$$y_1=b+a\sin(2\pi f_1 t) \text{ for } 0<t\le 60 \qquad (6)$$

$$y_2=b \text{ for } 60<t\le 90 \qquad (7)$$

$$y_3=b+a\left[\sin(2\pi f_1 t)+\sin(2\pi f_2 t)\right] \text{ for } 90<t\le 150 \qquad (8)$$

$$y_4=b+a\left[\sin(2\pi f_1 t)+\sin(2\pi f_2 t)+\sin(2\pi f_3 t)\right] \text{ for } 150<t\le 210 \qquad (9)$$

$$y_5=b+a\sin(2\pi f_2 t) \text{ for } 210<t\le 270 \qquad (10)$$

$$y_6=b+a\sin(2\pi f_4 t) \text{ for } 270<t\le 366 \qquad (11)$$

$$y_t=c\sin(2\pi f_5 t)+y \qquad (12)$$

where,

$a=2, b=10, c=25$

$f_1=0.1 cycles/day, f_2=0.2 cycles/day,$

$f_3=0.4 cycles/day, \ f_4=0.04 cycles/day$

and $f_5=0.0014 cycles/day$

Figure 2(b) shows the spectral analysis using Fourier transformation (Equation 4) where four highest peaks at frequencies 0.2 cycles/day, 0.4 cycles/day, 0.1 cycles/day and 0.04 cycles/day respectively are obtained. The frequencies are similar to the synthetic time series as shown in Fig. 2a, c shows the instantaneous frequency with time using Hilbert analysis (Equations 1-3) where the defined frequencies at different time spans are also visualized. Resulted frequency f = 0.02 cycles/day within time, 0<t<=60 days is similar to the first proportion of the Fig.2a. The 2nd proportion of Fig.2c started with the frequency, f = 0 cycles/day within the time, 60<t<=90 days is also similar to the 2nd proportion of the Fig.2a. The 3rd proportion of Fig.2c where the frequency limits from 0.04 cycles/day to 0.1 cycles/day within the time 90<t<=150 days are showing similarity with the 3rd proportion of Fig.2a. In the 4th proportion of Fig.2c, the frequency, f = 0.17 cycles/day to 0.24 cycles/day within the time 150<t<=210 days are also likely to the 4th proportion of Fig.2a. Fifth proportion of the Fig.2c started with the frequency 0.08 cycles/day and lowered up to 0.025 cycles/day within the time period 210<t<=270 days and the last proportion of Fig.2c obtained frequency less than 0.02 cycles/day within time 270<t<=366 days are quite similar to the last proportion of Fig.2a. Figure 2b shows the spectral analysis and providing the same characteristics of the same time series as peaks appeared at frequencies 0.0014, 0.04, 0.1, 0.2 and 0.4 cycles/day.

