

High temporal and spatial resolution observations of meso-scale features of pre- and mature summer monsoon cloud systems over Bangladesh

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Abstract Meso-scale characteristics of disturbances that bring about atmospheric disasters in pre- and mature monsoon seasons in Bangladesh are analyzed. Several types of meteorological instruments capable of observations with high temporal and spatial resolutions were introduced for the first time in this area to capture the meso-scale structure of rainfall systems. We installed an automatic weather station (AWS) and several automatic raingauges (ARGs) and utilized the weather radar of Bangladesh Meteorological Department (BMD). From the radar image in the summer of 2001 (16–18 July), a striking feature of the systematic diurnal variation in this area was elucidated. In these 3 days, the diurnal evolutions of convective activity were remarkably similar to each other, implying that this pattern can be understood as a typical response of local cloud systems to the diurnal variation of insolation under some summer monsoon situations. The ARG data show the difference in characteristics of rainfall between pre- and mature monsoon seasons. The short intense downpour tends to occur more frequently in the pre-monsoon season than in the mature monsoon season. The pre-monsoon rainfall also has clear diurnal variation with a peak that is more strongly concentrated in time. In the northern part the rainfall peak is found in between midnight and early morning, while it is observed in the daytime in central to western parts of the country. Two disaster cases caused

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by meso-scale disturbances are analyzed. Although they occurred in the same season, the structures of the cloud systems were largely different from each other. The disturbance brought about tornadoes on 14 April 2004, consisting of many spherical cloud systems of approximately 20 km size. On the other hand, another one that caused the tragic river water transport accident on 23 May 2004 had meso-scale rain band structure. The latter case was captured by the AWS located at Dhaka. Sudden changes in temperature, wind and pressure were observed clearly, showing the typical structure of convective rain bands.

Keywords Bangladesh · Severe storms · Rainfall intensity · Diurnal variation · Pre-monsoon

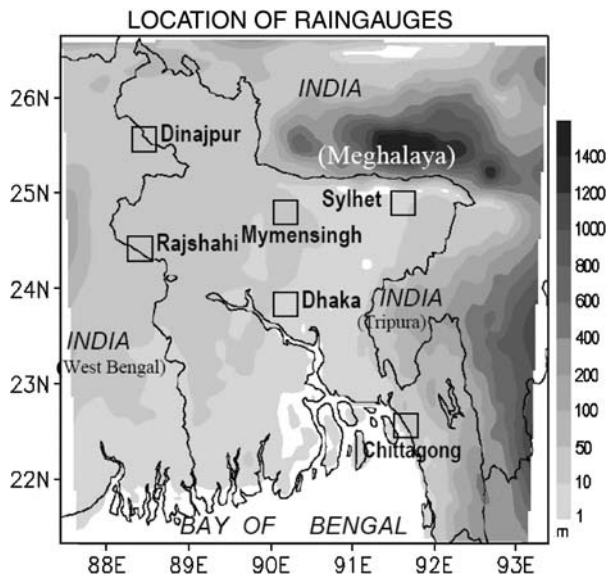
1 Introduction

The Bengal Plain, including Bangladesh, is known as one of the highest rainfall areas in South Asia. Various types of disasters, such as flash floods, tornadoes, and down-bursts, occur in this area associated with the meso-scale cloud systems. However, because of the lack of data with high potential resolution, it has been difficult to investigate the meso-scale features of cloud systems over this country.

To make a breakthrough in this research status, we installed an automatic weather station (AWS) at Dhaka and automatic raingauges (ARG) in six locations in the country, as shown by squares in Fig. 1. We also utilized the weather radar of Bangladesh Meteorological Department (BMD) to capture the spatial pattern of the meso-scale systems with heavy rainfall.

