Weather variability and rainfall pattern of *Sidr*, the post-monsoon cyclonic storm of 15 November 2007 in the Meghalaya Plateau, India

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Atmospheric depressions sometimes initiate tropical cyclones in the pre- and post-monsoon season in the Bay of Bengal, which move to land and create havoc. Their intensity and pattern vary individually. After hourly monitoring of the weather parameters of cyclone *Sidr* of 15 November 2007 which created severe disaster and weather variability in the Bangladesh plains and hills of Meghalaya Plateau, India a noticeable depression of cool air masses in the starting phase of the cyclone was found, which created the atmospheric disturbance for a shorter time. As a result, the psychrometric index fell slightly with significantly higher thermal efficiency values in the starting phase of cyclone, thus inviting speedy wind with heavy rains in its last phase. The pattern of cyclonic rainfall is highly influenced by southerly (Northward) speedy winds, especially on the windward areas of the cyclone. Two-peaked pattern of diurnal rainfall was observed at Cherrapunji and its surroundings, which was the active path of *Sidr* on the windward slopes of the Plateau. On the other hand, leeward areas of the Plateau experienced one-peaked pattern of diurnal rainfall with lower intensity.

Keywords: Atmospheric depression, cyclonic storm, psychrometric index, rainfall intensity.

IT is difficult to establish parametric relationships of the world's great weather system extending from the Tibetan Plateau to the south Indian Ocean at local or even regional scale[1–5]. Sadhuram and Murthy[6] established the relationship between sea-surface temperature (SST) and summer rainfall in order to arrive at a particular conclusion for the assessment of damages, prediction and forecasting of tropical cyclones. Thermodynamic aspects were also used to differentiate the tropical cyclones[7]. Cyclonic disturbances are largely dependent on two parameters: SST and wind fields that contribute towards thermal and dynamic potential for the growth and intensity of tropical cyclones[8]. However, analysis of cyclones based on the annual frequencies is associated with the Southern Oscillation Index for stochastic prediction, which is also helpful in understanding their trend – surface nature of the movement and intensity of the cyclones[9,10]. Therefore, severity and duration of cyclones based on relationship of cyclonic days with maximum SST is the main aspect for analysis of the nature and movement of tropical cyclones[8].

Atmospheric circulation over South Asia is a dynamic phenomenon controlled by the vertical air motion[3,7]; however at local scale, steep gradients of atmospheric pressure create cyclonic conditions over the ocean surface[11]. On 12 November 2007, a tropical cyclone (*Sidr*) with wind speed of 60–90 km/h was observed over the Andaman and Nicobar Islands, which moved towards coastal areas of Orissa and West Bengal. It intensified in the next few days with wind speed of about 120–140 km/h, i.e. on the 13 and 14 November 2007. The cyclone moved towards Bangladesh with a wind speed of 235 km/h on 15th night resulting in 5 m tidal waves in the southernmost part of Bangladesh. More than 4000 persons died, as has been estimated by Bangladesh Disaster Management Bureau, Ministry of Food and Disaster Management, Dhaka. Several parts of National Highway 40 in India were damaged between Shillong and Silchar[12]. It was so severe that its vertical depth was about 8–10 km and horizontal extent around 400–700 km. In the next two days, i.e. the 15 and 16 November 2007, maximum wind speed at the centre of the cyclone was about 235 km/h (Figure 1). This cyclone was associated with heavy rains in Bangladesh and its surrounding hill areas including Cherrapunji, Pynursla, Amlarem, Jowai, Thangkarang (windward side) as well as Nongpoh and Byrnihat (leeward side) of the Meghalaya Plateau, India.

In order to understand the characteristic features of *Sidr*, the features of weather variability and diurnal rain-

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fall pattern of cyclonic days have been analysed. Diurnal rainfall pattern has been analysed using the hypothesis of nocturnal jet and its effects on diurnal rainfall, which has been used by Prasad[13] for rainfall variation in India and by Terao *et al.*[14] for the northeastern part of Bangladesh. In the present study, psychrometric index and thermal efficiency coefficient (Appendix 1) were used to analyse the results of weather variability and diurnal rainfall pattern, with special focus on the spatial perspective, which would be useful to understand the momentary changes of weather conditions of *Sidr* as it passes over the Meghalaya Plateau.

Material and methods

In order to analyse the weather conditions and spatial variations of rainfall in the Meghalaya Plateau, which is located between the Bangladesh plains close to the Bay of Bengal in the south and the Tibetan Plateau in the north, the upper air weather analysis was done by downloading radio sonde sounding data of two stations, Dhaka (representative of the first landing region of the cyclone on the Bangladesh plains) and Guwahati (located in the foothills of Meghalaya Plateau representing the weakening conditions), from the website: http://www.weather.uwyo.edu/upperair/sounding.html. The upper air weather observations of Dhaka were available only three times for two days (at 12 UTC 14 November 2007, and 00 UTC and 12 UTC 15 November 2007), whereas for Guwahati station, six observations were downloaded (00 UTC 14 to 00 UTC 17 November, except 12 UTC 14 November 2007).

The surface weather conditions were analysed by considering an hourly data of weather parameters of 48 h (15 and 16 November 2007) which have been collected for seven stations to show spatial variations of the weather phenomenon. It was the time of the most disturbing weather not only in the frontal part of, but also over the whole Meghalaya Plateau. Continuous hourly monitoring of temperature, rainfall, relative humidity and atmospheric pressure at three stations, viz. Cherrapunji (most vulnerable site in the active front area of *Sidr*), Nongpoh and Byrnihat (located on the leeward slopes of Meghalaya Plateau), was done using Automatic Weather Stations (AWS), Virtual Scientific Products, Roorkee, India. The least count of the tipping bucket of the AWS was 0.254 mm. In addition to these three weather stations, four automatic tipping-bucket rain gauges (Dynalab, Pune, India) with loggers (manufactured by HOBO, USA) were installed at various sites on the frontal face of *Sidr*, viz. at Cherrapunji, Mawsynram (about 12 km west of Cherrapunji), Pynursla (about 20 km east of Cherrapunji), Thangkarang (3 km south of Cherrapunji on the steep down slopes at an elevation of about 1000 m asl) and Amlarem (located 42 km east of Cherrapunji; Figure 2 and Table 1). The least count of the rain gauges was 0.50 mm. The rainfall monitoring error of two such types of rain gauges with different least count was checked by establishing a relationship of the hourly data of