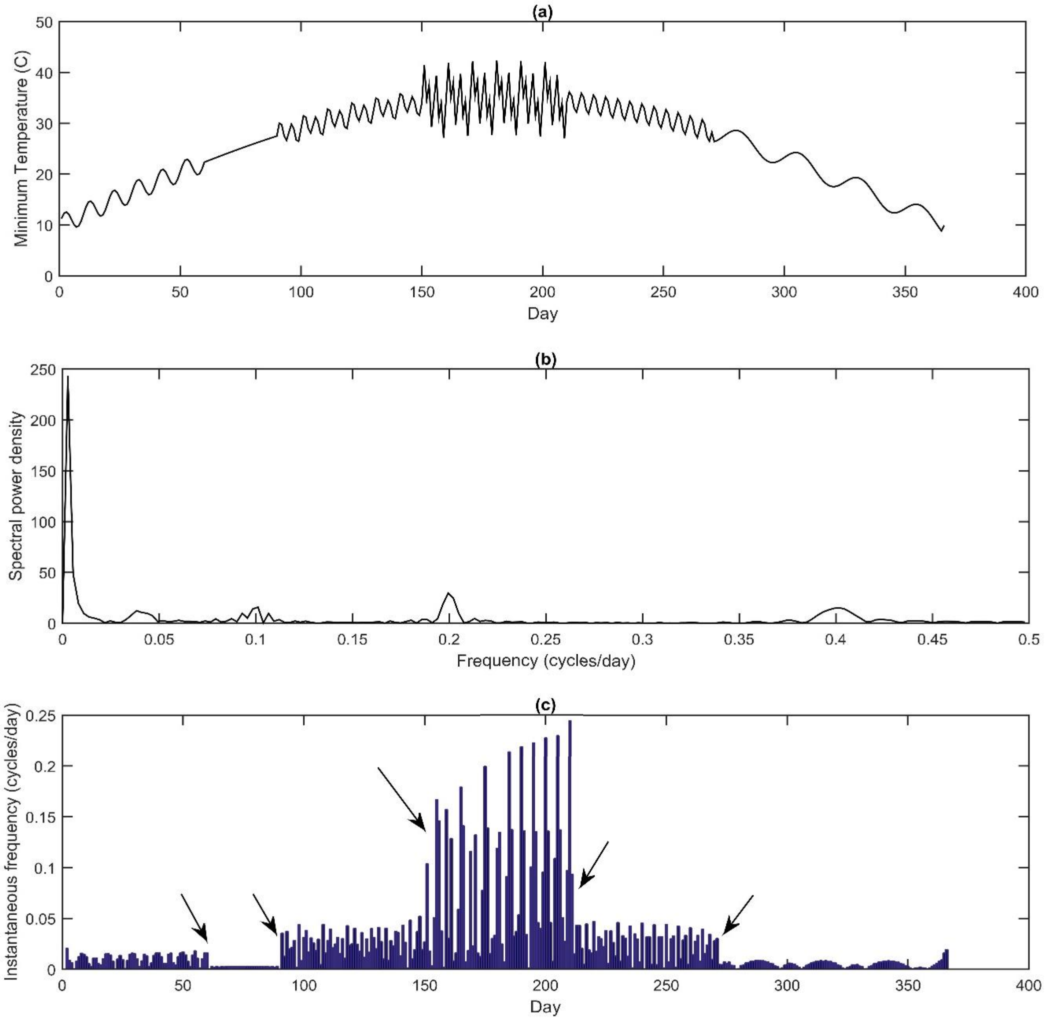

Figure 2. Hilbert frequency analysis of example time series, (a) synthetic daily minimum temperature, (b) spectral analyis of the synthetic daily minimum temperature and (c) instantaneous frequency analysis of the synthetic daily minimum temperature

Hilbert transform produces better spectral analysis as frequency can be learned at any time in the time series. But there are some limitations also, in the analyzed result done by

Hilbert Transform of Fig.2c it has observed that the frequencies are varying with times (3rd proportion of Fig.2c) and year to year analyses may mislead to estimate the expected frequency. That's why real data analyses are to be averaged of successive four years for better frequency estimations. The philosophy behind averaging is that a similar frequency at a particular time would greatly increase while dissimilar would not.

4. Results and Discussions

Climate data used for the analysis exhibits few missing values. This is very common in the climate data portal. Missing values observed are 276 (0.79%) days in minimum temperature, 321 (0.92%) days in maximum temperature, 35 (0.10%) days in humidity and 02 (0.01%) days in rainfall of total 3 × 11688 days data of each. There are many techniques to approximate the missing values but each technique has its advantages and disadvantages according to its purposes. Missing values are derived in this work using a cubic spline interpolation technique. Any suitable other technique may also be employed to fill up the gaps but it is believed that the cubic spline interpolation technique can lead to making small errors (North and Livingstone, 2013; Barsky et al., 1998). After filling up all missing values and as shown time-frequency analysis using Hilbert transform in example time series, the temperature, atmospheric pressure, humidity and rainfall daily data of Rajshahi division for three stations of 28 years from 1988 to 2015 are analyzed. Time-frequency analysis are then averaged for successive four years. It is believed that the higher values of average frequencies at a particular time would indicate the seasonal boundaries in the year and consistent for the four years. Four years based average time-frequency analysis of minimum and maximum temperature, humidity, and rainfall for each station data are investigated. Fig.s 3-5 show the four years based average time-frequency analyses from 1988 to 1991. Higher values of instantaneous frequencies are then identified as the boundary of the seasons in the year. Four years-based boundaries in the year are then tabulated as shown in Tables 1-3.

It was expected to be determined by all the seasonal boundaries in the year. However, all seasonal boundaries in the year in time-frequency analysis are required more careful calibration and appeared to be difficult to identify all the seasonal boundaries. But two seasonal boundaries according to the higher values of instantaneous frequencies are well determined as shown in Figures 3-5 and Tables 1-3.

Two seasonal boundaries marked as B1 and B2 as the number of days are determined using time-frequency analysis over minimum and maximum temperature, humidity, and rainfall as shown in Figures 3-5 and the results are shown in Tables 1-3. The first boundary B1 for Rajshahi station (Table 1) is attained from 64th to 77th day in minimum temperature, 77th to 81st day in maximum temperature, 65th to 87th day in humidity and 73rd to 82nd day in rainfall. While, the second boundary B2 is obtained 283rd to 297th day in minimum temperature, 292nd to 298th day in maximum temperature, 292nd to 299th day in relative humidity and 290th to 301st day in rainfall. While estimated boundaries are examined with the temperature and humidity data, it has realized that estimated boundaries are the similar boundaries of the rainfall data to be discussed more on later in this section and eventually, the duration in between boundaries is actually the monsoon period or rainy season.

