On the turbulence and levels of condensation and free convection in the troposphere associated with local severe storms and their distribution over Bangladesh and neibourhood during the pre-monsoon season

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Abstract: Attempts have been made to study turbulence of the atmosphere in terms of Bulk Richardson Number (BRN), the levels of condensation and free convection associated with 5 local severe storms which occurred in Bangladesh. The Bulk Richardson Number has been found to range from 80 to 300 over Bangladesh on 3 May 2009, from 20 to 120 over Bangladesh on 24 February 2010, from 20 to 80 over Bangladesh on 13 April 2010, from 20 to 120 over Bangladesh on 26 April 2010, and from 0 to 100 over Bangladesh and from 100 to 500 over Orissa and adjoining West Bengal on 11 May 2011 respectively. These values of the **Bulk Richardson Number (BRN)** indicate unstable atmosphere and extreme turbulence, delineating the environmental conditions favorable for supercell development. The **Bulk Richardson Number (BRN)** is found to be maximum in the south or southwest of Bangladesh in the morning of the occurrence dates of most cases

The Levels of Free Convection (LFCs) have been found to be below 802 hPa over Dhaka on the dates of occurrence of four local severe storms except 3 May 2009, when LFC is found to be 579.91. The exception may be due to the place and time of occurrence of the storms and the station of which data has been used. The LFCs indicate lower altitudes one day before the dates of occurrence of local severe storms. The high pressure of LFC are found favourable for the development of local severe storms. The study reveals that LFCs become higher in around the place of occurrence prior to the occurrence of local severe storms.

Lifted Condensation Level (LCL) over Dhaka on the dates of occurrence of 5 local storms has been found to occur at relatively low altitudes, i.e. LCL values are higher in terms of pressure. Such lower altitudes of LCL indicate favourable situation for the development of convective storms. On the dates of non-occurrence of local severe storms, the LCL shows higher altitudes in most cases, which are not favourable for the occurrence of local severe storms. The spatial distribution of LCL has indicated favourable conditions for the development of deep convection in the troposphere on the dates of occurrence of local severe storms. The development of strong deep convection has been responsible for the occurrence of local severe storms.

Key words: Turbulence, Lifted Condensation Level (LCL) and Level of Free convection (LFC)

1. Introduction

A thunderstorm, also known as an electrical storm, a lightning storm, thundershower or simply a storm, is a form of turbulent weather characterized by the presence of lightning and its acoustic effect on the Earth's atmosphere known as thunder (NWS, 2005). The meteorologically assigned cloud type associated with the thunderstorm is the cumulonimbus. Thunderstorms are usually accompanied by strong winds, heavy rain and sometimes snow, sleet, hail, or no precipitation at all. Those that cause hail to fall are called hailstorms. Thunderstorms may line up in a series or rainband, known as a squall line. Strong or severe thunderstorms may rotate, known as supercells. While most thunderstorms move with the mean wind flow through the layer of the troposphere that they occupy, vertical wind shear causes a deviation in their course at a right angle to the wind shear direction.

Thunderstorms result from the rapid upward movement of warm, moist air. They can occur inside warm, moist air masses and at fronts. As the warm, moist air moves upward, it cools, condenses, and forms cumulonimbus clouds that can reach heights of over 20 km (12.45 miles). As the rising air reaches its dew point, water droplets and ice form and begin falling the long distance through the clouds towards the Earth's surface. As the droplets fall, they collide with other droplets and become larger. The falling droplets create a downdraft of air that spreads out at the Earth's surface and causes strong winds associated commonly with thunderstorms.

The thunderstorms, which occur during the Pre-monsoon season in Bangladesh are severe, causing loss of lives and damages to properties every year. It is because of the fact that warm and moist air flows from the Bay of Bengal in the south to the land areas of Bangladesh and at the same time cold and dry air flows from the northwest and/ or north. These two types of air masses interact over Bihar/West Bengal and adjoining Bangladesh, causing sufficient instability and convection in the troposphere. As a result, severe thunderstorms occur over the country and adjoining areas.

Moderate-to-severe turbulence associated with thunderstorms constitutes a significant hazard to commercial aviation. Trier *et al*. (2009) simulated the environment supporting widespread turbulence within the upper-level outflow of a Mesoscale Convective System (MCS). They found that the turbulence is its location several hundred kilometers from the active deep convection (i.e., large reflectivity) regions of the MCS. The MCS life cycle and the turbulence environment in its upper-level outflow are studied using Rapid Update Cycle (RUC) analyses and cloud-permitting simulations with the Weather Research and Forecast Model (WRF). It is demonstrated that strong vertical shear beneath the MCS outflow jet is critical to providing an environment that could support dynamic (e.g., shearing type) instabilities conducive to turbulence. Comparison of a control simulation to one in which the temperature tendency due to latent heating was eliminated indicates that strong vertical shear and corresponding reductions in the local Richardson number (Ri) to ~0.25 at the northern edge of the anvil were almost entirely a consequence of the MCS-induced westerly outflow jet. The large vertical shear is found to decrease Ri both directly, and by contributing to reductions in static stability near the northern anvil edge through differential advection of (equivalent) potential temperature gradients, which are in turn influenced by adiabatic cooling associated with the mesoscale updraft located upstream within the anvil. On the south side of the MCS, the vertical shear associated with easterly outflow was significantly offset by environmental westerly shear, which resulted in larger Ri and less widespread model turbulent kinetic energy (TKE) than at the northern anvil edge.