In spite of the difficulty of obtaining high-quality data in this area, some attempts have been made to elucidate characteristics of these cloud systems. These studies have clarified some aspects of these disturbances. Rainfall pattern in this area has clear diurnal variation (Ohsawa et al. 2001; Islam et al. 2005; Terao et al. 2006). In the northeastern part of the country, which is the area with the highest rainfall, the midnight–early morning rainfall peak

Fig. 1 Map of Bangladesh. Topography is shown by shading, in meters. Locations of AWS (Dhaka) and automatic rain gauge stations (Dinajpur, Rajshahi, Mymensingh, Sylhet, and Chittagong) are noted by squares



is dominant. Recently Terao et al. (2006) emphasized the importance of the daytime deceleration of lower tropospheric southerly due to the frictional force by vertical momentum transport in the convections over the Bengal Plain. They argued that the shallow convections over the central part of country are a precondition for the development of strong convections in the northeastern part of country, through the mechanism of the nocturnal jet (Blackadar 1957). However, the use of 3-hourly rainfall data of BMD with not so dense spatial coverage is not enough to resolve the structure of clouds covering the Bengal Plain. The radar data will be effective to check the existence and characteristics of daytime convections.

Another notable known feature in Bangladesh rainfall is the dominance of the pre-monsoon meso-scale disturbance known as nor'westers that frequently bring about severe disasters such as tornadoes and strong gusty winds (Rai Sircar 1953; Chowdhury and Karmakar 1986; Hayashi et al. 1997; Karmakar and Alam 2005). It has qualitatively and intuitively been pointed out that the rainfall intensity in the pre-monsoon season is much stronger than that of the mature monsoon season. However, because of the shortage of high temporal resolution rainfall observations, there has been no quantitative evidence that shows the intuition discussed above. The AWS and ARGs installed by us will show the difference in rainfall characteristics between these two seasons, although the length of data is limited. Especially, the AWS is expected to show some intrinsic parameters that show the meso-scale structure of these disturbances.

The present study aims to show some results obtained by our special observations and data collection to advance our knowledge on the meso-scale characteristics of the cloud systems developing over this area. The next section is devoted to the case study of the typical diurnal variation of radar echo.

2 The diurnal evolution of radar echo patterns over Bangladesh in the mature monsoon season

In this section, an example of the diurnal variation in convective activity over the Bangladesh region in the mature monsoon season will be shown with data obtained from Dhaka radar. This radar system replaced the old one in spring 2000. Usually, it is run every 3 h: 5:00 to 6:00, from 8:00 to 9:00, from 11:00 to 12:00, ... and from 23:00 to 24:00 in BST. It scans approximately every 3 min.

Figures 2 and 3 show that diurnal variations appeared in the radar images. The patterns of radar echos in these 2 days are strikingly similar to each other. At 8:30 in the morning, few echoes are found in these radar images. From 11:30 to 17:30, over the region from West Bengal in India to the western part of Bangladesh, the images are covered with scattered small radar echoes. They seem to be organized gradually and decay in the evening before 20:30. On the other hand, over the eastern part of the image, some large organized disturbances tend to develop from afternoon to midnight. Some scattering of echoes appear at 14:30. They are rapidly organized into two large echoes over the Rangamati region in the southeastern hilly part of Bangladesh (23° N, 92° E) at 17:30. The location and shape of these echoes are almost the same for these two different days. Three hours later (20:30), other organized convections appear over north to northeastern parts of the country. This disturbance is characterized by a rain-band-like shape, oriented west to east. It seems to be along the topography, although it is located approximately 50 km south of the Meghalaya Mountains (25–26° N, 90–93° E). The distance between the mountains and the rain band is consistent with the feature of the rain bands calculated in the meso-scale model by Kataoka and Satomura (2005).

