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L E T T E R S

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A CASE STUDY OF SEVERE THUNDERSTORM OVER DELHI AND SURROUNDING AREAS ON 25th MAY 2011

1. Thunderstorms are the manifestation of the convective activity in atmosphere. It's destructive off springs are the hailstorms, lightening, high winds, heavy rains and most violent of all are the tornadoes (IMD, 1980). Essential conditions for the formation of a severe thunderstorm are (*i*) Conditional instability (*ii*) Availability of moist air at lower levels (*iii*) Insolation and orography for initial lifting of moist air at higher levels (*iv*) Presence of high lapse rate of temperature, due to dry westerly at upper levels and moist southerly/southwesterly air at lower levels (*v*) Presence of trough or cyclonic circulation in lower levels over the region. In addition, strong vertical wind shear is found to be one of the important factors for the occurrence of severe thunderstorm as the release of latent energy in an environment of strong vertical wind shear often leads to the development of severe convective storms (Stephen *et al*. 2000). Though each one of the conditions is considered favourable for convective development, their relative importance and the weightage to be given to each factor have not yet been clearly established. Thus, any discussion on this will have to be only qualitative and in general terms.

Thunderstorms occur in northwest India and west Uttar Pradesh in all the months of pre-monsoon season. The activity is more in western Himalayas than in the plains. In the plains the activity is more in the second half than in the first half of the season (IMD, 1973).

Dust storm occurs only in the plains. Significant dust storm activity begins in April and reaches its maximum in June. These dust storms are locally known as Andhi (IMD, 1980).

One of the objectives of this study is to examine critically the different stages of its development and the special characteristics or signatures in satellite cloud imagery, which may be considered to be indicative of such development well in advance. Secondly, we have analyzed different features of thermodynamic indices and parameters, synoptic situations and various products of numerical weather prediction model and tried to find out probable dynamic and thermodynamic aspects of such weather phenomenon.

Some of the studies related to the occurrence of thunderstorm over Delhi and surrounding areas are as follows.

Dhawan *et al*. (2008) developed an expert system for thunderstorm forecasting (ESTF) during pre-monsoon season over Delhi the representative location over northwest India by using technique of approaching the problem "bottom up" by using inductive machine learning techniques to automatically acquire the knowledge about thunderstorm forecasting from the weather development data set consisting of TEMP data for Delhi; for the months of May and June for the years from 1995-1999. To compare the ESTF with the objective techniques, they have developed dynamical-statistical methods for yes or no type thunderstorm occurrence forecast over Delhi during pre-monsoon months of May and June by using graphical discrimination method and multiple regression method. They found that in multiple regression method the parameters were significant by stepwise screening procedure. The three methods developed by them were tested with independent data sets of May and June for the year from 2000-2001. Comparison of verification parameters of the forecast issued by graphical discrimination method, Multiple Regression Technique and by ESTF indicates that results of multiple regressions are better than those of graphical discrimination method. The results obtained by using ESTF are better than those by using dynamical statistical models.

Duraisamy *et al.* (2011) investigated different stability indices in relation to the occurrence of thunderstorms in order to determine the critical values of these indices for Delhi (28.35° N / 77.12° E) using pre monsoon data for the years 1999-2004. They found that critical values of thermodynamic indices like Showalter Index (SI), Lifted Index (LI), K Index (KI), Total Totals Index (TTI) and SWEAT Index and the corresponding common critical ranges of Lifted Condensation Level (LCL), Level of Free Convection (LFC), Equilibrium Level (EL) and Precipitable Water (PW) during pre-monsoon seasons of the year 2005 and 2006 are matched well with respective critical values/ranges in most of the thunderstorm days over Delhi.