In the past, a number of studies have been made about severe thunderstorms known as Nor'westers or Kalbaishakhis to find out the secrets of the atmospheric conditions favourable conditions associated with them. Even then, more studies are required in this regard. The studies made by Akram andKarmakar(1998), Ananthakrishnan *et al.*(1965), Bose (1955), Chowdhury (1961), Chowdhury and Karmakar (1986), Chowdhury *et al.* (1991), Das *et al.*,(1994), Haydu and Krishnamurty (1981) Karmakar (2005), Karmakar and Alam (2005, 2005, 2006), 2007, 2007, 2011), Koteswaram and Srinivasan (1958), Mukherjee and Bhattacharya (1972) and Mukherjee *et al.* (1977) may be cited as examples. No studies have been made in relation to the turbulence and levels of condensation and free convection associated with thunderstorms over Bangladesh.

The present study has been undertaken to study turbulence, Lifted Condensation Level (LCL) and Level of Free Convection (LFC) associated with thunderstorms over Bangladesh.

2. Theoretical background

2.1 Bulk Richardson Number

The **Bulk Richardson Number (BRN)** is a dimensionless number in meteorology relating vertical stability and vertical shear (generally, stability divided by shear). It represents the ratio of thermally produced turbulence and turbulence generated by vertical shear. High values indicate unstable and/or weakly-sheared environments; low values indicate weak instability and/or strong vertical shear. Generally, values in the range of around 50 to 100 suggest environmental conditions favorable for supercell development. BRN is calculated with the following formula:

BRN= CAPE / (0.5*(shear differential)^2)

Where

$$\mathrm{CAPE} = \int_{z_f}^{z_n} g \left(\frac{T_{\mathrm{v,parcel}} - T_{\mathrm{v,env}}}{T_{\mathrm{v,env}}} \right) dz$$

And the shear differential may be calculated using the winds and geometrical heights at 900–500-mb pressure heights. Dupilka and Gerhard (2006) calculated the shear by:

$$\mathrm{SHR} = \frac{\sqrt{(u_2 - u_1)^2 + (v_2 - v_1)^2}}{|z_2 - z_1|}$$

2.1.1 *Critical values and interpretation of* BRN

There is no exact interpretation of BRN values but, in general, for a BRN less than 10, vertical shear dominates over buoyancy and the storm will likely be eviscerated by the shear. For BRN values between 10 and 45, the shear tends to balance the buoyancy favoring strong convective supercells. A BRN larger than 40 supports ordinary cell or multicell convective storms but due to updraft tilt stemming from the lack of shear, supercells are not likely to be observed.

2.1.2 *Difficulties in interpretation*

Different combinations of Convective Available Potential Energy (CAPE) and shear can lead to identical BRN values so the same BRN can represent a myriad of convective situations. Another source of difficulty in forecasting convective storm potential with BRN is that the BRN does not include important assessment parameters like wind direction or air moisture. Insignificant levels of CAPE and shear can also produce significant BRN so it is important that CAPE or the lifted index (LI) is used as a primary measure of atmospheric instability first. Since CAPE is difficult to compute by hand, a computer program is often used to calculate and report BRN given a vertical temperature profile.

2.2 *Level of Free Convection (LFC)*

The **level of free convection** (**LFC**) is the altitude in the atmosphere where the temperature of the environment decreases faster than the moist adiabatic lapse rate of a saturated air parcel at the same level. The usual way of finding the LFC is to lift a parcel from a lower level along the dry adiabatic lapse rate until it crosses the mixing ratio line of the parcel: this is the lifted condensation level (LCL). From there on, follow the moist adiabatic lapse rate until the temperature of the parcel reaches the air mass temperature, at the equilibrium level (EL). If the temperature of the parcel along the moist adiabat is warmer than the environment on further lift, one has found the LFC.

A LFC closer to the surface is more supportive of tornadoes in a severe thunderstorm.

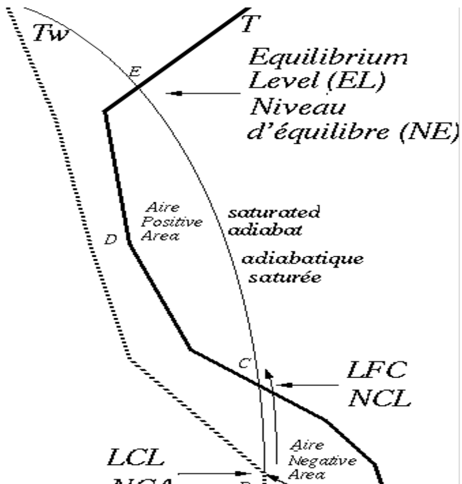

Fig. 1.1 Diagram showing an air parcel path when raised along B-C-E compared to the surrounding air mass Temperature (T) and humidity (Tw)

2.2 The **lifted condensation level** or **lifting condensation level** (**LCL**)

The **lifted condensation level** or **lifting condensation level** (**LCL**) is formally defined as the height at which the relative humidity (RH) of an air parcel will reach 100% when it is cooled by dry adiabatic lifting. The RH of air increases when it is cooled, since the amount of water vapor in the air (i.e., its specific humidity) remains constant, while the saturation vapor pressure decreases almost exponentially with decreasing temperature. If the air parcel is lifting further beyond the LCL, water vapor in the air parcel will begin condensing, forming cloud droplets. (In the real atmosphere, it is usually necessary for air to be slightly supersaturated, normally by around 0.5%, before condensation occurs; this translates into about 10 meters or so of additional lifting above the LCL.) The LCL is a good approximation of the height of the cloud base which will be observed on days when air is lifted mechanically from the surface to the cloud base (e.g., due to convergence of air masses).