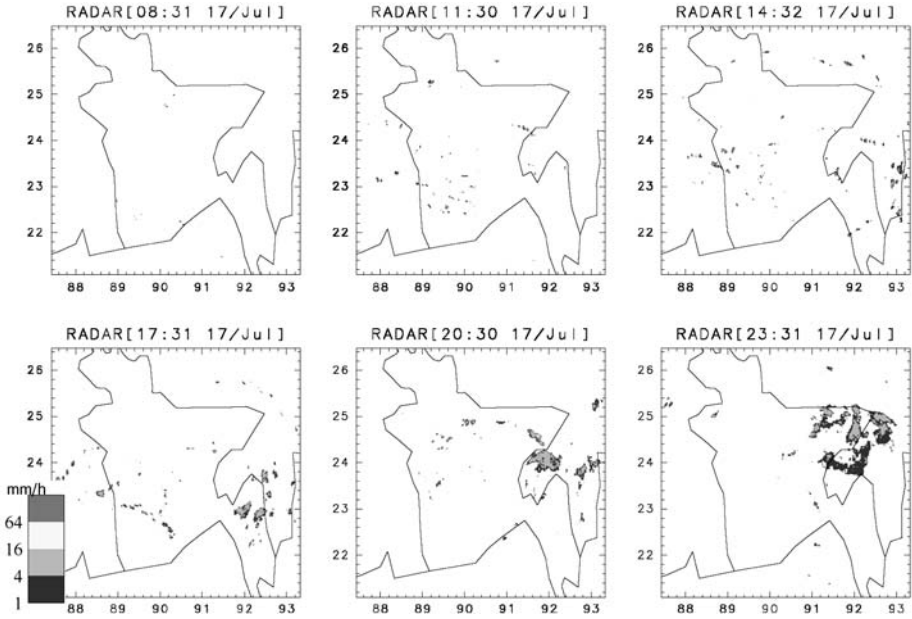


Fig. 2 Almost 3-hourly BMD Dhaka radar images for 17 July 2001. Rainfall intensities are indicated by the legend. Local times of observation are shown on the top of each panel. Coast lines and border lines are indicated by *thin lines*. *Vertical and horizontal axes* are the latitude and longitude, respectively

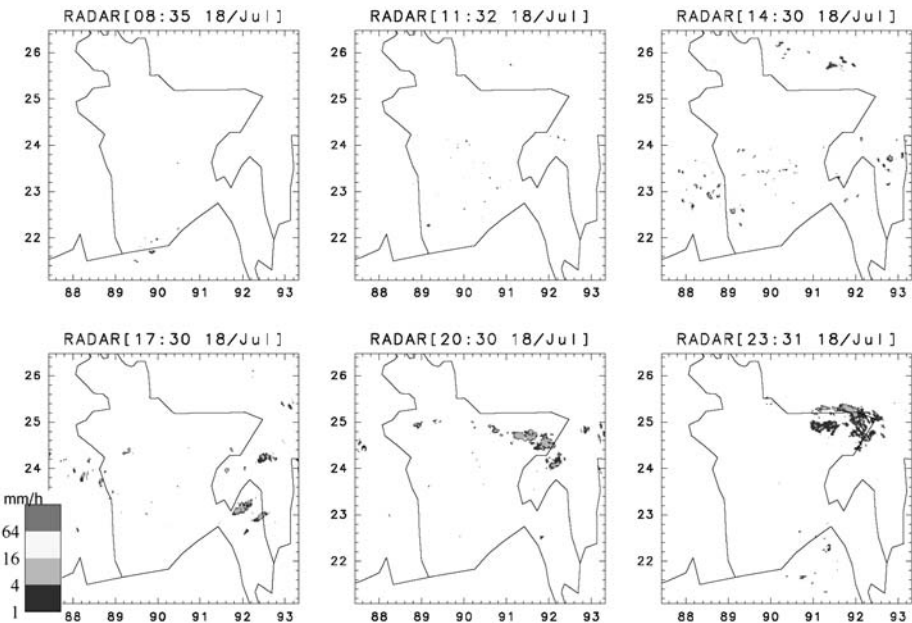


Fig. 3 As Fig. 2 but data relate to 18 July

Near midnight (23:30), the radar echo is intensified and spreads over the area in the northeastern most part of this country (24–25° N, 91–93° E). Over the Meghalaya Mountains, some echoes develop mainly only in the afternoon (14:30).