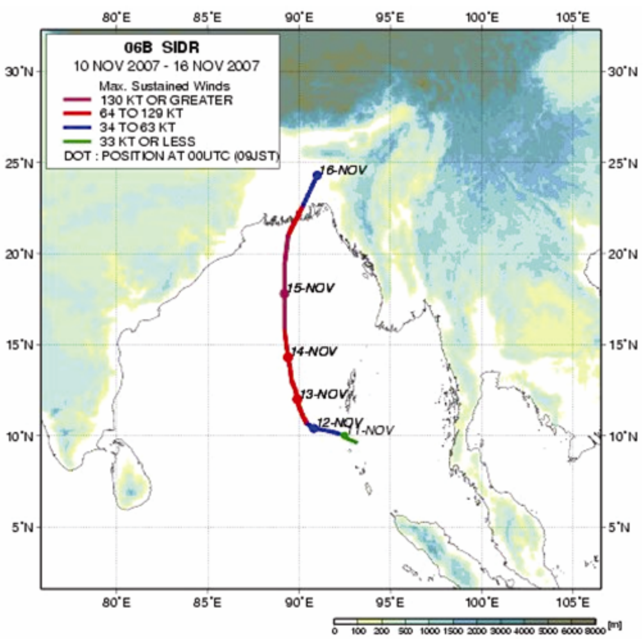

Figure 1. Path of cyclone *Sidr* in the Bay of Bengal and North East India during 11–16 November 2007 (1 KT, i.e. 1 nautical mile per hour = 1.852 km/h = 0.514 m/s). Source: http://sharaku.eorc.jaxa.jp/ADEOS2/JAXA_TYP_DB/TYP_DB_COMMON/track/bst_2007s.06B.SIDR.jpg.

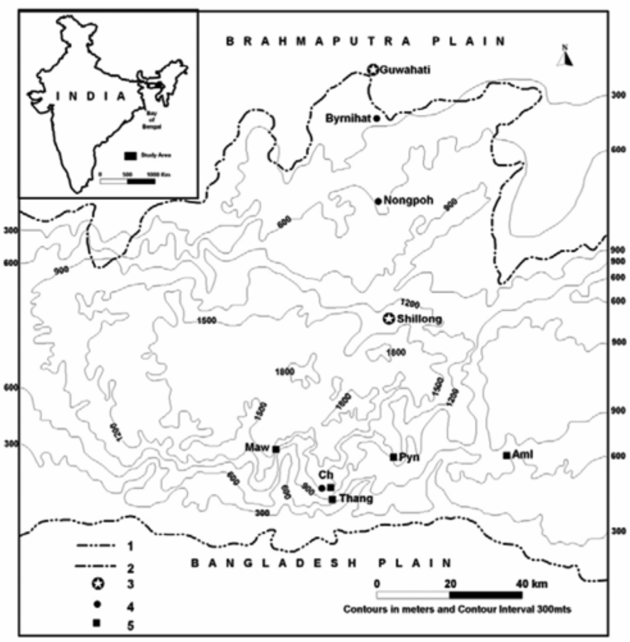

Figure 2. Location of weather monitoring stations. 1, International boundary; 2, State boundary; 3, State capital; 4, Automatic Weather Station (AWS) sites; 5, Rain gauge sites; Maw, Mawsynram; Ch, Cherrapunji; Thang, Thangkarang; Pyn, Pynursla, and Aml, Amlarem.

Table 1. Coordinates and elevations of weather monitoring stations

Station	Latitude	Longitude	Elevation (m asl)	Weather monitoring
Cherrapunji (windward upper slopes)	25°17′56″N	91°42′41″E	1300	AWS and digital rain gauge
Nongpoh (leeward middle slopes)	25°54′10″N	91°54′22″E	600	AWS
Byrnihat (leeward down slopes)	26°02′52″N	91°52′36″E	200	AWS
Mawsynram (windward upper slopes)	25°17′29″N	91°35′41″E	1300	Digital rain gauge
Pynursla (windward upper slopes)	25°19′07″N	91°54′26″E	1300	Digital rain gauge
Amlarem (windward upper slopes)	25°18′52″N	92°07′57″E	750	Digital rain gauge
Thangkarang (windward down slopes)	25°16′27″N	91°44′09″E	700	Digital rain gauge

AWS, Automatic Weather Station.

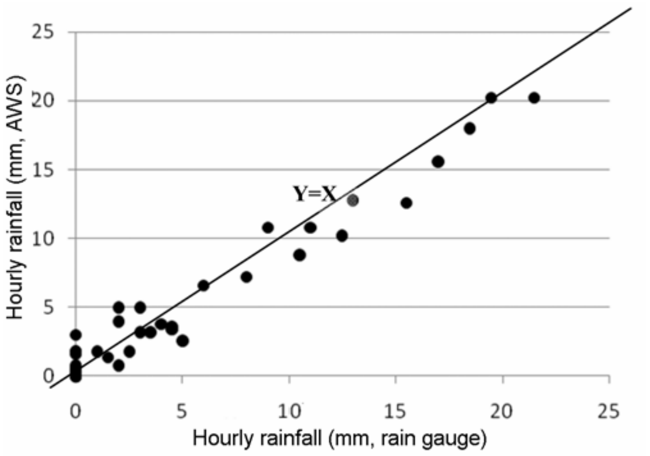

Figure 3. Scatterings of hourly rainfall measured by two different rain gauges at Cherrapunji for 48 h (15–16 November 2007).

both monitoring recorders installed on the same site at Cherrapunji. Figure 3 shows a graph of rainfall measurements of cyclonic period of the whole duration of 48 h for both the recorders. It was statistically tested using 'best fit method' of distribution; there was almost complete agreement between the used statistics of rainfall recorded by AWS and data recorded by the installed rain gauges. The rainfall data used for the purpose produced a highly regressed 45° straight line slope and a very low degree of standard error (SE) in the distribution (r = 0.98013, R^2 = 0.96066, b = 0.9924 at 1.0% significance level, SE = 0.0266 mm and n = 48). Pre- and post-cyclonic weather conditions were analysed to compute the severity of the cyclone at three stations having AWS. Rainfall patterns were analysed considering the spatial perspectives as an effort to understand the effects of topographic features on the rainfall pattern and movement of the cyclone.

Upper air conditions

Figure 4 shows the results of the upper-layer observations at Dhaka and Guwahati during the passage of *Sidr* from 14 to 17 November 2007. The difference in vertical profile between temperature and dew point temperature was much larger between 800 and 250 hPa at both stations, at 00 UTC 14 November 2007. Therefore, the air in the upper layer was dry up to 250 hPa, before the approach of the cyclone. The difference became gradually smaller as the cyclone approached to the coastline of the Bay of Bengal (Figure 4 *a–c*).