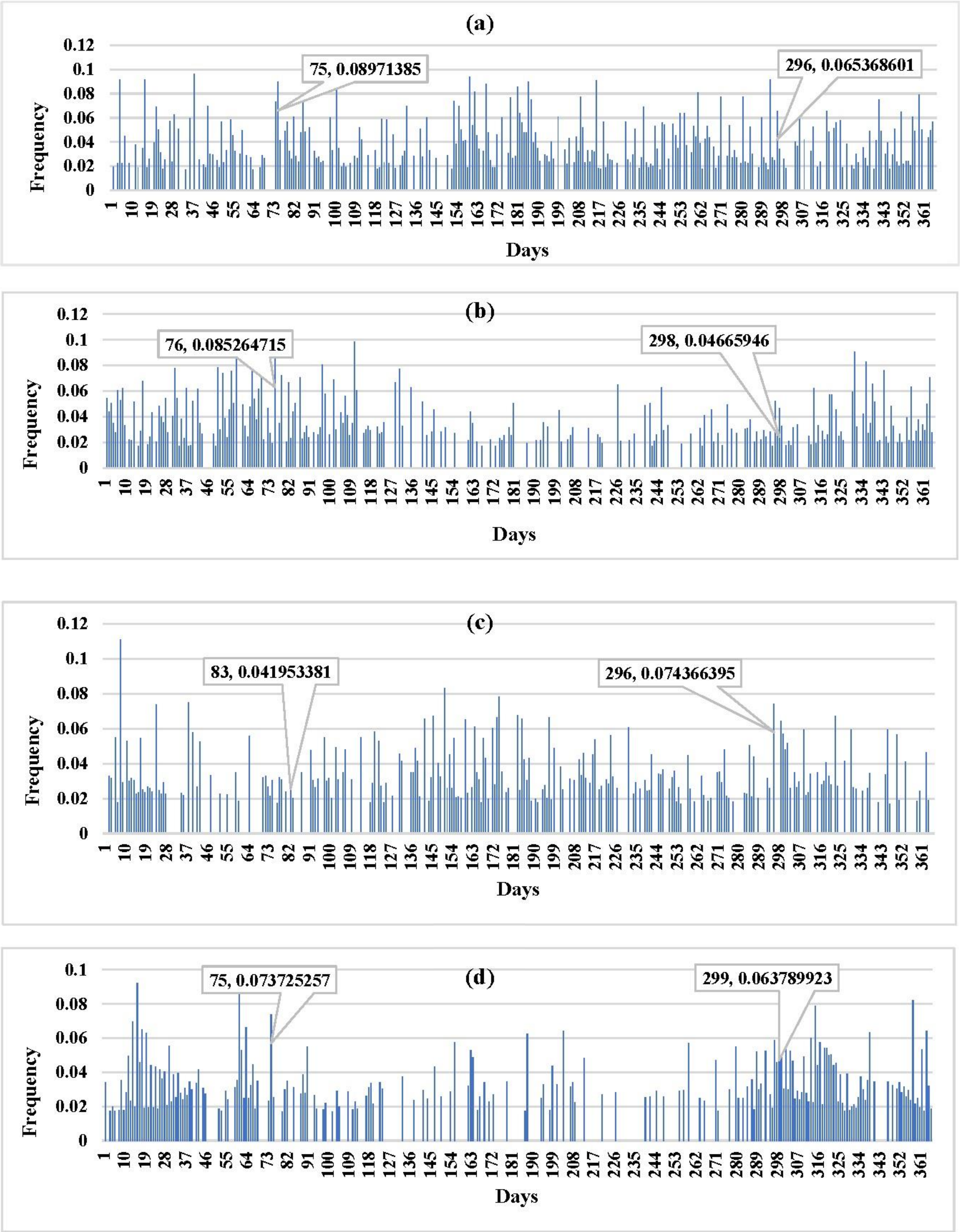

Figure 3. Average of yearly instantaneous frequency analysis of climate data from1988 to 1991 recorded at Rajshahi station for a) minimum temperature, b) maximum temperature, c) relative humidity and d) rainfall