This diurnal variation over Bangladesh is consistent with the result shown by Terao et al. (2006) and Ohsawa et al. (2001). Radar data show that, over the southwestern part of the country, scattered echoes appear mainly from late morning to the afternoon. This corresponds to the maximum convection time detected by Terao et al. (2006) and Ohsawa et al. (2001) over the southwestern part of Bangladesh and West Bengal. The scattered echoes indicate the existence of many shallower convective systems in this area. This supports the discussion of Terao et al. (2006) that emphasized the importance of the convections over the Bengal Plain for the daytime vertical momentum mixing. The result of another analysis of GMS data conducted by Islam et al. (2004) is also consistent with ours. Just south of the Meghalaya mountains, strong radar echoes are found after late evening until midnight, supporting the results of Prasad (1974) and Ohsawa et al. (2001), who have also pointed out that the maximum convections are found around midnight over this region.

It should be emphasized again that the patterns of the radar echoes are strikingly similar to each other for these 2 days. Although the figures are not shown here, the evolution of radar echo is also almost the same on 16 July. This result shows that these patterns appear under some necessity. We must clarify the physical processes through which these evolutions of convection occur.

In this period, there was a break phase of the monsoon activity in this area, since monsoon rainfall was relatively weak and the lower tropospheric wind was southeasterly (Ohsawa et al. 2000). For 17 and 18 July 2001, the operational rawinsonde observations by BMD at 00 Coordinated Universal Time (UTC) showed southeasterly wind at 850 hPa (151° and 136°, respectively). In the active phase of the monsoon rainfall, the pattern might be different.

Some typical radar echo patterns in the pre-monsoon seasons are shown later.

3 Rainfall characteristics of pre- and mature monsoon seasons

Using data obtained by AWS and ARGs, we analyzed the climatological rainfall patterns in Bangladesh in both pre- and mature monsoon seasons.

Figure 4 shows the rainfall records of each month at each raingauge. Monsoon season in Bangladesh begins in June and continues to September. The main focus of this study was to investigate the difference between rainfall characteristics in pre- and mature monsoon seasons. The transition from the pre-monsoon season to the mature monsoon season occurs usually in June. Therefore, we excluded the data for June. The data for January to May, and those for July to December, are assumed to exhibit the characteristics of rainfall in pre-monsoon and mature monsoon seasons, respectively. The latter contain some post-monsoon data. However, the rainfall fractions observed in October–December are 21.2%, 13.2% and 14.1% for Sylhet, Dhaka and Chittagong, respectively. For Mymensingh, one should be somewhat careful, because the fraction is 37.4%, which is rather larger than that for other locations.

Firstly, the difference in rainfall characteristics between pre- and mature summer monsoon seasons is analyzed. The contribution ratios from several rain rate categories are tested for each raingauge. This is done for 1 min, 10 min, 1 h and for the daily rainfall rate. Here, the result of a 10 min rainfall rate is shown in Fig. 5. Except for that of Chittagong, the contribution ratios of intensive rainfall greater than 5 mm/10 min are greater than 50%