The cyclone *Sidr* landed at the SW coast of Bangladesh at around 05 UTC on 15 November 2007. The difference between temperature and dew point temperature over Dhaka at 12 UTC on 15 November was negligible up to 450 hPa. Thus, a very wet condition developed in the upper layer of the atmosphere. In Guwahati, a similar phenomenon was seen at 12 UTC on 16 November 2007, whereas the magnitude of the wet conditions was lower than that of Dhaka. As the cyclone passed towards the west of Dhaka, the surface wind directions at Dhaka changed cyclonically from SE at 12 UTC on 14 November to NE at 12 UTC on 15 November 2007. Southerly winds blew strongly in the middle and upper layers over Dhaka at 00 UTC on 14 November 2007.

The wind direction change at Guwahati was difficult to explain, since the phenomenon was far from the cyclone compared to the data available at Dhaka which was close to the cyclone. After landing, the cyclone gradually weakened because it had to negotiate over physical barriers (Meghalaya Plateau). Such upper air conditions contribute largely to the variability of surface weather.

Identification of duration of cyclone

The duration of most disturbing weather conditions was identified by comparing trends of hourly surface weather elements like air temperature, atmospheric pressure, wind speed, relative humidity and rainfall of 192 hours (00 h 12 November to 23 h 19 November 2007) of the windward area at Cherrapunji. The atmospheric pressure recorded gradually decreased to 864 hPa with a temperature of 15°C in the mid-part of the cross-section. Inversely, wind speed gradually increased from normal (2–5 m/s) to speedy (15–20 m/s) with high relative humidity (88–97%) associated with heavy rainstorms of more than 200 mm during the main cyclonic period. After this, rainfall rapidly decreased during the post-cyclonic period (as in the last part of the section; see Figure 5).

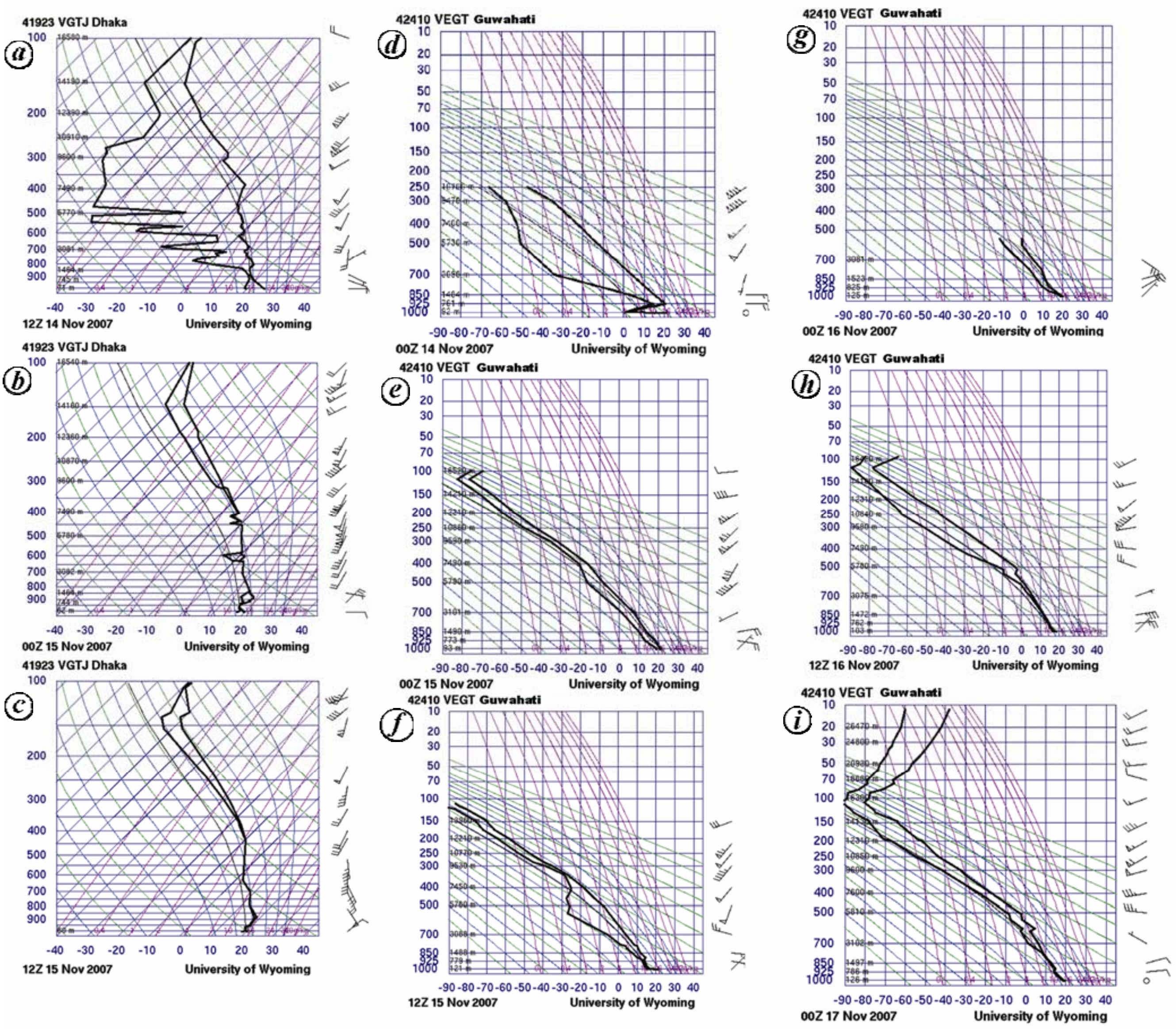

Figure 4. Upper air observation results. Profiles of temperature (horizontal axis) and dew point temperature (vertical axis) at Dhaka (***a–c***) and Guwahati (***d–i***) for (***a***) 12 UTC 14 November 2007, Dhaka; (***b***) 00 UTC 15 November 2007, Dhaka; (***c***) 12 UTC 15 November 2007, Dhaka; (***d***) 00 UTC 14 November 2007, Guwahati; (***e***) 00 UTC 15 November 2007, Guwahati; (***f***) 12 UTC 15 November 2007, Guwahati; (***g***) 00 UTC 16 November 2007, Guwahati; (***h***) 12 UTC 16 November 2007, Guwahati, and (***i***) 00 UTC 17 November 2007, Guwahati.