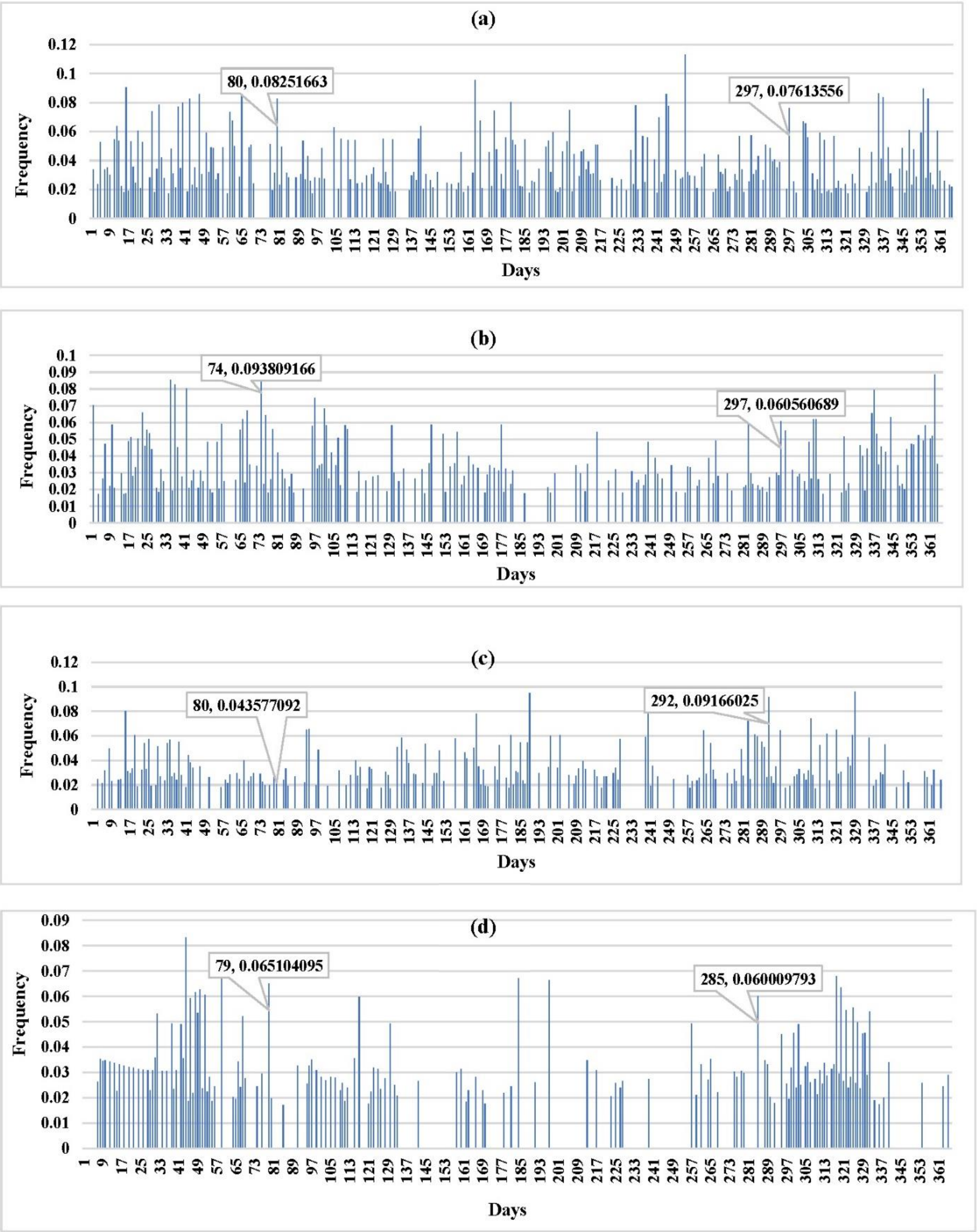

Figure 4. Average of yearly instantaneous frequency analysis of climate data from1988 to 1991 recorded at Ishwardi station for a) minimum temperature, b) maximum temperature, c) relative humidity and d) rainfall