As an air parcel is lifted, its pressure and temperature decrease. Its dew point temperature also decreases when the pressure is decreased, but not as quickly as its temperature decreases, so that if the pressure is decreased far enough, eventually the air parcel's temperature will be equal to the dew point temperature at that pressure. This point is the LCL; this is graphically depicted in the diagram.

Using this background, the LCL can be found on a standard thermodynamic diagram as follows:

1. Start at the initial temperature (T) and pressure of the air parcel and follow the dry adiabatic lapse rate line upward (provided that the RH in the air parcel is less than 100%, otherwise it is already at or above LCL).
2. From the initial dew point temperature (Td) of the parcel at its starting pressure, follow the line for the constant equilibrium mixing ratio (or "saturation mixing ratio") upward.
3. The intersection of these two lines is the LCL.

3. Data used

In the present study, following data have been collected from Bangladesh Meteorological Department (BMD) and other sources:

- Rawinsonde data of Bangladesh and Indian stations during March-May of 2010. The upper stations under study are given in Fig. 3.1. These rawinsonde data has been collected from BMD and the Department of Atmospheric Science, College of Engineering, University of Wyoming, Laramie, USA.
- Five cases of local severe storms.

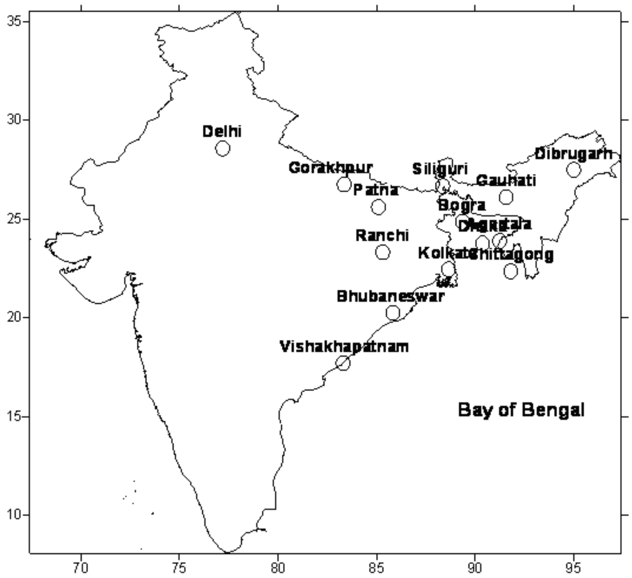

Fig. 2.2: Rawinsonde stations under study

4. Results and discussion

4.1 Spatial distribution of Bulk Richardson Number

The **Bulk Richardson Number (BRN)** is a dimensionless number in meteorology relating vertical stability and vertical shear (generally, stability divided by shear). It represents the ratio of thermally produced turbulence and turbulence generated by vertical shear. High values indicate unstable and/or weakly-sheared environments; low values indicate weak instability and/or strong vertical shear. Generally, values in the range of around 50 to 100 suggest environmental conditions favorable for supercell development.

Spatial distributions of **Bulk Richardson Number (BRN)** for the dates of occurrence of 5 local severe storms under study are given in Figs. 4.1-4.5.

In the morning of 3 May 2009, the Bulk Richardson Number (BRN) ranges from 80 to 300 over Bangladesh and adjoining areas (Fig. 4.1). These values indicate unstable atmosphere and extreme turbulence, and suggest environmental conditions favorable for supercell development. On 24 February 2010, the Bulk Richardson Number (BRN) ranges from 20 to 120 over Bangladesh (Fig. 4.2). These values also indicate moderate to strong unstable atmosphere with moderate turbulence and suggest environmental conditions favorable for the development of local severe storms. Fig. 4.3 shows the spatial distribution of **Bulk Richardson Number (BRN)** on 13 April 2010 when Bulk Richardson Number (BRN) is found to range from 20 to 80 over Bangladesh indicating weak to moderate instability and turbulence over the country.