Ravi *et al*. (1999) developed two objective methods using data from May and June for 1985-89 in order to forecast thunderstorms during the pre-monsoon season at Delhi. They have also tested the developed methods with independent data sets of May and June for the years 1994 and 1995. The first method is based on a graphical technique. Fifteen different types of stability index were used by them in combinations of different pairs. It is found that Showalter index versus Totals total index and Jefferson's modified index versus George index can cluster cases of occurrence of thunderstorms mixed with a few cases of non-occurrence along a zone. Their second approach was use of a multiple regression method to predict the occurrence/non-occurrence of thunderstorms. Out of the two methods tested, it is found by them that the multiple regression method gives consistently better results with developmental as well as independent data sets; it is a potential method for operational use.

For this study, description of the thunderstorm along with the synoptic conditions and current weather observations, Satellite imageries, various products of ECMWF model and Doppler Weather Radar products have been collected from India Meteorological Department, New Delhi and Thermodynamic indices and parameters are collected from the web link (http://weather.uwyo.edu/upperair/sounding.html).

2. Case description

On 25th May 2011, a severe thunderstorm affected the Indira Gandhi International (IGI) Airport, New Delhi and neighbouring areas in the evening hours. The thunderstorm lasted for about an hour between 1700 UTC and 1800 UTC and resulted in disruption of many flights. Thunder squall actually started at 1700 UTC which continued till 1735 UTC. The downdraught started at 1658 UTC and continued till 1800 UTC. The wind speed varied between 15 to 30 knots from westerly-northwesterly direction to easterly direction. A number of AWS stations installed northwest of Delhi were reporting wind speed varying between 15 to 35 knots as the thunderstorm passed through the area. The thunderstorm was moving towards southeast direction with an estimated speed of about 12 kilometer per hour. The surface wind at IGI Airport was initially from west south west direction, which progressively became westerly, then west-northwesterly, northerly and eventually northeasterly at around 1730 UTC. Visibility which was around 3500 meter at 1500 UTC reduced to 1500 meter due to dust storm. As the orientation of Runway at airport is east-west; the crosswind component increased as the storm approached the station thereby rendering the takeoff/ landing operation difficult. The flights approaching the airport from east were more affected as there were multiple cells in the east and southeast sector and this resulted in to diversion of many flights.