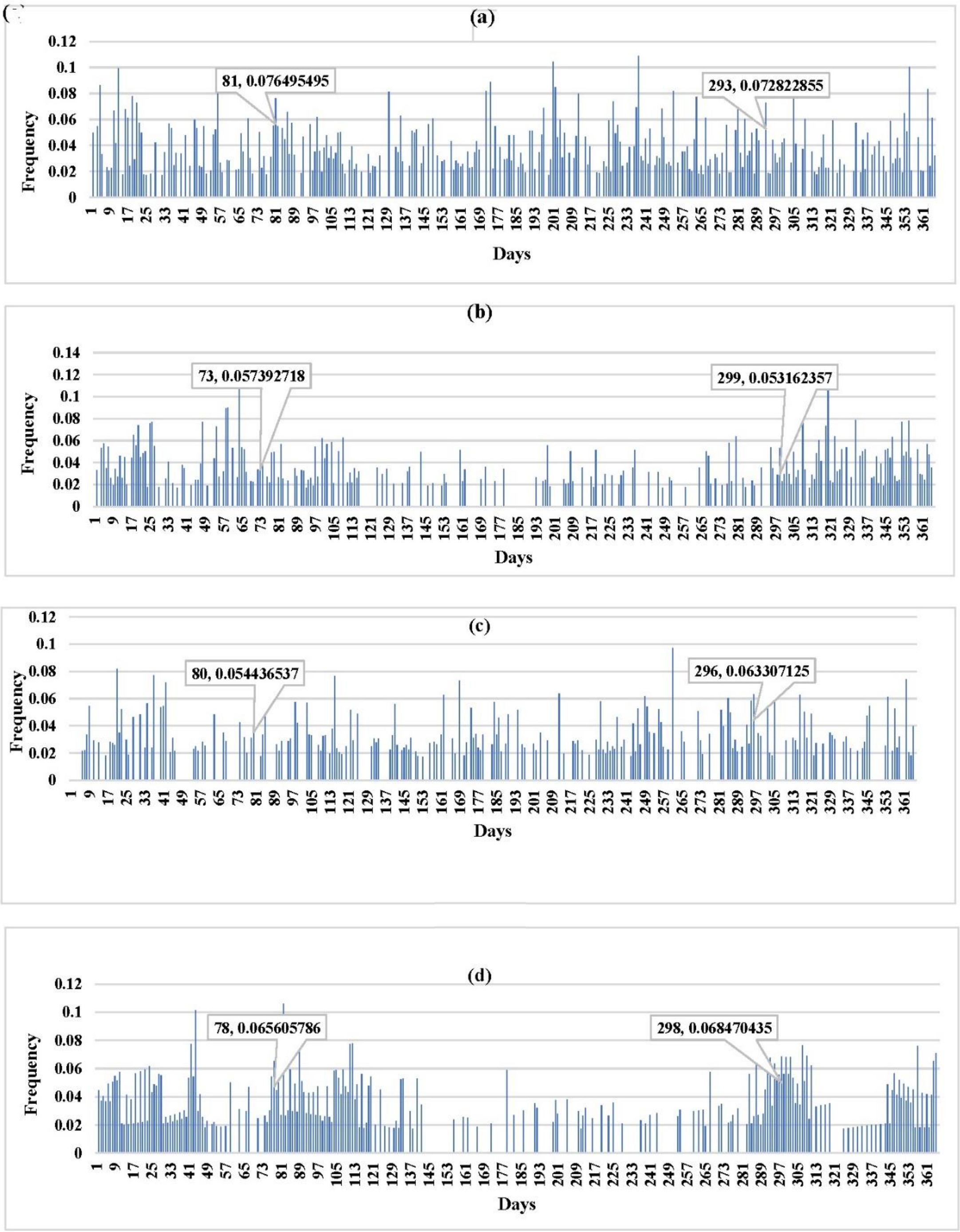

Figure 5. Average of yearly instantaneous frequency analysis of climate data from1988 to 1991 recorded at Bogura station for a) minimum temperature, b) maximum temperature, c) relative humidity and d) rainfall

Table 1. Estimated boundaries in climate time series recorded at Rajshahi

Year		Min Temperature				Max Temperature				Relative Humidity				Rainfall			
From	To	B1	C.Frq	B2	C.Frq	B1	C.Frq	B2	C.Frq	B1	C.Frq	B2	C.Frq	B1	C.Frq	B2	C.Frq
1988	1991	75	0.08971	293	0.09170	79	0.07204	298	0.04665	65	0.05578	296	0.07436	75	0.07370	299	0.06378
1992	1995	69	0.11352	297	0.08134	80	0.08376	292	0.10795	78	0.06193	288	0.05785	78	0.07227	301	0.08370
1996	1999	75	0.07893	296	0.07078	77	0.04953	287	0.09385	71	0.07896	292	0.05698	73	0.06700	299	0.06069
2000	2003	77	0.09056	297	0.07162	81	0.06958	297	0.10594	78	0.03366	297	0.07934	78	0.05240	301	0.05139
2004	2007	70	0.10906	291	0.08273	79	0.07198	292	0.09105	87	0.07742	299	0.05665	75	0.04269	301	0.10549
2008	2011	64	0.12257	283	0.10224	80	0.05378	298	0.07957	81	0.07960	296	0.08672	75	0.07520	294	0.08806
2012	2015	68	0.09378	296	0.08871	78	0.08473	297	0.09214	71	0.10732	291	0.05698	82	0.05010	290	0.06565

B- indicates Boundary on the day of year, C.Frq stands for Corresponding Frequency cycles/day