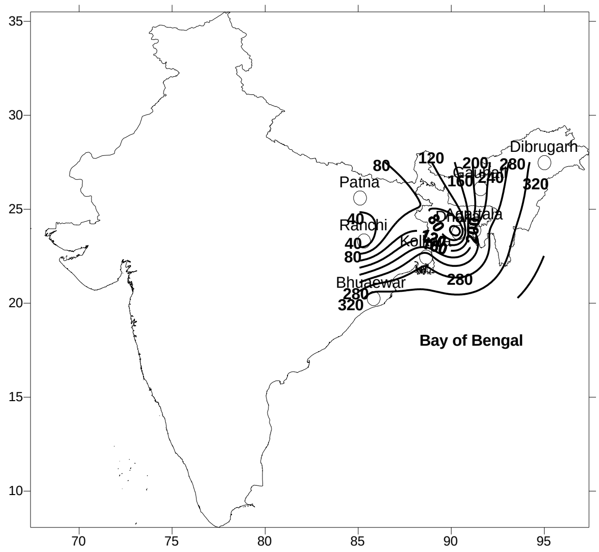

Fig.4.1: Spatial distribution of Bulk Richardson Number on 03 May 2009 at 00 UTC

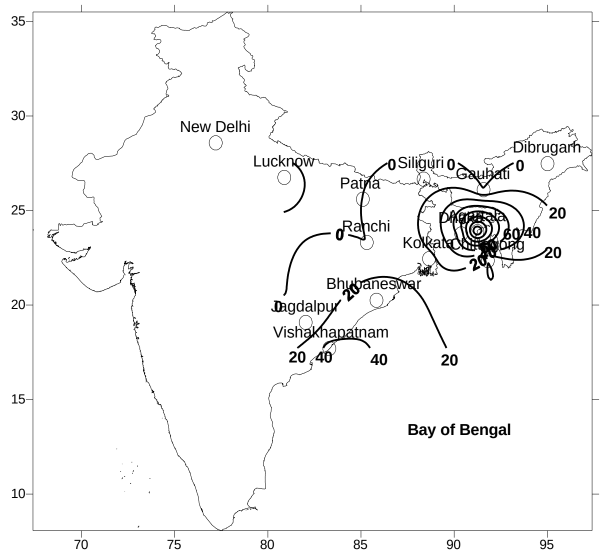

Fig.4.2: Spatial distribution of Bulk Richardson Number on 24 February 2010 at 00 UTC

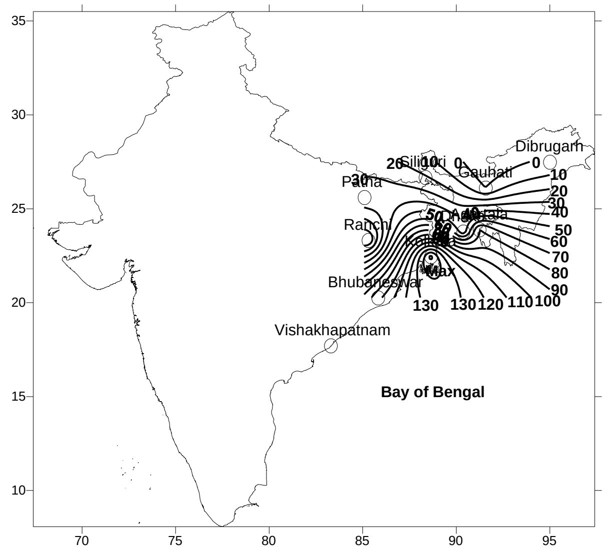

Fig. 4.3: Spatial distribution of Bulk Richardson Number on 13 April 2010 at 00 UTC

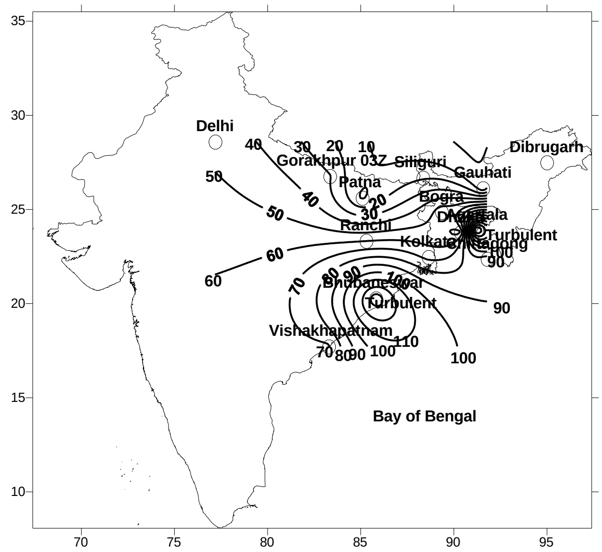

Fig. 4.4: Spatial distribution of Bulk Richardson Number on 26 April 2010 at 00 UTC

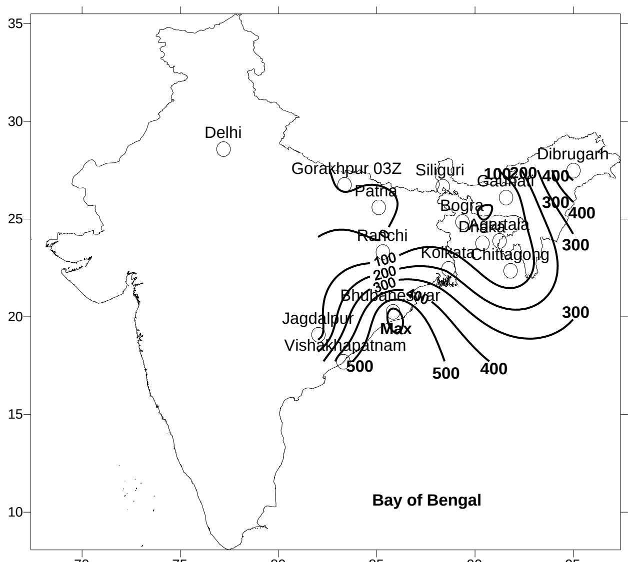

Fig. 4.5: Spatial distribution of Bulk Richardson Number on 11 May 2011 at 00 UTC

On 26 April 2010, Bulk Richardson Number (BRN) ranges from 20 to 120 over Bangladesh having maximum value over eastern part of Bangladesh (Fig. 4.4). Another maximum area of Richardson Number (BRN) ranging 50-120 lies over Orissa of India, indicating weak to moderate instability and turbulence, and suggests environmental conditions favorable for supercell development. In the morning of 11 May 2011 (Fig. 4.5), the Bulk Richardson Number ranges from 0 to 100 over Bangladesh and from 100 to 500 over Orissa and adjoining West Bengal indicating significant turbulence over Bangladesh and extreme turbulence over Orissa-West Bengal as well as favourable conditions for supercell development.