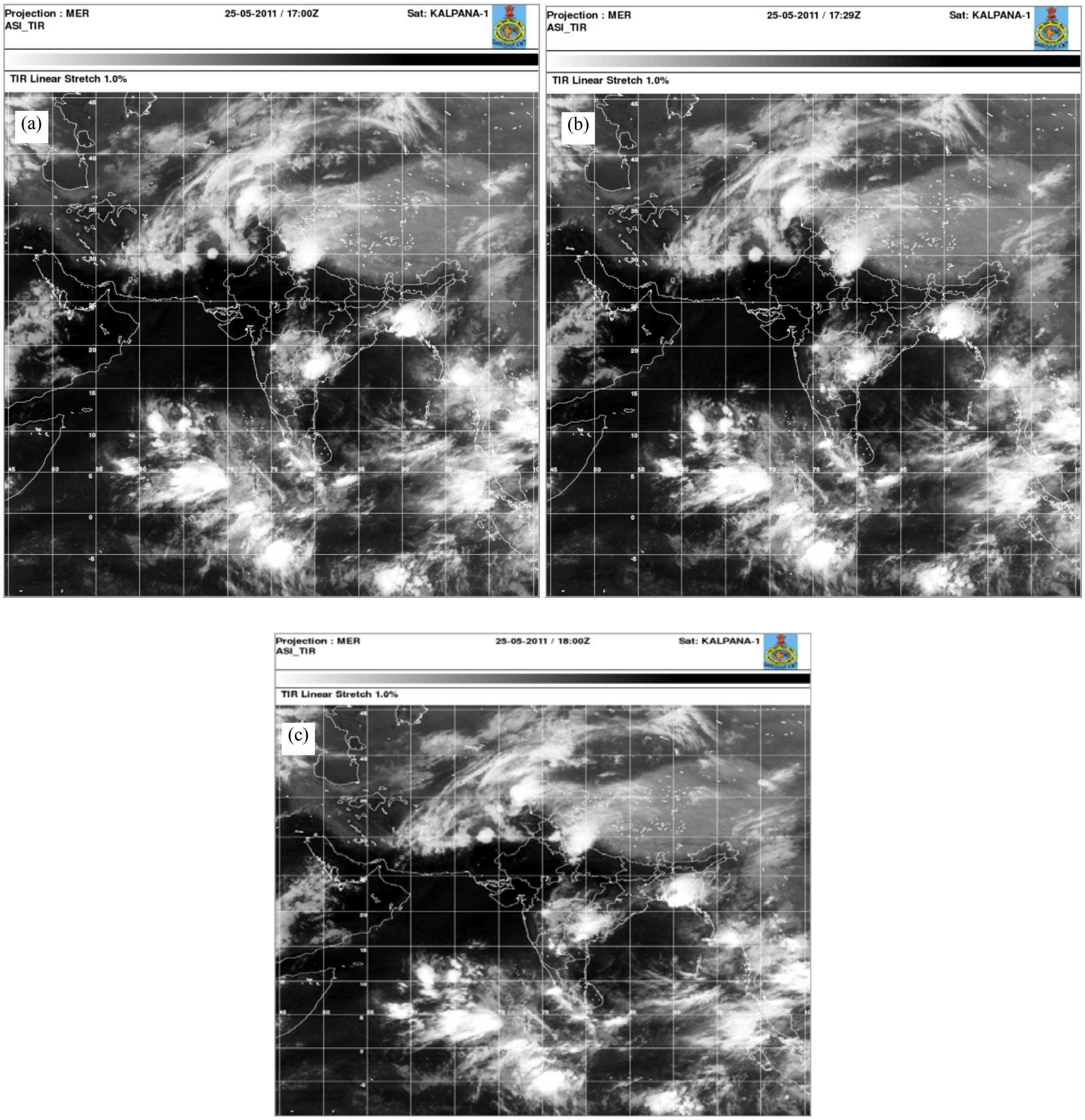
3. Brief description of various weather conditions at IGI airport during 2030 to 2330 hrs IST of 25th May, 2011

Current weather reports issued by India Meteorological Department for the period shows that the airport was having visibility at 2030 IST as 3500 meter in haze with low and medium clouds of height 4000 to 10000 feet with westerly wind of 10 kmph which deteriorated to 3000 meter at 2052 hours IST when CB cloud was also reported for the first time during the period. The observations from the Integrated Automatic Surface Weather Observing Instruments (IASWOI) confirms the weather conditions started deteriorating at 2230 hours IST when the RWY 27 end experienced squall/gusty winds of 62 kmph from 040° which subsequently spread to various other five RWY ends. Accordingly, a SPECIAL weather report was issued at 2230 hours IST to ATC with prevailing weather condition as Thunderstorm/Dust storm and gusty winds of 040/20 knots gusting to 30 knots. In view of gusty wind condition continuing with visibility falling to 1500 meter in thunder-storm another 2nd SPECIAL weather report was issued to ATC at 2251 hours IST when surface wind was reported as 050/20 knot gusting to 30 knots with current weather as thunderstorm. Hereafter the weather started improving and by 2330 hours IST, the visibility was improved to 2500 meter in haze and ceased off thunderstorm.

A number of AWS stations over northwest of Delhi reported wind speed varying between 15 to 35 knots during the passage of thunderstorm through the area.

4. Synoptic conditions

Although thunderstorm is a meso scale phenomenon, the realization of the instability is largely depends upon the large scale synoptic situation - Particularly the vorticity of motion in atmosphere. Significant thunderstorm activity is generally associated with some synoptic system or the other of the cyclonic type. However, many of these systems are generally weak. These necessitates a careful analysis of the charts, great need to maintain space and time continuity in the analysis and also the need for the forecaster to be well aware of the diurnal variations and local peculiarities of the area (IMD, 1973). Synoptic condition based on 0530 hours IST shows that there was an upper air cyclonic circulation over central Pakistan and adjoining northwest Rajasthan in the lower level. A trough from this system extends up to Gangetic West Bengal across Haryana, Uttar Pradesh and Jharkhand. The low level southwesterly penetrating over the region from the Arabian Sea supplied the necessary moisture in the region and low level convergence was provided by the above mentioned synoptic conditions.

