Asymmetric thermodynamic structure of monsoon depression revealed in microwave satellite data

The central parts of India receive 80–90% of rainfall during the monsoon season (June–September). A major portion of rainfall occurring over these parts is associated with monsoon depressions moving across the area. During the monsoon season, generally 6–7 monsoon depressions form over north Bay of Bengal and move along the monsoon trough. These systems have the potential to produce widespread distribution, with very heavy to exceptionally heavy rainfall. These synoptic systems attracted the attention for serious research by many researchers[1–5].

One of the important aspects of monsoon depression is the asymmetric distribution of rainfall around its centre. Chowdhury and Gaikwad[6], Venkataraman *et al.*[7], and Rajamani and Rao[8] have shown that a primary zone of the heaviest rainfall occurs in the south-west sector about 200 to 400 km from the centre, while a secondary zone of comparatively less rainfall is located about 800 km west of the depression centre. The area around the first 100 km of the depression centre is generally free from intense rainfall activities. Rajamani and Rao[8] suggested that this observed feature of maximum zone of rainfall over the south-west sector can be explained by the omega (ω) equation for the vertical velocity. Due to the maximum pressure gradient south of the centre, the maximum vorticity at the surface would be in that region and minimum at west to north-west. Rao[9] speculated that at the initial stage as a depression over the sea, it might have a uniform pattern of rainfall. Due to paucity of observations over the north Bay of Bengal, this aspect was however not confirmed. The distribution of water vapour, cloud amount, and cloud liquid water content around the depression over the sea are also not examined. With the availability of geophysical products derived from microwave satellite data, it is now possible to examine these aspects more in detail. Two main objectives of this scientific communication are: (i) To demonstrate the potential of use of satellite microwave radiometry, for monitoring the formation and development of synoptic systems like monsoon depression over the sea. (ii) To confirm the asymmetric thermodynamic structure of monsoon depression during the initial stage of depression over the sea, where it is stationary.

We have used very high-resolution (of the order of 25 km) daily satellite microwave data to prepare the composite thermodynamic structure of monsoon depressions over the north Bay of Bengal.

Special Sensor Microwave/Imager (SSM/I) geophysical products are being produced as part of National Aeronautics and Space Administration's (NASA) pathfinder programme. The SSM/I was flown by the Defense Meteorological Satellite Programme (DMSP) on operational polar orbiting platforms. SSMI is a scanning microwave radiometer that operates at four frequencies, 19.35, 22.235, 37.0 and 85.5 GHz, respectively. SSM/I data have been earlier used to examine large-scale aspects of monsoon circulation[10,11]. The products that we have used have been obtained from the Remote Sensing Systems, Santa Rosa, USA in binary format. Each binary data file consists of 0.25×0.25 degree grids, morning and evening data separately. A unified physically-based algorithm was used to simultaneously retrieve wind speed (10 m), water vapour, cloud water and rain rate[12,13]. We have used daily water vapour, cloud liquid water and rain rate data at a resolution of 0.25×0.25 degrees to prepare the composite of thermodynamic structure around the monsoon depression. The rms accuracies of water vapour and cloud liquid water are 1 mm and 0.03 mm respectively. However, these data are available only over the ocean. Since the DMSP satellite is a low earth orbit satellite, data covering the whole area of monsoon depression cannot be obtained in one satellite pass. Therefore, data from many satellite passes are to be averaged to reveal the spatial distribution of thermodynamic parameters around the monsoon depression.