It is, therefore, clear that the **Bulk Richardson Number (BRN)** is found to be favourable for strong to extreme instability and supercell development in all the cases under study. The **Bulk Richardson Number (BRN)** is found to be maximum in the south or southwest of Bangladesh in the morning of the occurrence dates of most cases.

6.4.2 Spatial distribution of LFC

The LFC (Level of Free Convection) is the level at which a lifted parcel begins a free acceleration upward to the equilibrium level. Recent preliminary research suggests that tornadoes become more likely in supercells when LFC heights are less than 2000-m above ground level. The EL (equilibrium level) is the level at which a lifted parcel becomes cooler than the environmental temperature and is no longer buoyant (i.e., "unstable”). The EL is used primarily to estimate the height of a thunderstorm anvil. The height difference between this parameter and the LCL is important when determining convection initiation. The smaller the difference between the LFC and the LCL, the more likely deep convection becomes. The LFC-LCL difference is similar to CIN (convective inhibition).

Level of Free Convection (LFC) at Dhaka on the dates of occurrence and non-occurrence of local storms at 00 UTC is shown in Table 4.1. The table shows that values of LFC are higher (lower altitudes) than 802 hPa for four cases and LFC is 579.91 on 3 May 2009. These LFCs are favourable for the development of convective storms on 24 February 2010, 13 April 2010, 26 April 2010 and 11 May 2011. It is interesting to see from the table that the LFCs indicate lower altitudes one day before the dates of occurrence of local severe storms. Normally, the LFCs should indicate lower altitudes on the dates of occurrence of local severe storms. The anomaly may be attributed to the (i) difference in time of observation and the time of occurrence of local severe storms and (ii) difference in the place of observation and place of occurrence of local severe storms.

Table 4.1: Level of Free Convection (LFC) at Dhaka on the dates of occurrence and non-occurrence of local storms at 00 UTC

Dates of non-occurrence of local severe storms	LFC (hPa) on the dates of non-occurrence of local severe storms	Dates of occurrence of local severe storms	LFC (hPa) on the dates of occurrence of local severe storms
02 May 2009	674.51	03 May 2009	579.91
23 February 2010	-	24 February 2010	802.81
12 April 2010	937.38	13 April 2010	913.36
25 April 2010	971.47	26 April 2010	947.13
9 May 2011	969.54	11 May 2011	879.85

Spatial distributions of the **Level of Free Convection (LFC)** for the dates of occurrence of 5 local severe storms under study are given in Figs. 4.6-4.10.

In the morning of 3 May 2009 (Fig. 4.6), the LFC is found to range from 650 to 800 hPa over Bangladesh with higher values in the east and west of Bangladesh. LFC of 650 hPa indicates that the LFC is at higher altitude and is not so favourable for the setting of convection in the country but the values of LFC (more than 700 hPa) over Bihar and West Bengal is at lower altitudes and is favourable for the development of convection. On 24 February 2010, the LFC ranges from 740 to 920 hPa over West Bengal, Bangladesh, Assam and Tripura, having the maximum value over Tripura and these values of LFC indicate the lower altitudes for the development of convection, which is conducive for the development of local severe storms in and around Bangladesh (Fig. 4.7).

On 13 April 2010 (Fig. 4.8), the LFC is found to range from 880 to 920 hPa over Bangladesh and its surroundings, having the maximum values over southwestern part of the country. These values of LFC are favourable for the development of local severe storms. In the morning of 26 April 2010 (Fig. 4.9), the range of LFC is 740-940 hPa over Bangladesh having the maximum value over southern part of the country and indicates that convection is likely to start at significantly lower altitude, which is very conducive for the development of local severe storms. The LFC is found to range from 720 to 880 hPa over Bangladesh and adjoining West Bengal on 11 May 2011 as shown in Fig. 4.10. These values of LFC are also favourable for the development of local severe storms. It is clear from the distributions of LFC that LFCs become higher in terms of pressure in around the place of occurrence prior to the occurrence of local severe storms.