Table 2. Estimated boundaries in climate time series recorded at Ishwardi

Year		Min Temperature				Max Temperature				Relative Humidity				Rainfall			
From	To	B1	C.Frq	B2	C.Frq	B1	C.Frq	B2	C.Frq	B1	C.Frq	B2	C.Frq	B1	C.Frq	B2	C.Frq
1988	1991	80	0.08251	297	0.07614	74	0.09381	297	0.06056	80	0.04357	292	0.09166	79	0.06510	285	0.06010
1992	1995	74	0.05125	301	0.10097	78	0.07474	296	0.07724	67	0.05087	299	0.06933	78	0.06790	298	0.05988
1996	1999	64	0.08591	302	0.09801	76	0.11649	298	0.06574	70	0.09186	299	0.06752	76	0.05470	284	0.06379
2000	2003	84	0.10992	307	0.07499	82	0.09318	288	0.08379	77	0.05028	293	0.06986	81	0.04821	294	0.04762
2004	2007	83	0.08102	291	0.08361	79	0.04416	288	0.09720	68	0.06177	295	0.05819	80	0.04772	296	0.06623
2008	2011	81	0.10496	301	0.09390	73	0.08171	292	0.05981	75	0.05964	299	0.06231	83	0.07475	284	0.05764
2012	2015	77	0.07584	300	0.09218	83	0.08965	296	0.05571	68	0.08566	299	0.03081	70	0.07422	297	0.06322

B- indicates Boundary on the day of year, C.Frq stands for Corresponding Frequency cycles/day

Table 3. Estimated boundaries in climate time series recorded at Bogura

Year		Min Temperature				Max Temperature				Relative Humidity				Rainfall			
From	To	B1	C.Frq	B2	C.Frq	B1	C.Frq	B2	C.Frq	B1	C.Frq	B2	C.Frq	B1	C.Frq	B2	C.Frq
1988	1991	81	0.07649	293	0.07282	64	0.11526	309	0.11848	80	0.05443	305	0.07899	82	0.10609	298	0.06847
1992	1995	71	0.10054	298	0.08597	65	0.09229	310	0.08491	70	0.06781	289	0.05651	60	0.09453	304	0.06881
1996	1999	78	0.10295	288	0.08467	65	0.11377	307	0.06375	75	0.05772	293	0.08540	79	0.05993	300	0.09911
2000	2003	73	0.07820	298	0.06288	67	0.08145	309	0.06545	68	0.07705	295	0.07088	68	0.06700	305	0.05750
2004	2007	80	0.06534	288	0.08265	78	0.05314	306	0.08887	66	0.05448	297	0.04871	76	0.06540	297	0.08020
2008	2011	77	0.12005	298	0.05522	79	0.07684	292	0.05981	80	0.05008	299	0.06384	82	0.09900	291	0.06790
2012	2015	73	0.07810	300	0.06265	77	0.08373	297	0.08831	77	0.05870	293	0.05529	78	0.08340	293	0.07870

B- indicates Boundary on the day of year, C.Frq stands for Corresponding Frequency cycles/day

Boundaries are estimated for Ishwardi station as shown in Table 2 as the first boundary B1 is accredited from 64th to 84th day in minimum temperature, 73rd to 83rd day in maximum temperature, 67th to 80th day in relative humidity and 70th to 83rd day in rainfall. While second boundary B2 is obtained in between 291st to 307th day in minimum temperature, 288th to 298th day in maximum temperature, 288th to 299th day in humidity and 284th to 298th day in rainfall.

Table 3 shows the estimated boundaries for Bogura station respectively the first boundary B1 in between 71st to 81st day, 64th to 79th day, 66th to 80th day, 60th to 82nd day and second boundary B2 in between 288th to 300th day, 292nd to 310th day, 289th to 305th day, 291st to 305th day, in minimum temperature, maximum temperature, relative humidity and in rainfall.

Results show that the useful application of Hilbert frequency analysis is capable to estimate the seasonal boundaries as estimated rainy season over temperature and humidity climate time series. A detail dry and wet season according to rainfall data for 28 years for Rajshahi, Ishwardi and Bogura stations are estimated using the difference in intensity of rainfall of successive days less than the standard deviation, approximately 12.00 mm of the total length. The estimated rainy seasons for the different stations are shown in Fig. 6. These seasonal boundaries are well agreed with boundaries estimated in temperature and humidity along with the rainy seasonal boundaries shown in few contributions (Shahid, 2010; Rakib, 2013; Syed and Amin, 2016).