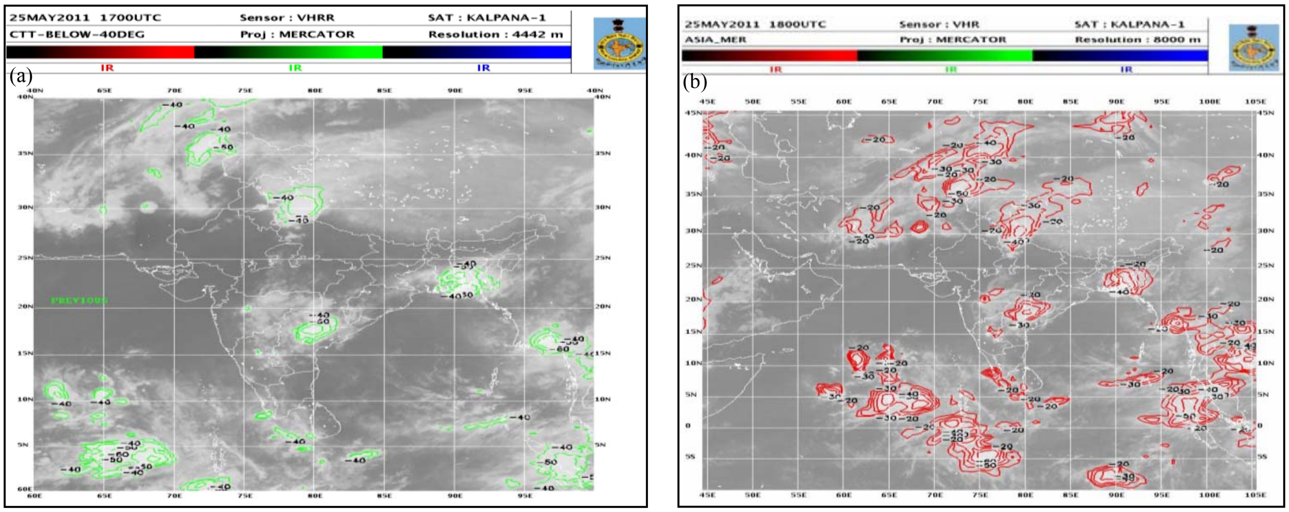


Figs. 1(a-c). Satellite imagery (KALPANA-1) at (a) 1700 UTC (b) 1730 UTC and (c) 1800 UTC of 25th May, 2011

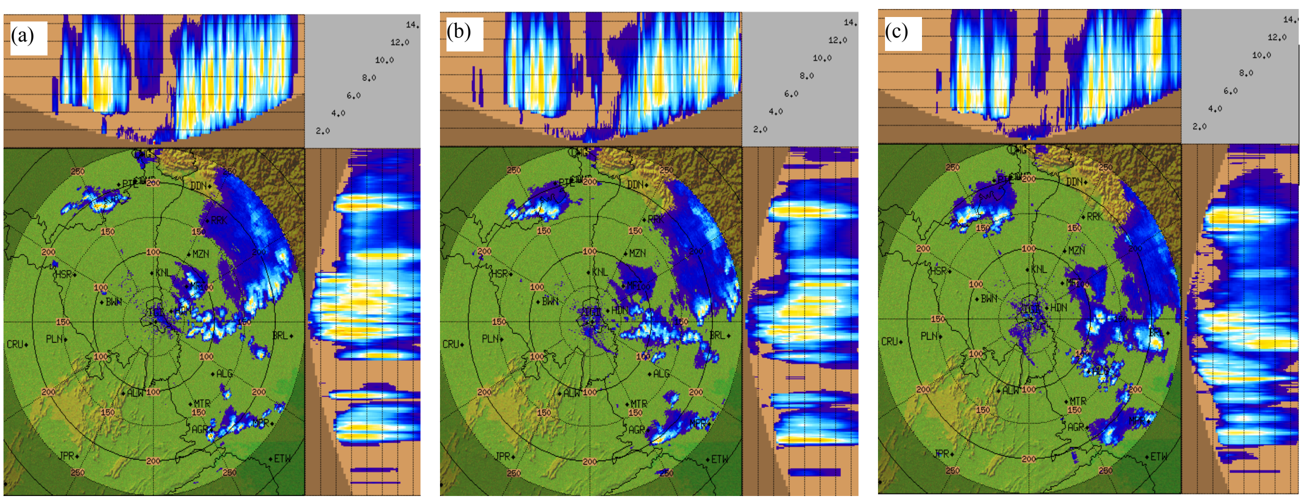
5. Analysis of satellite cloud imagery and Doppler Weather Radar picture