On the basis of such hourly variations of surface weather conditions, the 48 hours duration starting from 00 h on 15 November 2007 to 23 h on 16 November 2007 was identified as the cyclonic period. For comparison of weather conditions of the cyclonic period, the same duration of 48 hours starting from 00 h on 13 to 15 November 2007, and 00 h on 16 November to 23 h on 17 November 2007 was considered as pre-cyclonic and post-cyclonic periods respectively (Figure 5).

Weather variability

Rapid changes in weather conditions were indicated by increasing mean temperature from 17.12°C to 14.4°C, moderate rise of surface air pressure from 865 to 870 hPa, along with increasing wind velocity from 10 to 15 m/s during pre-cyclonic to cyclonic period respectively. Wind direction and velocity exert a major influence on rainfall records.

The plot of hourly wind direction shows that the magnitude and intensity of rainfall are influenced by wind direction. Southerly and southeasterly winds had a direct effect on the heavy rainfall hours during the cyclonic period. High-speed southerly winds and fluctuations in wind direction affected rainfall variability in the short duration of the cyclonic period. As a result, there was a record amount of 205 mm of rainfall during the cyclone, with an average intensity of about 4.27 mm/h and a fast

Table 2. Mean and coefficient of variation (CV) of weather components during the pre-cyclonic, cyclonic and post-cyclonic conditions at three stations

AWS			Hourly temperature (°C)	Hourly barometric pressure (hPa)	Hourly wind speed (m/s)	Hourly relative humidity (%)	Total rainfall (mm)	Hourly mean rainfall (mm)
Cherrapunji	Mean	1	17.12	866.90	6.00	72.59	0	0
		2	14.38	867.28	8.68	97.83	204.8	4.27
		3	15.99	868.78	2.83	88.35	2.0	0.041
	CV (%)	1	11.81	0.11	48.46	19.65	–	0
		2	5.24	0.17	58.69	4.46	–	132.54
		3	11.42	0.14	57.06	11.42	–	56.42
Nongpoh	Mean	1	18.84	952.66	2.73	80.77	0.2	0.004
		2	17.12	954.90	5.52	86.20	38.6	0.804
		3	18.18	955.16	1.90	91.10	0	0
	CV (%)	1	26.67	0.14	124.22	21.57	–	692.8
		2	7.45	0.16	59.21	9.76	–	189.3
		3	13.72	0.14	109.74	9.23	–	–
Byrnihat	Mean	1	20.88	998.73	2.10	86.55	0	0
		2	18.86	1001.90	4.06	94.60	7.5	0.156
		3	20.30	1001.68	1.60	92.43	0	0
	CV (%)	1	22.09	0.15	116.58	15.06	–	0
		2	5.81	0.17	59.37	5.58	–	314.24
		3	22.69	0.14	96.46	12.92	–	–

1, Pre-cyclonic condition (48 h: 13 and 14 November 2007); 2, Cyclonic (48 h: 15 and 16 November 2007), and 3, Post-cyclonic conditions (48 h: 17 and 18 November 2007); Hourly mean rainfall = (Total amount of rainfall/48 h); CV = [(Standard deviation/mean) ∗ 100]; Wind speed, 1 m/s = 3.6 km/h; Barometric pressure, 1000 mb = 1000 hPa = 100 kPa).

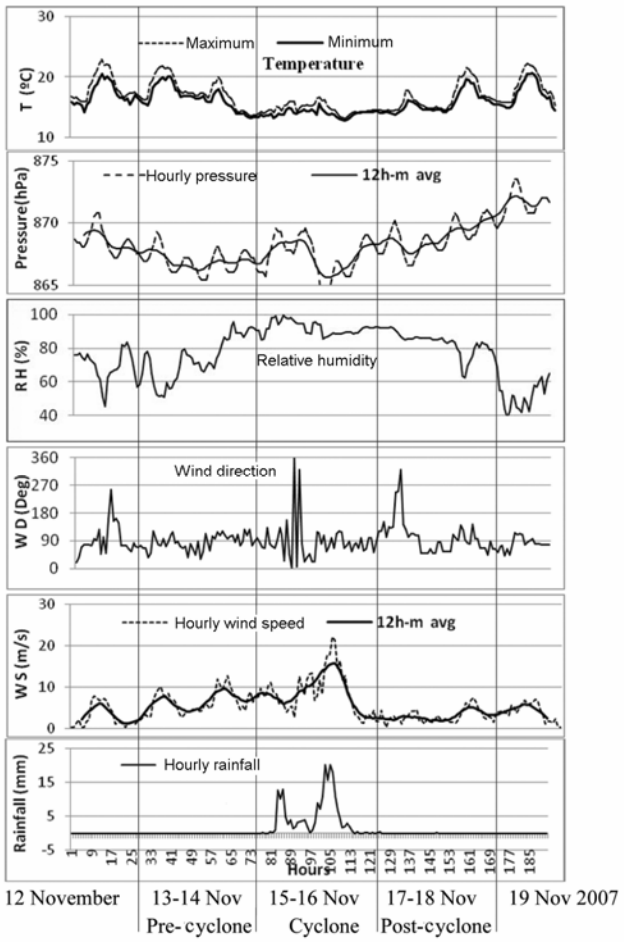

Figure 5. Weather conditions of 8-days duration of pre-cyclone, cyclone and post-cyclone stages starting from 00 h 12 November to 2300 h 19 November 2007 at Cherrapunji. 12 h m avg, Twelve hours moving average.

increase in relative humidity from 70% to 98% at Cherrapunji (Table 2 and Figure 5). Similar observations were also made by Soja *et al.*[15] for the Cherrapunji spur. The leeward areas of Meghalaya Plateau have low relative humidity accompanied by low rainfall during the cyclone (Table 2). This explicitly explains the orographic effect consequently leading to the 'rain shadow' phenomenon[11].

There is a general agreement that wind speed influences intensity and pattern of rainfall[16]. In fact, wind acceleration disturbs the atmospheric calmness, reinforces upslope air motion and invites cyclonic rain. Recorded hourly mean wind speed was moderate (6 m/s) in the pre-cyclonic period, which increased to 8.7 m/s with a higher degree of variability in the cyclonic period at Cherrapunji. This means that the variable high-speed winds created much more variability in the rainfall pattern as variability coefficients of hourly wind speed and hourly rainfall have been recorded as 58.69% and 132.54% respectively (Table 2). These figures are far higher than the variability calculated for pre- and post-cyclonic periods at Cherrapunji. However, the wind speed was observed to be much lesser in the leeward areas (Nongpoh and Byrnihat) with increasing fluctuation in hourly rainfall (Table 2). As a result, high-speed winds blowing throughout the cyclonic period continued, but rainfall duration was concentrated only for a few hours in the leeward areas of the Plateau. Another feature of the cyclone was the large diurnal temperature variability, high at daytime and low at night-time in the pre- and post-cyclonic periods.