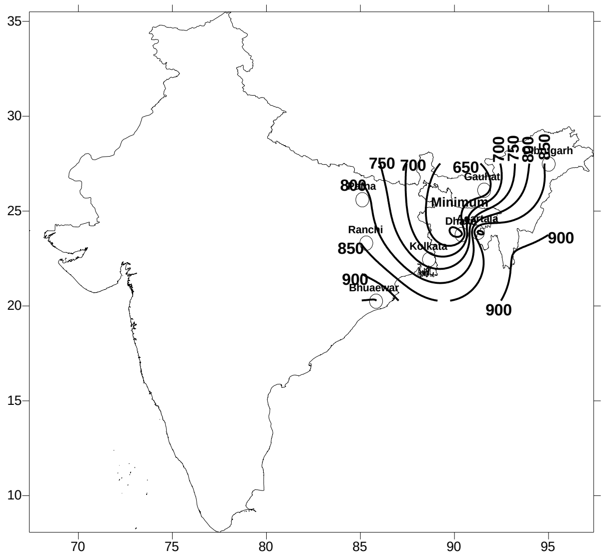

Fig. 4.6: Spatial distribution of LFC (hPa) on 03 May 2009 at 00 UTC

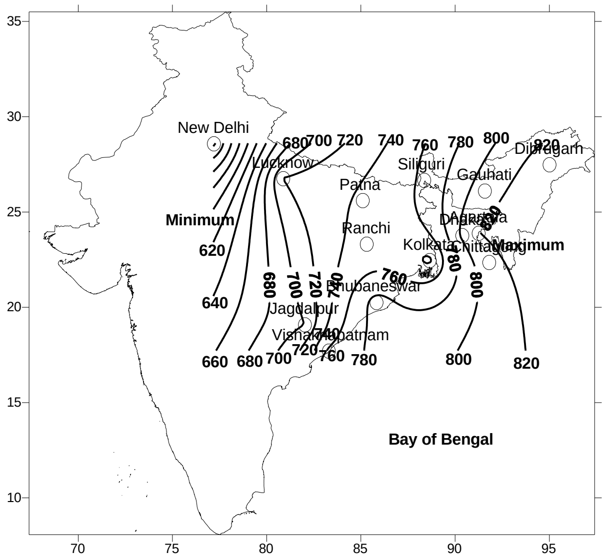

Fig. 4.7: Spatial distribution of LFC (hPa) on 24 February 2010 at 00 UTC

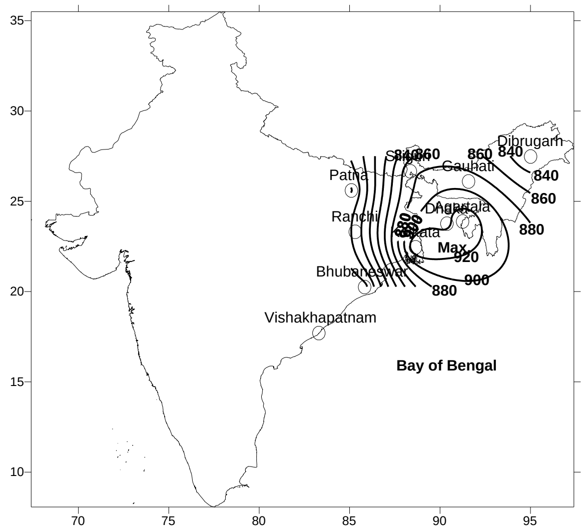

Fig. 4.8: Spatial distribution of LFC on 13 April 2010 at 00 UTC

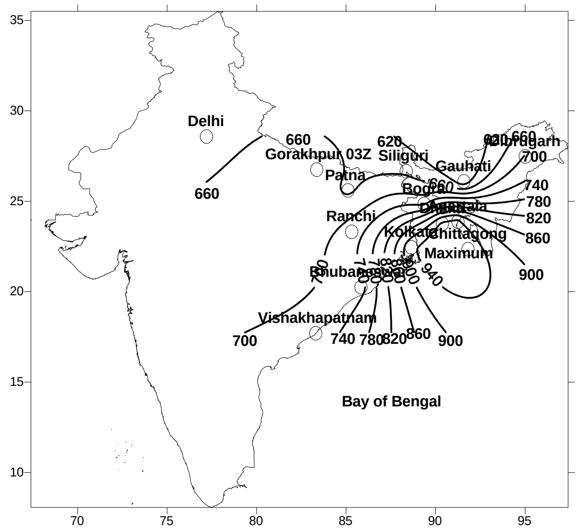

Fig. 4.9: Spatial distribution of LFC on 26 April 2010 at 00 UTC

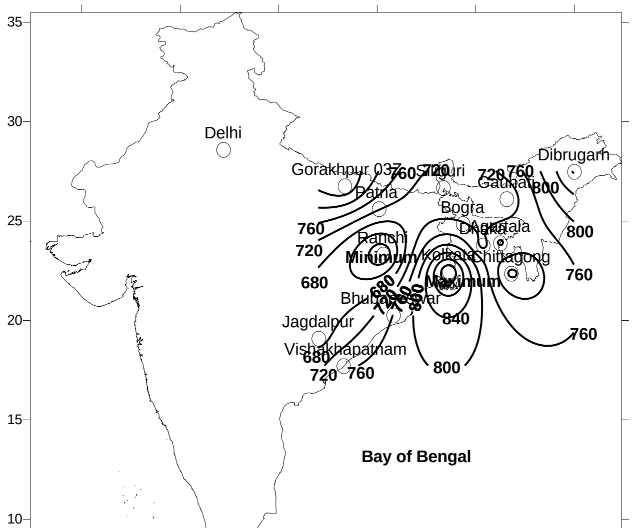

Fig. 4.10: Spatial distribution of LFC on 11 May 2011 at 00 UTC

6.4.3 Spatial distribution of LCL

Condensation Level is the altitude at which a rising air parcel reaches saturation, usually the cloud base height. The LCL is a good approximation of the height of the cloud base which will be observed on days when air is lifted mechanically from the surface to the cloud base (e.g., due to convergence of air masses).