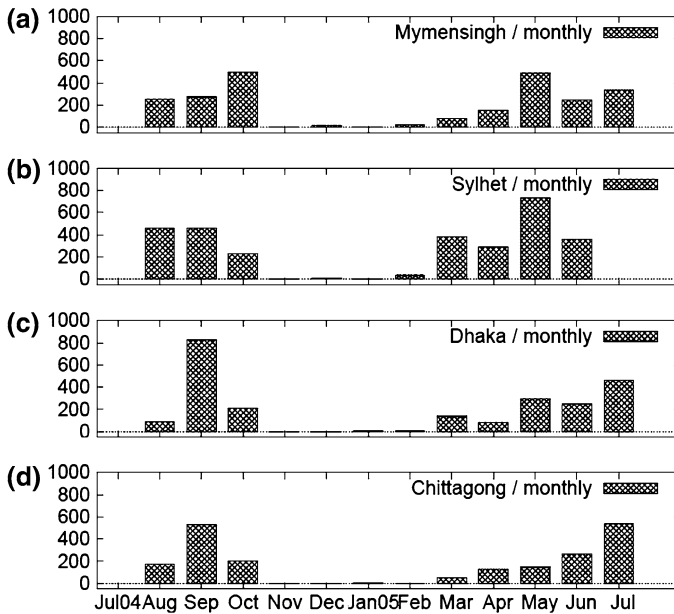


Fig. 4 Rainfall records observed in each month from July 2004 to July 2005 at (a) Mymensingh, (b) Sylhet, (c) Dhaka, and (d) Chittagong. The measurements are in millimeters

in the pre-monsoon season. Since this result is seen only in the pre-monsoon season, the possibility of short intense downpour is higher in the pre-monsoon season than in the mature monsoon season.

The pattern of diurnal rainfall variation exhibits a remarkable difference between pre-and mature monsoon seasons (Fig. 6). For instance, at Mymensingh, while the rainfall peak is found in the daytime in the mature monsoon season, it is observed between midnight and early morning in the pre-monsoon season. The peak is steeper in the pre-monsoon season. At Dhaka, the time of the peak is not so different between these two seasons. However, the rainfall is more strongly concentrated in the 3 h from 9:00 to 12:00 UTC (from 15:00 to 18:00 local time). Interestingly, the peak of rainfall is obvious at almost all stations. For Mymensingh, Dinajpur and Sylhet, it is found around midnight, 0:00–3:00, in local time, while it is found at 15:00–18:00 in Dhaka and Rajshahi.

4 Disturbances that brought about disasters in the pre-monsoon season

4.1 Case I: 14 April 2004

Meso-scale characteristics of cloud systems that brought about disasters in Bangladesh are also described using data from automatic meteorological instruments and radar data obtained from operational observations by BMD. It was shown that different types of disturbances cause disasters in this country.

In the evening of 14 April 2004, strong meso-scale cloud systems with tornadoes swept through villages in the Mymensingh and Netrokona districts in the northern part of Bangladesh, causing more than 70 deaths. It is very common in this area for these types of