It is universally accepted for normal weather conditions that there is an inverse relationship between the air temperature and atmospheric pressure, especially for tropical weather systems such as tropical cyclones. If

Table 3. Hourly weather conditions for 16 h (21 h 15 November to 12 h 16 November 2007) of most disturbed weather at Cherrapunji

Date	Time (h)	Air temperature (°C)	Relative humidity (%)	Wind speed (m/s)	Wind direction	Hourly rainfall (mm)	Barometeric pressure (hPa)	Psychrometric index (hPa/°C)	Saturation vapour pressure (hPa)	Vapour pressure (hPa/°C)
Starting phase										
15 November	21:00	14.33	89.78	13.05	NNE	3.6	869.6	0.57855	16.32270	1.139058
15 November	22:00	14.88	89.19	13.35	NE	4.0	869.0	0.57815	16.91270	1.136606
15 November	23:00	15.33	88.21	6.60	NNE	1.8	868.7	0.57795	17.40929	1.135635
16 November	0:00	14.61	95.13	7.65	NNE	0.2	868.1	0.57755	16.62076	1.137629
16 November	1:00	15.81	95.86	11.55	SEE	0.8	866.6	0.57655	17.95306	1.135551
16 November	2:00	16.07	94.17	8.10	SEE	3.2	866.3	0.57635	18.25378	1.135892
16 November	3:00	15.97	85.65	15.00	E	8.8	864.5	0.57515	18.13760	1.135730
16 November	4:00	14.76	95.86	17.85	SE	7.2	864.8	0.57535	16.78240	1.137019
Heavy rainfall phase										
16 November	5:00	14.70	96.94	17.85	SSE	10.8	864.8	0.57535	16.71758	1.137250
16 November	6:00	14.61	97.85	22.05	SEE	20.2	864.5	0.57515	16.62076	1.137629
16 November	7:00	14.51	97.57	21.30	E	15.6	865.1	0.57555	16.51377	1.138096
16 November	8:00	13.86	98.27	14.40	SSE	20.2	866.0	0.57615	15.83292	1.142347
16 November	9:00	13.38	98.08	16.35	SE	18.0	866.9	0.57675	15.34611	1.146944
16 November	10:00	13.22	96.16	11.40	SE	10.8	866.9	0.57675	15.18679	1.148774
16 November	11:00	12.96	95.78	12.60	SE	6.6	866.6	0.57655	14.93100	1.152083
16 November	12:00	13.07	94.40	8.85	NEE	5.0	866.0	0.57615	15.03875	1.150631

hourly weather data of the most disturbing period for 16 h of cyclonic period (21 h 15 November to 12 h 16 November 2007) are examined, two phases of weather variability may clearly be distinguished: (i) the starting phase of 8 h from 21 h 15 November (night-time when solar radiation was minimum) and (ii) the phase of heavy rainfall of another 8 h starting from 5 h to 12 h 16 November 2007 (when temperature was declining slightly from 14.7°C (morning) to 13.07°C (around noon) instead of rising as usual). It is obvious from hourly temperature data that the night temperature was slightly higher than the day temperature during this disturbing period of the cyclone. Therefore, abrupt changes in diurnal temperature created an abnormal condition where a decreasing barometric pressure was observed from 869.6 to 864.8 hPa during the starting phase of the cyclone, whereas it gradually increased from 864.5 to 866.0 hPa in the heavy-rainfall phase. These measurements neither match with the general observations drawn on the diurnal variation of rainfall precipitated during monsoon season in Cherrapunji where precipitation peak occurs at late night – early morning hours[13,17] nor the nocturnal (night) jet mechanism which explains the late night–early morning precipitation peaks during summer rainfall[14]. In such anomalous conditions of temperature during the cyclone, the psychrometric index (i.e. saturation vapour pressure per unit of temperature) recorded is much higher (0.5855 hPa/°C) than the psychrometric constant (i.e. 0.5757 hPa/°C for the elevation of 1330 m asl; Appendix 1) of Cherrapunji station. The psychrometric index diminished marginally in 8 h of the starting phase from 0.578 to 0.575 hPa/°C with the moderate increase of hourly rainfall from 0.2 to 8.8 mm associated with winds at hourly speeds of 6–17 m/s. It was because of rapid fall in barometric pressure at a constant rate of 0.728 hPa/h touching the level of 864.8 hPa with almost stable range of moderately cool temperature varying from 14.33°C to 14.76°C in this period of the cyclone that an anomaly occurred (Table 3). The weather variability in diurnal temperature distribution recorded an increase towards morning hours of 16 November (starting phase), while it decreased during the day when there was heavy rainfall. During the heavy rainfall phase, the psychrometric index gradually increased from 0.5751 to 0.5767 hPa/°C, associated with heavy rainfall varying hourly from 5 to 20.2 mm and a higher degree of relative humidity. On the other hand, winds with higher speed (9–22 m/s) were much stronger during the heavy-rainfall phase in the frontal core areas of Cherrapunji (Table 3).

There are evidences of high vapourization in the first phase of the cyclone as the saturation vapour pressure increased marginally from 16.3227 to 18.25378 hPa (11.831%). With a rise in diurnal temperature from 14.33°C to 16.07°C (12.142%), the temperature condition was much higher than the heavy-rainfall phase and, therefore, the thermal efficiency for vapourization became higher ($\dot{\eta}$ = 0.974386) in the cyclonic phase (Table 4). Secondly, as described earlier, wet conditions were recorded in the upper air over Dhaka at 450 hPa as well as over Guwahati at 850 hPa at 12 UTC (i.e. 21 h IST) 15 November 2007, during the starting phase of the cyclone at Cherrapunji (Figure 4 *c* and *f*). These evidences show that high thermal efficiency and wet conditions of the upper air in the starting phase are likely to be the

Table 4. Psychrometric index and thermal efficiency coefficient for vaporization in different phases of weather variability at Cherrapunji

Phase	Duration (h)	Hourly mean temperature (°C)	Psychrometric index (hPa/°C) Maximum	Minimum	Mean	Thermal efficiency for vaporization: Change in saturation vapour pressure (%)	Change in temperature (%)	Thermal efficiency coefficient ($\dot{\eta}$)
I Starting	8	14.5	0.57855	0.57515	0.57695	11.8310	12.142	0.974386
II Heavy rainfall	8	13.8	0.57655	0.57515	0.57605	10.6868	11.088	0.963817

Thermal efficiency coefficient = proportionate change in saturation vapour pressure per unit proportionate change of temperature in different weather variability phases.