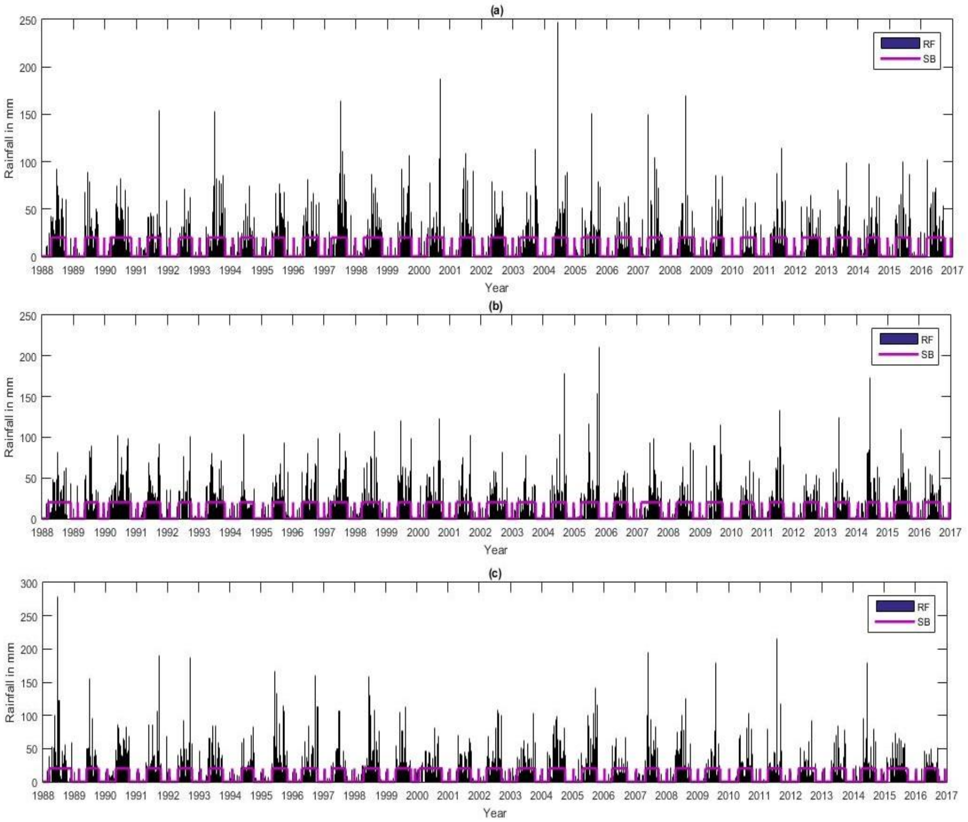

Figure 6. Estimated seasons in the year according to daily rainfall distribution over 30 years rainfall data from 1988 to 2017 for a) Rajshahi, b) Ishwardi and c) Bogura

An overall wet season along with boundaries in minimum and maximum temperature, humidity, and rainfall for each station is approximated using Hilbert analysis as shown in Table 4. Seasonal variations with time for different stations are shown in Figs.7(a-c). It has revealed that rainy seasons along with the seasonal boundaries with time for all stations remain almost the same. This work has realized that the only 28 years of climate data are not adequate to see the changes in seasonal variabilities.

Table 4. Summary of rainy seasons with boundaries in different stations

From	To		Tmax	Tmin	Rain Fall	Rel Hum.	Day Avg.	Tmax	Tmin	Rain Fall	Rel Hum.	Day Avg.	Duration
1988	1991	Rajshahi	75	79	75	65	74	293	298	299	296	297	223
1992	1995		69	80	78	78	76	297	292	301	288	295	218
1996	1999		75	77	73	71	74	296	287	299	292	294	220
2000	2003		77	81	78	78	79	297	297	301	297	298	220
2004	2007		70	79	75	87	78	291	292	301	299	296	218
2008	2011		64	80	75	81	75	283	298	294	296	293	218
2012	2015		68	78	82	71	75	296	297	290	291	294	219

From	To		Tmax	Tmin	Rain Fall	Rel Hum.	Day Avg.	Tmax	Tmin	Rain Fall	Rel Hum.	Day Avg.	Duration
1988	1991	Bogura	81	64	82	80	77	293	309	298	305	301	225
1992	1995		71	65	60	70	67	298	310	304	289	300	234
1996	1999		78	65	79	75	74	288	307	300	293	297	223
2000	2003		73	67	68	68	69	298	309	305	295	302	233
2004	2007		80	78	76	66	75	288	306	297	297	297	222
2008	2011		77	79	82	80	80	298	292	291	299	295	216
2012	2015		73	77	78	77	76	300	297	293	293	296	220
1988	1991	Ishwardi	80	74	79	80	78	297	297	285	292	293	215
1992	1995		74	78	78	67	74	301	296	298	299	299	224
1996	1999		64	76	76	70	72	302	298	284	299	296	224
2000	2003		84	82	81	77	81	307	288	294	293	296	215
2004	2007		83	79	80	68	78	291	288	296	295	293	215
2008	2011		81	73	83	75	78	301	292	284	299	294	216
2012	2015		77	83	70	68	75	300	296	297	299	298	224