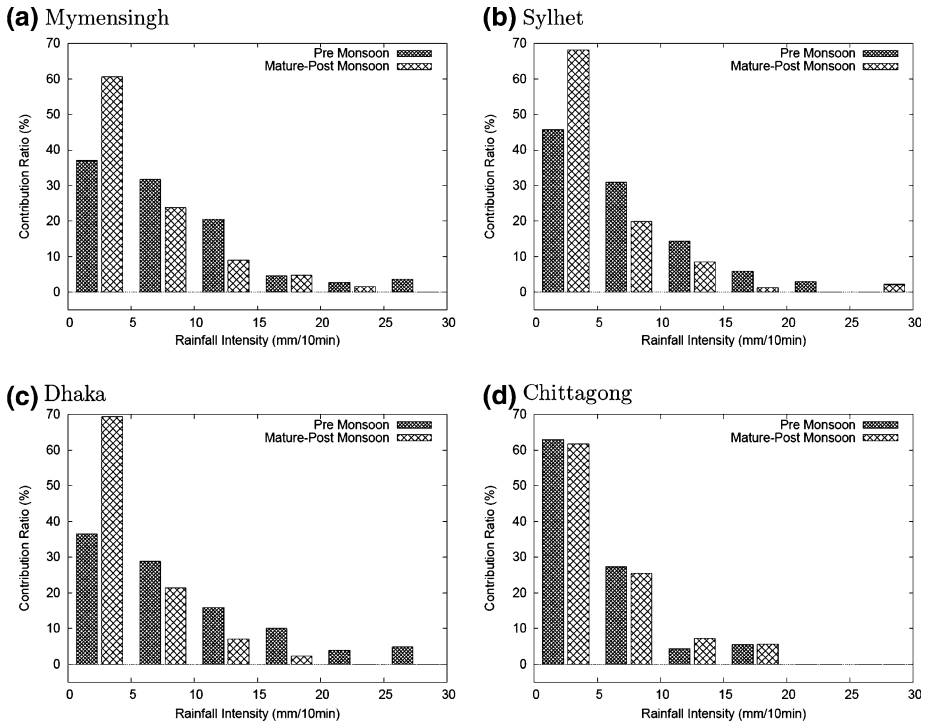


Fig. 5 Contribution ratio of rainfall within intensity categories indicated by the values on the horizontal axis at (a) Mymensingh, (b) Sylhet, (c) Dhaka and (d) Chittagong. As is shown in the text, the contribution ratios for the pre-monsoon season are calculated from the data for January to May, while those for the mature and post-monsoon seasons are obtained with raingauge records for July to December

severe storms to occur in the pre-monsoon season (Hayashi et al. 1997). The local people call these storms “Kalbaishakhi” or “Nor’wester” with fear.

This time, unfortunately, any AWSs or ARGs of ours were not under the disturbances, since the ARG at Mymensingh was just before the installation. However, the BMD radar caught the echo of the disturbances. In this image, many cloud systems moving east–southeastward had elliptical shapes, with their major axes being parallel to the direction of the movement of systems (Fig. 7a). The size of echoes was 10–30 km. Many meso-scale disturbances developed over the northern slope of the Meghalaya Mountains. They crossed the ridge and moved into northern Bangladesh.

The system somewhere to the southwest of 91° E, 25° N at 19:41 local time induced the tornadoes. Although the “hook echo” is not clearly seen, the elliptical shape does not controvert the possibility that the system has the supercell (Houze 1993) structure.

4.2 Case II: 23 May 2004

The cloud system occurred in early morning on 23 May 2004 and caused gusty winds. Some launches capsized, and hundreds of local people died or were lost during the storm on the Meghna river downstream of Dhaka. This type of river traffic accident occurs very frequently in this country.