Table 5. Rainstorm pattern during cyclone *Sidr* (48 hours from 00 h 15 November 2007)

Station	Duration (h) and amount of rainfall (mm)	Intensity (mm/h)	Hourly maximum rainfall (mm)	Hourly minimum rainfall (mm)	Hourly mean rainfall (mm)	Skewness (coefficient)	Kurtosis (coefficient)	SD (mm)	CV (%)	Active level of rainfall (mean + SD) (mm)
Cherrapunji	40 (204.6)	5.115	20.20	0.20	4.26	1.5663	1.5815	5.65	110.67	9.91
Thangkarang	34 (137.0)	4.030	21.00	0.50	2.85	1.6503	2.0904	3.93	97.65	6.78
Mawsynram	44 (157.5)	3.591	16.50	0.50	3.28	1.5304	2.2941	3.77	105.42	7.05
Pynursla	34 (220.5)	6.485	16.50	0.50	4.59	1.4592	1.5553	5.58	86.74	10.17
Amlarem	33 (113.0)	3.424	12.00	0.50	2.35	1.6190	2.7774	2.93	85.67	5.28
Nongpoh	26 (38.6)	1.484	6.00	0.20	0.81	2.2592	4.1643	1.52	102.86	2.33
Byrnihat	11 (7.5)	0.682	2.40	0.20	0.16	3.9185	17.5391	0.49	314.24	0.65

Rainfall intensity for the effective period was calculated dividing total amount of rainfall by duration of rainfall during the cyclonic period (as given in column 2); SD, Standard deviation; CV, Coefficient of variation.

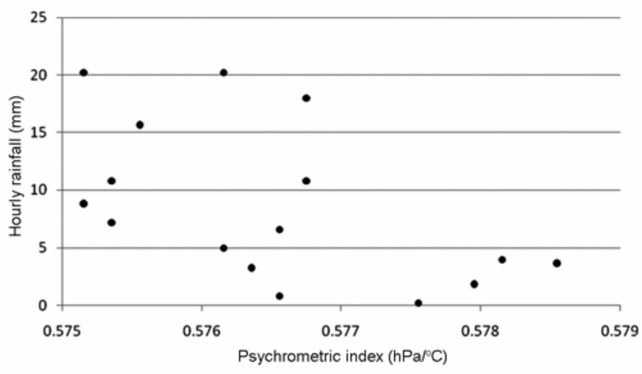

Figure 6. Psychrometric index and rainfall relationship in the cyclonic phase of 16 h (21 h 15 November to 12 h 16 November 2007) at Cherrapunji, the active path of cyclone.

causes of heavy rainfall in the second phase of the cyclone. As a result, correlation coefficient of rainfall with psychrometric index was found to be significantly negative ($r = -0.53977$ at $n = 16$) for the active path of the cyclone (Figure 6).

Diurnal rainfall pattern

Characteristics of rainfall distribution are interpreted by analysing rainfall pattern over space and time. Maximum rainfall during the cyclone was recorded at Pynursla (220.5 mm). It was precipitated in 34 h and followed by Cherrapunji (204.6 mm) in a span of 40 h. Therefore, intensity of rainfall was observed to be the highest at Pynursla (6.49 mm/h) and comparatively lower at Cherrapunji (5.11 mm/h). Duration of rainfall period varied across the Plateau. The frontal areas recorded 33–44 h of rainfall, whereas the leeward areas experienced only 11–26 h of rainfall. As a result, leeward areas had higher degree of rainfall variability and asymmetry in distribution. The degree of skewness (horizontal) and leptokurtic trends (toppedness) of the curves were found very high in the case of Nongpoh and Byrnihat, which are located on the leeward side of the Plateau (Table 5).

It is evident from the analysis that the movement of the cyclone is away from Cherrapunji but towards Pynursla, as explained by the active level of rainfall (Table 5). In the windward side (Cherrapunji, Mawsynram and Pynursla), the 'two-peaked' intensive rainfall distribution throughout the cyclone is indicative of the active influence of the cyclone (Figure 7), while also experiencing highly fluctuating trends at its entry (first day). However, duration–intensity relationship was positive and significant ($r = 0.7186$), displaying a gradual increase in rainfall intensity at the constant rate of 0.133 mm/h for every hourly increase in duration. As a result, longer duration rainfall during this cyclone caused higher rainfall intensity in the windward side of Meghalaya Plateau. Leeward areas showed 'one-peaked' distribution, which was