We have considered 10 monsoon depressions formed over north Bay of Bengal during the period 1989 to 1999. The cases of monsoon depressions considered are shown in Table 1. Seventeen cases have been used to prepare the composites. The centre of monsoon depression as given in the India Meteorological Department (IMD) reports and the corresponding time in Universal Coordinate time (UTC) are also given in Table 1. These cases have been carefully selected such that they all are of the same inten-

Table 1. Monsoon depressions considered for the composite analysis

Date	Time (UTC)	Latitude	Longitude
16 July 1989	03	16.5E	86.1N
	12	17.1E	85.0N
21 July 1989	03	–	–
	12	18.0N	87.6E
20 August 1990	03	19.5N	89.5E
	12	20.0N	88.0E
1 June 1991	03	18.0N	88.5E
	12	20.0N	89.5E
27 July 1991	03	20.5N	90.0E
	12	20.5N	88.5E
16 September 1995	03	19.0N	90.1E
	12	20.0N	89.2E
12 June 1996	03	–	–
	12	11.0N	86.0E
13 June 1996	03	12.5N	83.0E
	12	13.0N	82.0E
13 June 1998	03	–	–
	12	17.5N	87.5E
27 July 1999	03	21.0N	89.0E
	12	21.0N	88.5E

sity. And at the selected position, they are quasistationary. Special care also was taken to choose the depressions which are away from the coast, so that data from all sectors can be used for averaging. The averaging has been done with respect to a common origin. For individual cases, this common origin coincides with the centre of monsoon depression, as reported in IMD reports. Lau and Crane[14] who have compared the satellite and surface observations of cloud patterns in synoptic scale circulation systems, followed a similar method.

Figure 1 *a–c* shows the composite spatial distribution of atmospheric water vapour (mm), cloud liquid water content (mm) and precipitation rate (mm/h). The ordinate (abscissa) of each panel represents the latitudinal (longitudinal) displacements from the common origin, to which the individual reference data are aligned. The common origin is marked as black circle in these panels. Atmospheric water vapour exceeding 70 mm is observed around the monsoon depression (Figure 1 *a*). The 70 mm isoline extends more towards north of the common origin. At about 5° away from the common origin, the values are of the order of 62.5 mm. The spatial pattern does not show explicitly any preferred maxima. There is however a very large gradient in the western sector of the common origin.

The distribution of cloud liquid water content (Figure 1 *b*) shows a maximum exceeding 1 mm, about 200 km southwest of the common origin. In the northeast and southeast sectors, these values are generally less than 0.25 mm. The distribution of precipitation rate also shows an asymmetry pattern with clear-cut maxima in the south-west sector, around 200–300 km away from the common origin (Figure 1 *c*). There the precipitation rate exceeds 12–14 mm/h, which is equivalent to about 300 mm in 24 h. Within about 100 km of the common origin, there is not much rainfall. Secondary maximum is observed in the north-east sector with amounts exceeding 6 mm/h. The Figure 1 *b* and *c* clearly reveals that maximum precipitation in the south-west sector is due to the maxima in the cloud liquid water content observed in the south-west sector. It may be mentioned that on the other hand, atmospheric water vapour is distributed more or less uniformly around the centre. The maximum values of cloud liquid water content in the south-west sector indicate the presence of deep convective clouds, which may be ultimately linked to large vertical velocity observed in the south-west sector of the monsoon depression. It will be interesting to examine the spatial distribution of different types of clouds around the monsoon depression. For that very high resolution (of the order of 25 km used in this study) are required. We plan to examine this important aspect in a separate study.

Even though the composite pattern clearly reveals the asymmetric structure of monsoon depression, it may be interesting to examine the spatial structure for one or two individual cases. For this purpose, we have used the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) data (http://trrmm.gsfc.nasa.gov). The TMI represents the first microwave spacecraft sensor capable of accurately measuring sea-surface temperatures through clouds[15]. The daily TMI data also are available at Remote Sensing Systems, USA at a resolution of 0.25° × 0.25°. However these data are available only since 1998. We have examined the spatial pattern of cloud liquid water content and precipitation rate of a monsoon depression of 27 July 1999 over the Bay of Bengal derived from the TMI data.