Lifted Condensation Levels (LCL) at Dhaka on the dates of occurrence of 5 local storms under study at 00 UTC are given in Table 4.2 The Table 4.2 shows significantly higher pressure values i.e. lower altitudes. These lower altitudes indicate favourable situation for the development of convective storms. On the dates of non-occurrence of local severe storms, the LCL shows lower pressure i.e. higher altitudes in three cases on 2 May 2009, 23 February 2010 and 12 April 2010 and these values are not favourable for the development of convection. But on 25 April and 9 May 2011, LCL values are favourable for development of convection.

Table 4.2: Lifted Condensation Level (LCL) at Dhaka on the dates of occurrence and non-occurrence of local severe storms at 00 UTC

Dates of non-occurrence of local severe storms	LCL (hPa) on the non-occurrence of local severe storms	Dates of occurrence of local severe storms	LCL (hPa) on the occurrence of local severe storms
02 May 2009	907.96	03 May 2009	953.18
23 February 2010	876.55	24 February 2010	961.88
12 April 2010	959.84	13 April 2010	964.44
25 April 2010	971.47	26 April 2010	953.71
9 May 2011	972.82	11 May 2011	920.41

Spatial distributions of Lifted Condensation Level (LCL) for the dates of occurrence of 5 local severe storms under study are given in Figs. 4.11-4.15.

On 3 May 2009, the LCL ranges from 880 to 960 hPa over Bangladesh and east-northeastern India and this range of LCL are favourable for the development of moderate to deep convection/even extreme convection in the troposphere (Fig. 4.11). In the morning of 24 February 2010 (Fig. 4.12), the range of LCL is 900-920 hPa over Bangladesh, Assam and Tripura and indicates favourable situation for the development of deep convection over the country. LCL over Orissa coast and adjoining area ranges from 920 to 960 hPa, indicating deep/extreme convection.

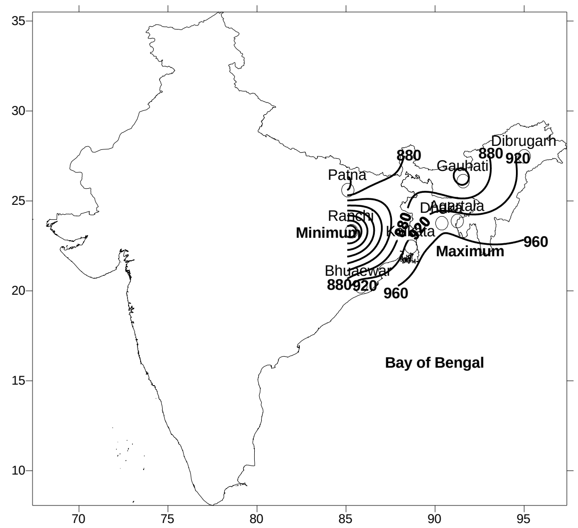

Fig. 4.11:Spatial distribution of LCL on 03 May 2009 at 00 UTC

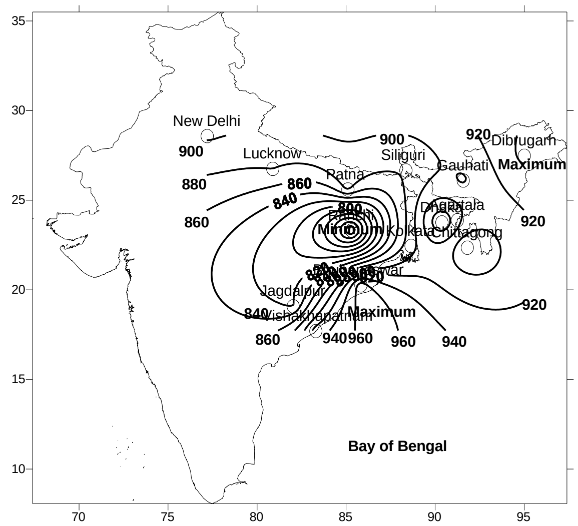

Fig4.12:Spatial distribution of LCL on 24 February 2010 at 00 UTC

On 13 April 2010 (Fig. 4.13), the value of LCL is around 950 over Bangladesh, Assam and Tripura and is good enough for the development of deep convection. Fig. 4.14 shows the spatial distribution of LCL on 26 April 2010. On this day, the LCL is from 900 to 950 hPa over Bangladesh and Assam and this value indicates favourable condition for the development of deep/extreme convection over the country and adjoining area. On 11 May 2011 (Fig. 4.15), the LCL is around 920 to 960 hPa over Bangladesh, indicating the favourable condition for the development of deep/extreme convection over the country.

From the analysis of LCL, it is seen that LCL was favourable for the development of deep/extreme convection in the troposphere on the dates of occurrence of 5 local severe storms. The development of deep/extreme convection was responsible for the occurrence of local severe storms.