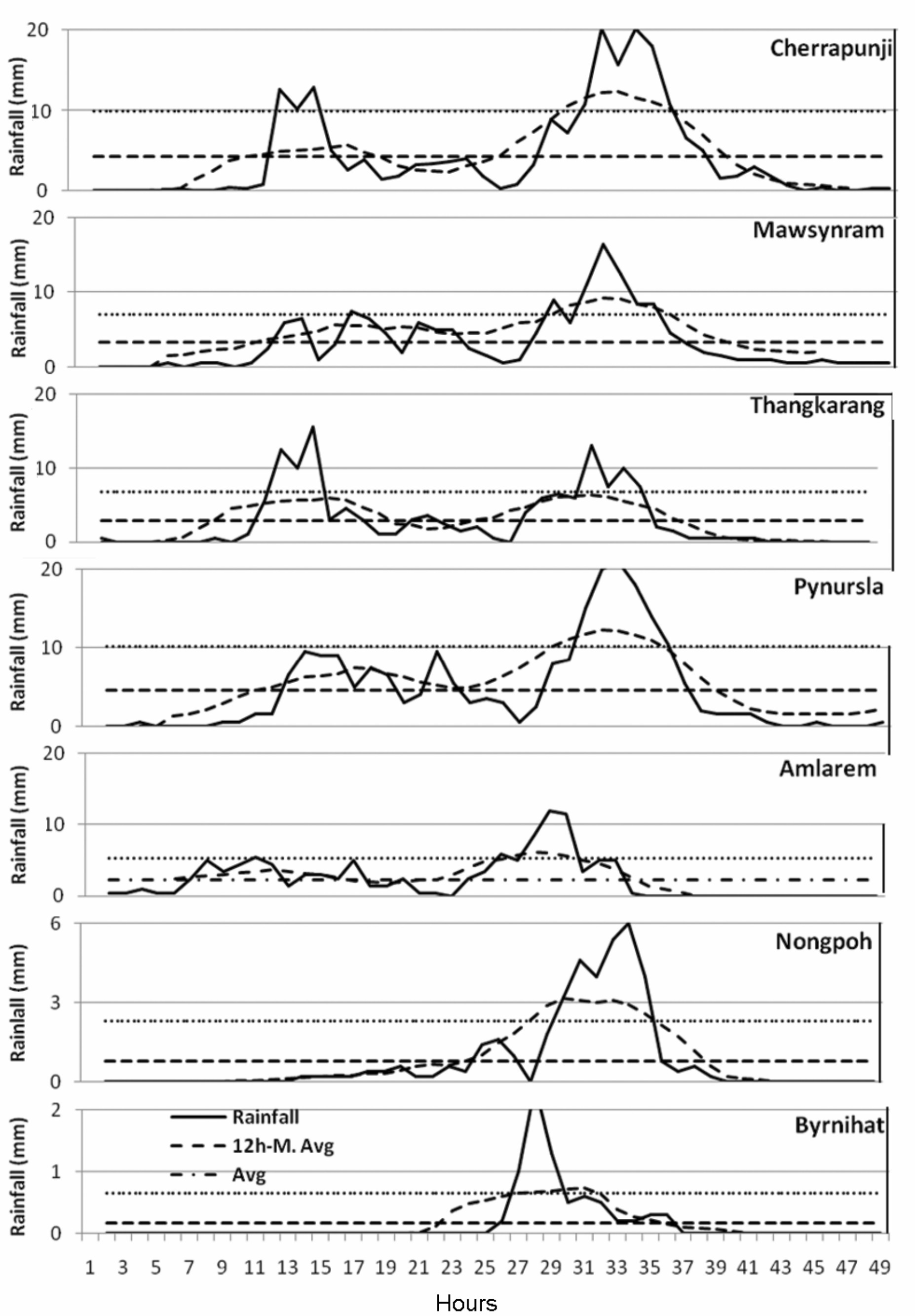

Figure 7. Rainfall distribution pattern. Solid line, Hourly rainfall; Dashed line, Twelve hours moving average; Large dashed lines, Mean rainfall, and Dotted line, Active level of rainfall.

concentrated on the second day with low intensities of 6.0–2.0 mm/h at noon on 16 November 2007.

The causes of such differential pattern of diurnal rainfall may be due to the variable nature of wind speed as observed earlier (Table 3). Wind speed–rainfall relationship was significantly positive ($r = 0.6063$) at Cherrapunji (frontal area), but weak ($r = 0.3436$) at Nongpoh (leeward area). Therefore, wind speed had an impact on the rainfall pattern, especially in the frontal areas (Figure 8).

Being hilly, the Plateau offered resistance to the cyclone, which had to spend its energy. Rainfall was distributed and varied spatially. Spatial variability in amount and intensity of rainfall showed that total amount of rainfall and its intensity diminished towards the north across the Plateau from the windward side at a rate of 0.81 mm/km with an intensity of 0.254 mm/h/km (refs 18 and 19). This influenced the saturation vapour pressure and consequently changed the rainfall pattern over space (Table 6).

Table 6. Spatial gradient of rainfall and its intensity from Cherrapunji during cyclone *Sidr* (48 h from 00 h 15 November 2007)

Station	Total amount of rainfall (mm)	Distance from Cherrapunji (km)	Spatial gradient of rainfall (mm/km)	Spatial gradient of rainfall intensity of effective period (mm/h/km)
Cherrapunji	204.6	–	–	–
Nongpoh	38.6	70.20	–2.33	–0.0522
Byrnihat	7.5	85.00	–2.32	–0.0521
Mawsynram	157.5	11.70	–4.02	–0.1311
Pynursla	220.5	19.70	+0.81	+0.2538
Amlarem	113.0	42.00	–2.18	–0.0403
Thangkarang	137.0	2.70	–25.04	–0.4020

Rainfall intensity for the effective period was calculated dividing total amount of rainfall by duration of rainfall of the cyclonic period. Gradients show the variability of rainfall over space.

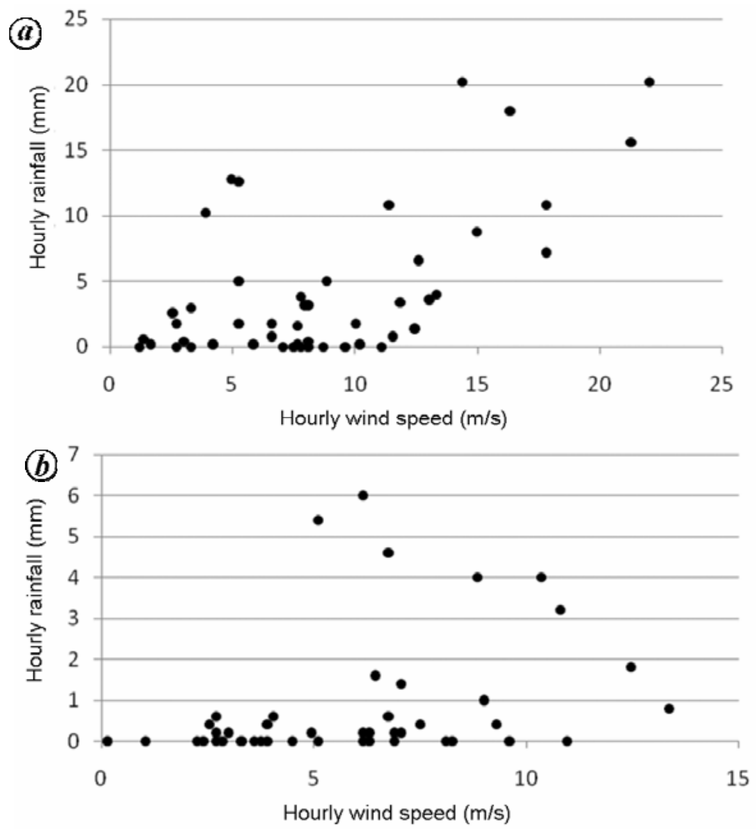

Figure 8. Wind speed–rainfall relationship in (***a***) windward areas (Cherrapunji) and (***b***) leeward areas (Nongpoh) during the cyclonic period.