Figure 2 *a* and *b* shows the spatial structure of precipitation rate (mm/h) and cloud liquid water content (mm). The centre of the depression (21°N, 89°E) is shown as a black circle. Maximum cloud liquid water content and precipitation rate are observed about 2° away from the centre and concentrated in the south-west sector. Cloud liquid water content in the south-west sector exceeded 0.3 mm, while the precipitation rate exceeded 2 mm/h. However, the precipitation pattern of the individual case is not as smooth as the composite pattern. Nevertheless, the south-west sector, about 200 km away from the centre, is certainly an area with large convection and intense rainfall.

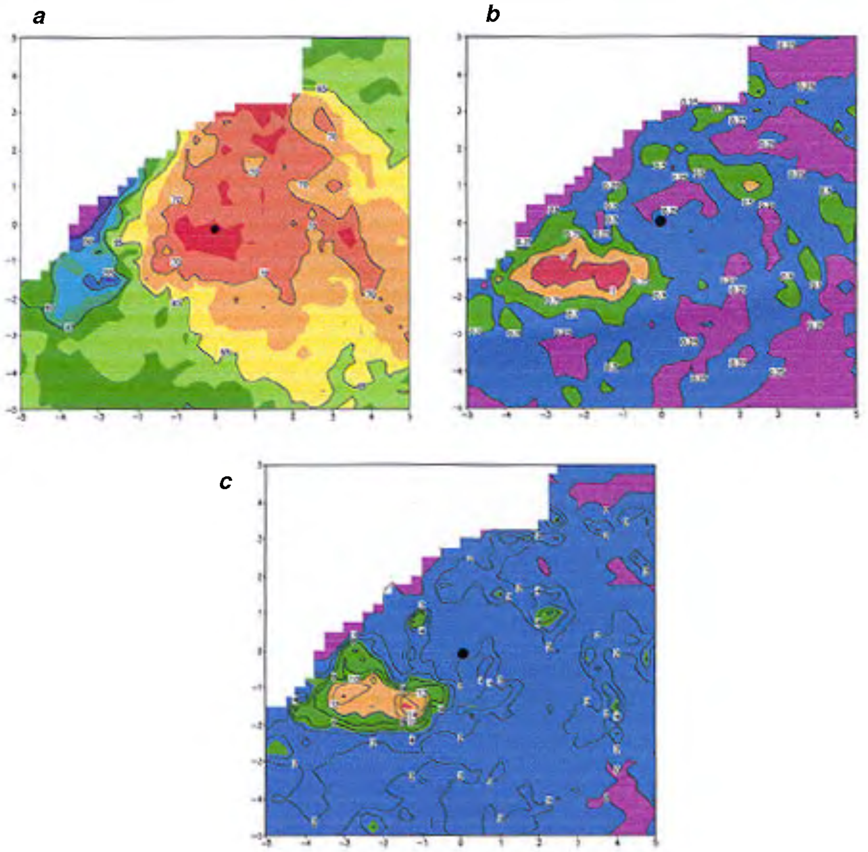

Figure 1. Composite distribution of ***a***, atmospheric water vapour (mm); ***b***, cloud liquid water content (mm); and ***c***, precipitation rate (mm/h) averaged for 17 cases of monsoon depression formed over north Bay of Bengal during the monsoon season (June–September) for the period 1989–1999. The ordinate (abscissa) of each panel represents the latitudinal (longitudinal) displacements from the common origin to which the individual reference data are aligned. The common origin is marked as a black circle in each panel.