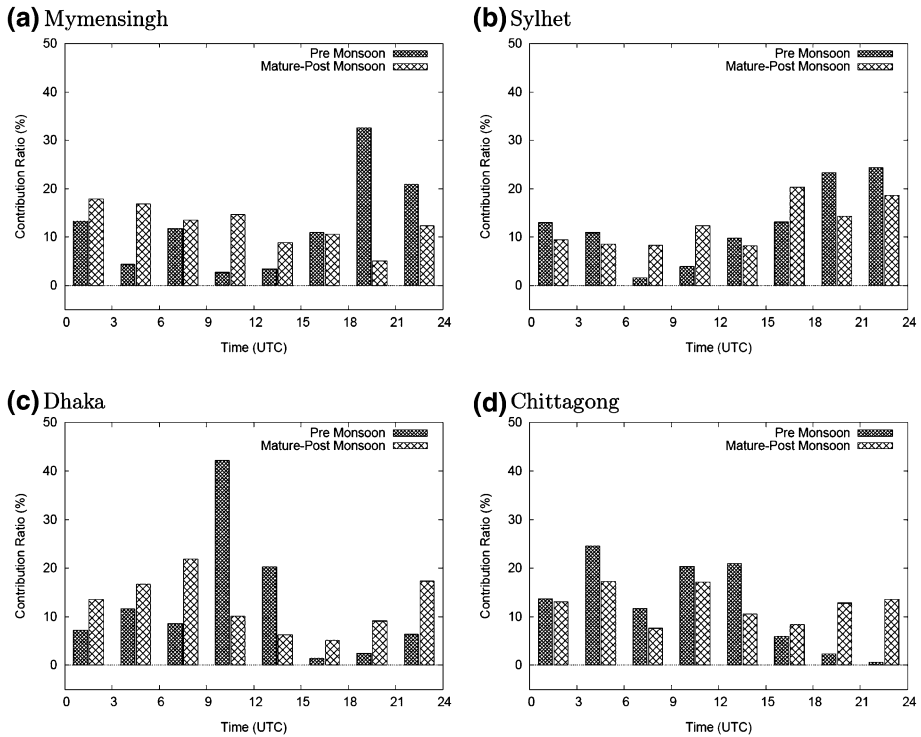


Fig. 6 Contribution ratio of rainfall within 3-hourly UTC time categories indicated by the values on the horizontal axis at (a) Mymensingh, (b) Sylhet, (c) Dhaka and (d) Chittagong. As is shown in the text, the contribution ratios for the pre-monsoon season are calculated from data for January to May, while those for mature and post-monsoon seasons are obtained with raingauge records for July to December

The echo of Dhaka's radar (Fig. 7b) shows the strong convective rain band and trailing stratiform cloud area with a size of hundreds of kilometers. The structure is largely different from that in the case of 14 April, in both size and shape.

This system was captured by our AWS at Dhaka. At almost the same time of the passage of the convective rain band seen in the radar echo, the AWS indicated very strong rainfall, 3.5 mm/min (Fig. 8a). A meso-high pressure system (Fig. 8b) and sudden temperature decrease (Fig. 8c) was clearly observed. Simultaneously, a strong northwesterly gusty wind was observed (Fig. 8d, e). This feature is similar to the meso-scale rainbands shown by Houze (1993).

It is noteworthy that the structures of the disturbances in these two cases are different from each other, while both of them occur in the same pre-monsoon season. This may be most clearly seen by comparing the radar echo in Fig. 7.

5 Summary

We analyzed some meso-scale characteristics of disturbances that bring about strong rainfall in pre- and mature monsoon seasons in Bangladesh using data that included those obtained by AWS and several ARGs installed by our research team.

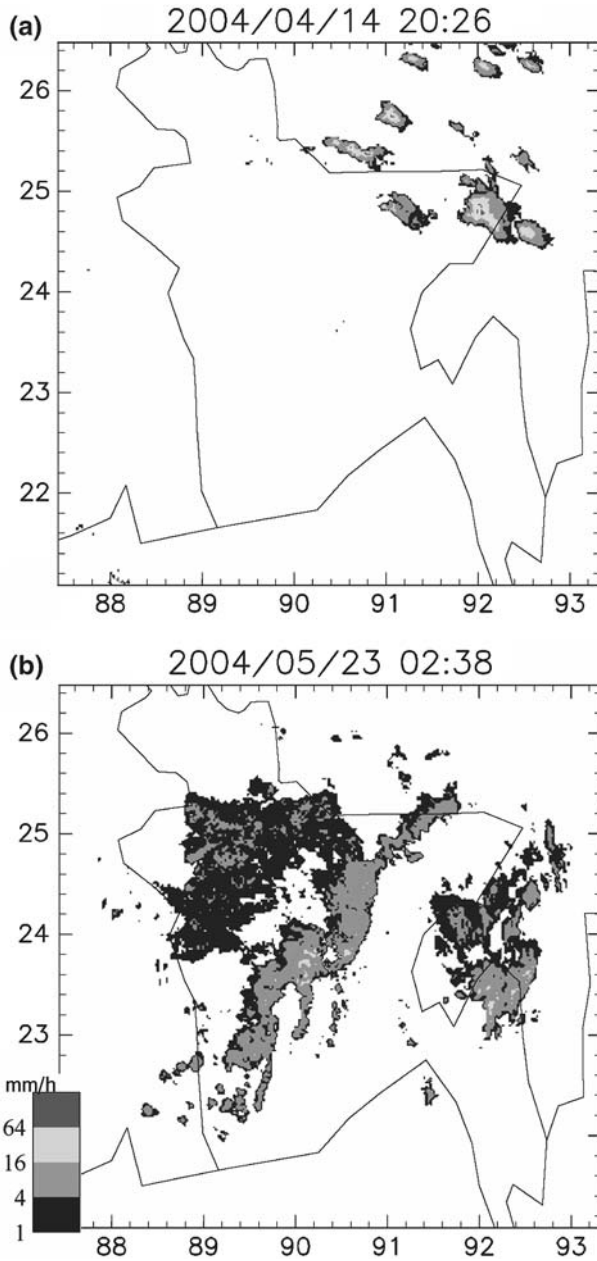
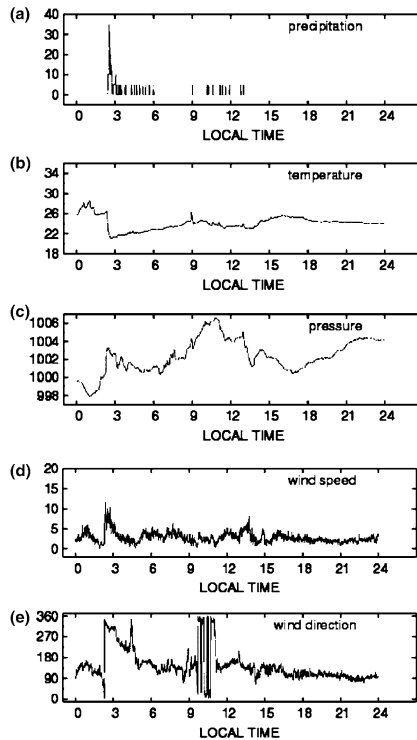