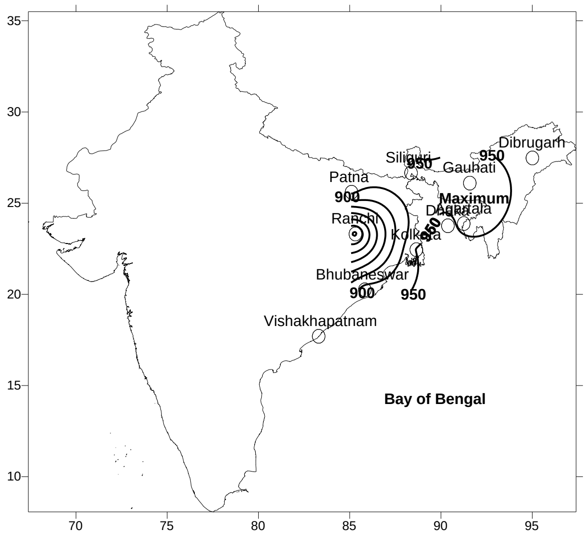

Fig. 4.13:Spatial distribution of LCL on 13 April 2010 at 00 UTC

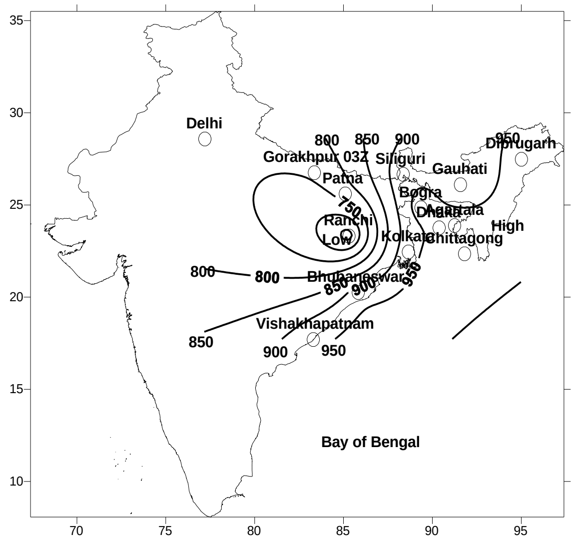

Fig.4.14 :Spatial distribution of LCL on 26 April 2010 at 00 UTC

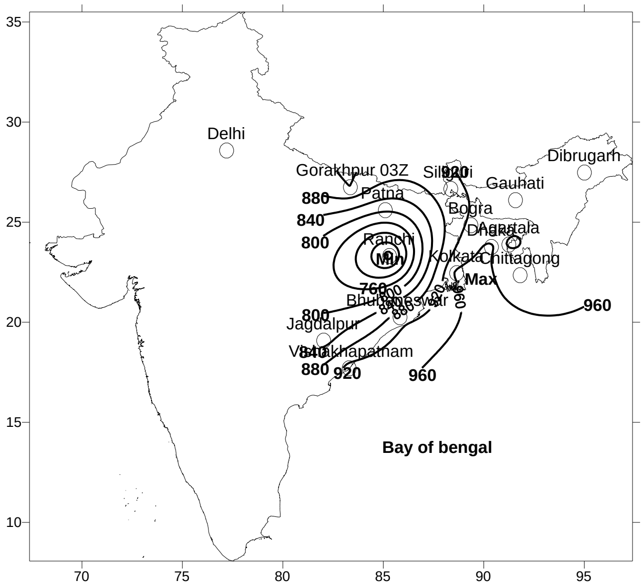

Fig. 4.15:Spatial distribution of LCL on 11 May 2011 at 00 UTC

5. Conclusions

i. The Bulk Richardson Number (BRN) ranges from 80 to 300 over Bangladesh on 3 May 2009, from 20 to 120 over Bangladesh on 24 February 2010, from 20 to 80 over Bangladesh on 13 April 2010, from 20 to 120 over Bangladesh on 26 April 2010, and from 0 to 100 over Bangladesh and from 100 to 500 over Orissa and adjoining West Bengal on 11 May 2011 respectively. These values of that the **Bulk Richardson Number (BRN)** indicate unstable atmosphere and extreme turbulence, and suggest environmental conditions favorable for supercell development.

ii. The **Bulk Richardson Number (BRN)** is found to be maximum in the south or southwest of Bangladesh in the morning of the occurrence dates of most cases.

iii. The Levels of Free Convection (LFC) are found to be below 802 hPa over Dhaka on the dates of occurrence of four local severe storms and LFC is 579.91 on 3 May 2009. The LFCs indicate lower altitudes (high pressure altitudes) one day before the dates of occurrence of local severe storms. The high pressure values of LFC are found favourable for the development of local severe storms. LFCs become higher in terms of pressure in around the place of occurrence prior to the occurrence of local severe storms.

iv. LFCs become higher in around the place of occurrence prior to the occurrence of local severe storms.

v. Lifted Condensation Level (LCL) at Dhaka on the dates of occurrence of 5 local storms revealed to occur at relatively low altitudes. Such lower altitudes of LCL indicate favourable situation for the development of convective storms. On the dates of non-occurrence of local severe storms, the LCL shows lower higher altitudes in most cases.

vi. The spatial distribution of LCL has indicated favourable conditions for the development of deep convection in the troposphere on the dates of occurrence of 5 local severe storms. The development of strong deep convection was responsible for the occurrence of local severe storms.

Acknowledgements

The present study is undertaken to investigate the mechanism of local severe storm in Bangladesh and its impact on the livelihood of the country, which is very important and timely in the present era.

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