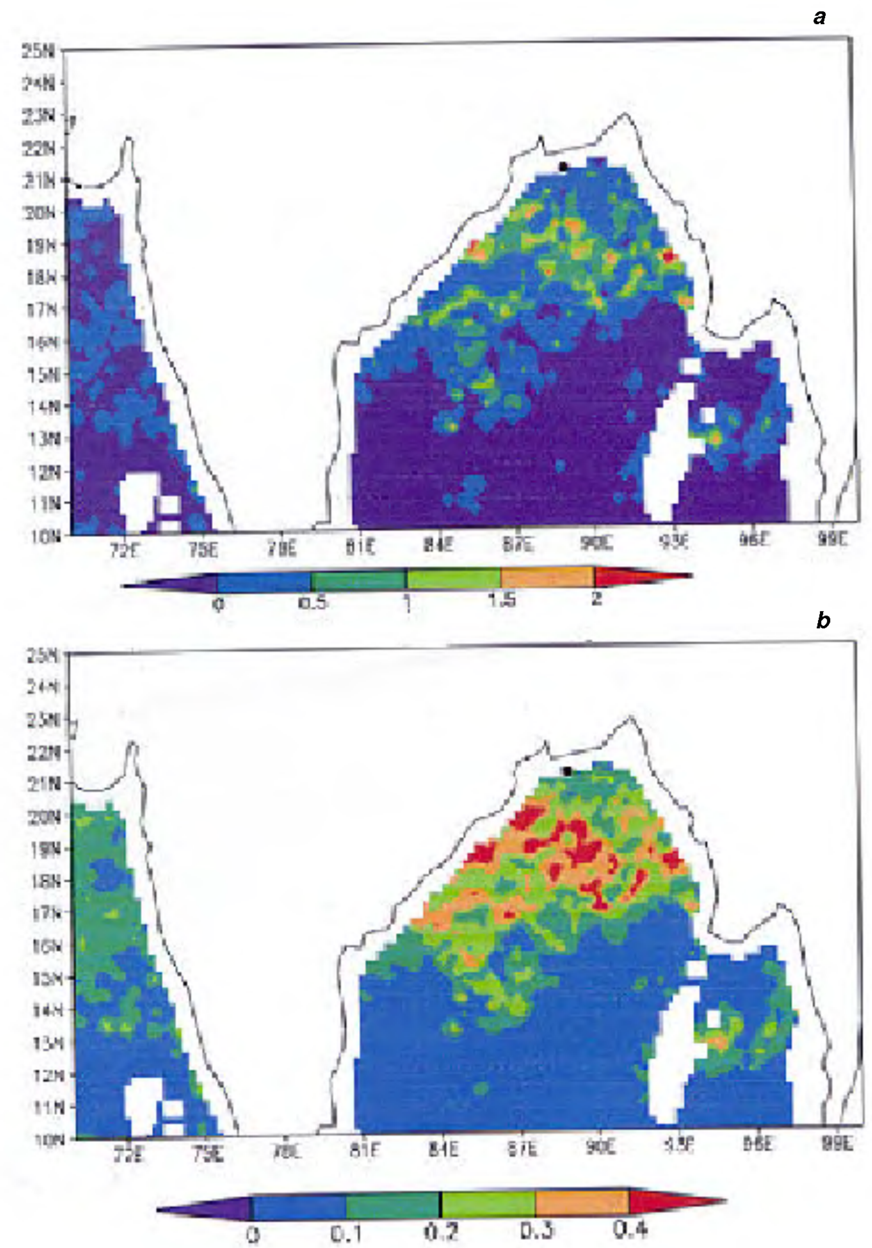

Figure 2. The spatial distribution of ***a***, precipitation rate (mm/h); and ***b***, cloud liquid water content (mm) on 27 July 1999, derived from the TMI data. The centre (21°N, 89°E) of the monsoon depression is shown as black circle.

In this study, with the microwave satellite data, we have confirmed the asymmetric distribution of precipitation associated with monsoon depressions over north Bay of Bengal. This asymmetric distribution of precipitation is due to the large values of cloud liquid water content in the south-west sector, which indicates the presence of very deep convective clouds. The present study also demonstrated the utility of the geophysical parameters derived from microwave satellite data for monitoring and analysis of synoptic systems like monsoon depression over Indian seas. Availability of data from the recently launched IRS P4 and forthcoming MeghaTropiques satellites will help the synoptic meteorologists and numerical weather prediction-modelling community in a very big way.

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