Fig. 7 Radar echo of Dhaka radar at (a) 20:26 local time on 14 April 2004, (b) 02:38 local time on 23 May 2004. Rainfall intensities are shown in the legend. *Vertical and horizontal axes* are the latitude and longitude, respectively

From the radar images in summer 2001 (16–18 July), features of the systematic diurnal variation in this area was elucidated. On these days, the diurnal evolutions of convective activity were remarkably similar to each other, implying that this pattern can be understood

Fig. 8 Record of Dhaka AWS on 23 May 2004. **(a)** Rainfall (unit: 0.1 mm per minute), **(b)** temperature (degrees Celsius), **(c)** pressure (hectopascals), **(d)** wind speed (meters per second) and **(e)** wind direction (degrees). The meso-scale severe storm passed over the AWS site just after 2 a.m.



as a typical response of local cloud systems to the diurnal variation in short-wave radiation intensity under some summer monsoon situations.

The ARG data show the difference in characteristics of rainfall between pre- and mature monsoon seasons. The short intense downpour tends to occur more frequently in the pre-monsoon season than the mature monsoon season. The pre-monsoon rainfall also has clear diurnal variation with a peak that is more strongly concentrated in time. The peak time is different from location to location. In northern parts it is found between midnight and early morning, while it is observed in the daytime in central to western parts of country.

Two disaster cases caused by meso-scale disturbances were analyzed from our AWS and ARG data and from the radar data of BMD at Dhaka. Although they occurred in the same season, the structures were largely different from each other. The disturbance that brought about tornadoes had a supercell structure, while another one that caused the tragic river water transport accident had a meso-scale rain-band structure. The latter case was captured by the AWS located at Dhaka. Sudden temperature, wind and pressure changes were observed clearly, showing the typical structure of such a type of convective rain band.

These results clearly show the potential of the modern meteorological instruments, such as radar, AWSs and ARGs, to resolve the meso-scale structures of disturbances that develop over the area in south Asia. They also indicate the difference in characteristic of meso-scale cloud systems evolving over this area. Construction of observation systems that are suitable for the prediction of severe meso-scale storms is highly expected to mitigate the damage caused by atmospheric disasters. Thus, the future improvement of the observation network is necessary for both the advance of science and disaster mitigation in local society.

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