Conclusions

Some important conclusions have been drawn from the present study of weather variability that occurred during the cyclone *Sidr* on 15–16 November 2007. Wet conditions in the upper air and fast falling gradient of saturated vapour pressure even at constantly low temperature created depression of cool air masses in the starting phase of the cyclone. As a result, there was atmospheric disturbance for a short period. Such depressions forced the development of specific conditions of speedy winds, heavy rainfall and higher relative humidity. Consequently, the psychrometric index diminished with elastic thermal efficiency conditions in the starting phase, which brought rain in the later phase of the cyclone. The following particular inferences have been drawn from the analysis:

(a) Upper air results showed that at Dhaka and Guwahati, very wet conditions prevailed in the middle part of the upper layers at 450 hPa during the starting phase of the cyclone.

(b) Rainfall pattern of all stations was highly influenced by the southerly and southeasterly speedy winds during the cyclone in its active path across the Meghalaya Plateau.

(c) Rainfall intensity had a positive relationship with storm duration during the cyclone. It shows the concentration of rainfall for longer duration in the areas of intense cyclonic activity on the windward side of the Meghalaya plateau.

(d) There was a change in rainfall pattern over space as the cyclone weakened. Spatial variability in rainfall intensity was found to be much higher than expected. It may also be noted that under this condition of high spatial variability, the complex nature of temperature–pressure relationship arising out of orographic conditions is important for the spatial distribution of rainfall over the Meghalaya Plateau. Hence, further research needs to be done on the developments that favour these conditions.

Appendix 1. Notes

(i) Psychrometric index (hPa/ºC) = [$\alpha(\beta/\lambda)$], where α = 0.00163 (constant), β is the given barometric pressure (hPa) and λ the latent heat of vaporization (i.e. $2.47*10^6$ J/kg and therefore $1/\lambda = 0.408$ MJ/kg). Psychrometric constant (hPa/°C) is the theoretical value for a weather station located at particular elevation from the mean sea level. For the calculation of psychrometric constant, a theoretical value of β (hPa) is considered as a function of elevation (E) as:

$$\beta = [1013\{(293.0 - 0.0065E)/293.0\}^{5.26}].$$

It is a power function of 'decreasing base at constant power when elevation increases'. The formula for calculation of psychrometric constant is the same as given above for psychrometric index.

(ii) Thermal efficiency coefficient is the proportionate change in saturation vapour pressure per unit proportionate change in temperature $\{(\partial P_w/P_w)/(\partial T/T)\}$ in different weather variability phases. The saturation vapour pressure (P_w in hPa) at a particular temperature (T in °C) is calculated using the Buck[20] function as

$$P_w = 6.1121\, e^{(17.502T/(240.97 + T))}.$$

Saturation vapour pressure as is a convex function of temperature.

1. O'Hare, G., The Indian monsoon, Part-1: the wind system. *Geographysics*, 1997, **82**(3), 218–230.
2. Matsumoto, J., Synoptic features of heavy rainfall in 1987 related to severe flood in Bangladesh. In *Bulletin*, Department of Geography, University of Tokyo, Japan, 1998, vol. 20, pp. 43–56.
3. Joseph, P. V. and Simon, A., Weakening trend of the southwest monsoon current through peninsular India from 1950 to the present. *Curr. Sci.*, 2005, **89**(4), 687–694.
4. Asada, H., Matsumoto, J. and Rahman, R., Impact of recent severe floods on rice production in Bangladesh. *Geogr. Rev. Jpn.*, 2005, **78**(12), 783–793.
5. Basu, T. K., Indian summer monsoon. *Geogr. Rev. India*, 2006, **68**(2), 227–246.
6. Sadhuram, Y. and Murthy, T. V. R., Long range forecasting of summer monsoon rainfall from SST in the central equatorial Indian ocean. *Vayu Mandal*, 2001, **31**(1–4), 40–45.
7. Clift, P. D. and Plumb, R. A., In *The Asian Monsoon – Causes, History and Effects*, Cambridge University Press, Cambridge, UK, 2008, pp. 5–9; 30–36.
8. Krishnakumar, G., Gadgil, A. S. and Rajeevan, M., Use of surface temperatures over the Indian Ocean in the estimation of tropical cyclone activity over Bay of Bengal. *Trans.*, *Inst. Indian Geogr.*, 2005, **27**(1), 63–70.
9. Bhalme, H. N., Trends and quasi-biennial oscillations in the series of cyclonic disturbances over the Indian region. *Indian J. Meteorol. Geophys*., 1972, **23**, 355–358.
10. Ghosh, S. K. and Prasad, K., On vulnerability of Orissa coast to cyclonic storms. *Vayu Mandal*, 1982, **12**, 444–448.
11. O'Hare, G., The Indian monsoon, Part-2: the rains. *Geographysics*, 1997, **82**(4), 335–352.
12. *The Times of India*, NE edn, In the eye of a cyclone, 16 November 2007, p. 1; 'Sidr' throws life out of gear in NE, 17 November 2007, p. 1 and Bangla cyclone toll over 2200 h 19 November 2007, p. 15.
13. Prasad, B., Diurnal variation of rainfall in India. *Indian J. Meteorol. Geophys.*, 1970, **21**, 443–450.
14. Terao, T., Islam Md, N., Hayashi, T. and Oka, T., Nocturnal jet and its effect on early morning rainfall peak over North Eastern Bangladesh during summer monsoon season. *Geophys. Res. Lett*., 2006, **33**, 1–5.
15. Soja, R., Starkel, L. and Singh, S., Water circulation and availability of water. In *Land Degradation and Ecorestoration in the Extremely Wet Monsoon Environment of Cherrapunji Area, India* (eds Singh, S., Starkel, L. and Syiemlieh, H. J.), Bookwell Publications, New Delhi, 2010, pp. 30–32.
16. Shakir, A., Prasad, S. N. and Sethy, B. K., Analysis of south-west monsoon for rainfed crop planning in Kota region of Rajasthan. *Indian J. Soil Conserv*., 2007, **35**(3), 189–193.
17. Ohsawa, T., Ueda, H. and Hayashi, T., Diurnal variations of conductive activity and rainfall in tropical Asia. *J. Meteorol. Soc. Jpn*, 2001, **79**, 333–352.
18. Singh, S. and Syiemlieh, H. J., Rainstorm characteristics of extremely humid area of the world – Cherrapunji. *Vayu Mandal*, 2001, **31**(1–4), 46–57.
19. Singh, S., Rainfall runoff conditions in the Meghalaya Plateau, Research Monogr. No. GE/UGC/SS/5, Department of Geography, North-Eastern Hill University, Shillong, 2007, p. 76.
20. Buck, A. L., New equations for computing vapour pressure and enhancement factors. *J. Appl. Meteorol*., 1981, **20**, 1527–1532.

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