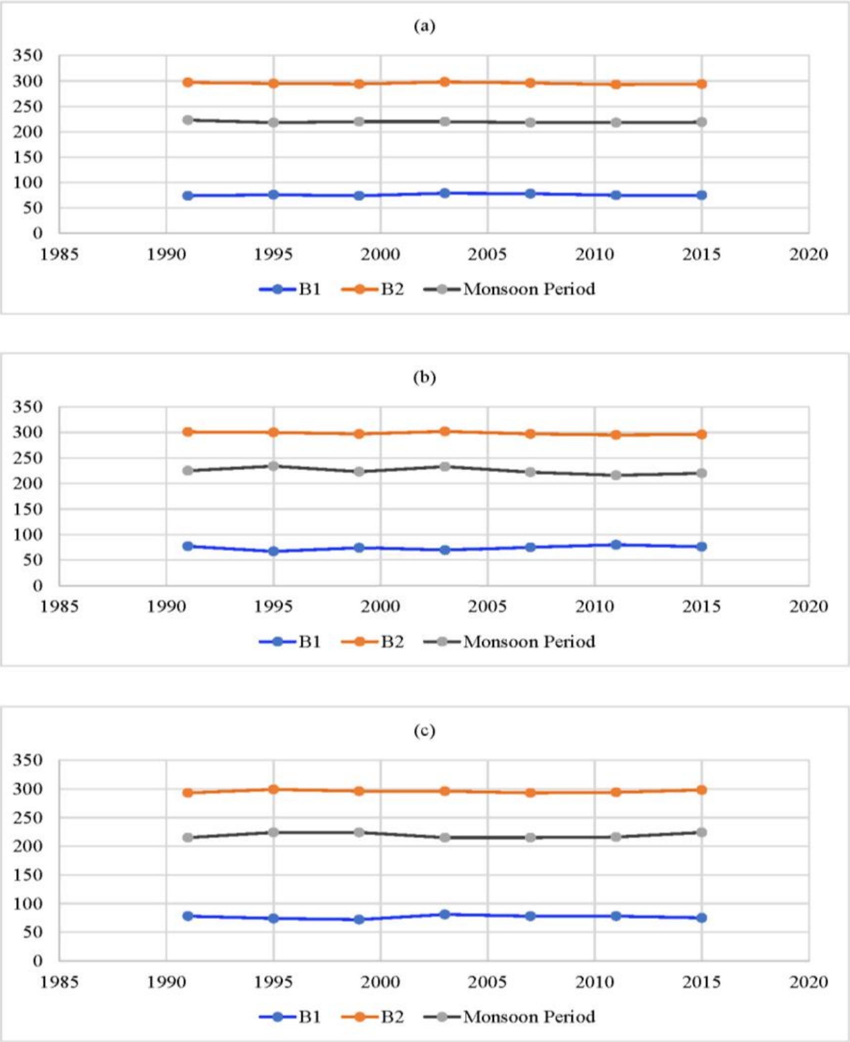

Figure 7. Seasonal boundaries and duration with time in year for a) Rajshahi station, b) Bogura station and c) Ishwardi station

5. Conclusions

Seasonal variability is a common focus all over the world to understand the climate as well as the weather of a region and it has many direct impacts over economic growth. This work has identified two seasonal boundaries of the wet season in the years in daily climate time series from 1988 to 2015 for Rajshahi division, Bangladesh using the time-frequency analysis with Hilbert transformation. The idea may assist further to asses earlier to forecast hot or cold wave in the region. Though identified using an average of four successive years, it was difficult to calibrate the instantaneous frequency with the season or seasonal boundary in the climate time series. It has realized that the work needs an additional technique further to accomplish better calibration. In the analyses, second and third with first-year analysis were not adequate to define the seasonal boundary. However, the average of four successive years produced the two boundaries according to higher values of instantaneous frequency in the daily data of a year. However, the analysis is little advantageous as leap year day comes to the analysis and shown to be a more practical seasonal boundary. In addition, the work suffers to identify other seasonal boundaries such as spring, autumn and/or the divisions in summer and rain. Instead of limitations, the time-frequency analysis in daily climate data has determined wet seasons of the Rajshahi region that start on 76th day (16 March) varying from 64th to 87th day and end with 295th day (20 October) varying from 283rd to 301st day with an average wet seasonal length of 219 days. It has not found significant variation in the estimated wet season in climate data analysis for three different stations. The average duration of the monsoon is highest in Bogura (≈ 234 days) in the year 1992-1995 and lowest in Ishwardi (≈ 215 days) in the year 1988-1991. The analyses have well agreed with the rainfall data of the region. Analyzed seasonal variability may assist further to delineate precise seasonal boundaries for the whole country and to take measures to utilize natural climate for better productions particularly in agriculture.

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