Thunderstorms appear bright white in all channels (infrared, visible) of satellite imagery because of the strong reflection from the convective cloud tops, low cloud top temperature and high moisture content respectively. In infrared images, thunderstorm anvils can be seen as bright white oval-shaped cloud masses blown away in the direction of the upper winds. In a visible image, the tall clouds may sometimes cast a shadow on the lower level clouds (Kelkar, 2006).

Satellite imagery gives viewer an immediate feeling for dynamics of severe weather situations. Synoptic and meso scale features, important in severe weather development, are readily detectable in satellite imagery. Satellite visible imagery often shows disturbed areas suggestive of shooting cumulonimbus tops and their shadows. The infrared observation shows that the



Figs. 2(a&b). Satellite imagery (KALPANA-1) at (a) 1700 UTC and (b) 1800 UTC of 25th May, 2011 showing cloud top temperature



Figs. 3(a-c). Delhi DWR pictures (Max Z) on 25th May, 2011 valid at (a) 1700 UTC (b) 1730 UTC and (c) 1800 UTC

equivalent black body temperature at the top of the cloud is substantially lower tending to confirm interpretation of shooting tops (Mandal, 1989).

Satellite imagery of 25th May, 2011 showed deep convective clouds over Uttarakhand and adjoining areas of Himachal Pradesh at about 1200 UTC. It led to the development of a severe thundercloud called cumulonimbus cloud. The clouds containing multiple cells got intensified and moved in east to southeastward direction and at about 1700 UTC moved over Uttarakhand and adjoining west Uttar Pradesh north east of IGI airport as seen in Doppler Weather Radar picture also [Figs. 1(a-c)] and [Figs. 3(a-c)]. Thereafter the system moved away north eastward almost in a squall line formation. From satellite imagery of 1700 UTC [Figs. 2(a&b)] it is seen that minimum cloud top temperature was of the order of -40 °C, which indicates that at this stage the cloud top might have reached above the height of about 10 km.

As per the Velocity Volume Processing Product which is a secondary product of DWR, the wind between surface and 2 km were uniform from 350° (northerly) at 1700 UTC but as the downdraft initiated there was a clear veering of the wind between the two level with the discontinuity occurring at 900 meters. Between 1710 and 1730 UTC the lower level wind becomes easterly. The resultant surface wind speed reached 30 knots in gust. As no significant rain was reported water loading could not have been the reasons of this downdraft. The downdraft strength based convective indices was found to be ≈600Feet/minute.

TABLE 1

Threshold values of the thermodynamic indices reported in literature along with the actual value of Delhi for 25th May, 2011

S. No.	Description of the index	Threshold value (Literature)	Actual value
1.	CAPE (J/kg)	≥ 1,000 (Tyagi *et al*., 2011)	1612
2.	Lifted Index (°C)	≤ 0 (Duraisamy *et al*., 2011)	-0.73
3.	Showalter index (°C)	≤2 (Duraisamy *et al*., 2011)	-6.56
4.	K Index (°C)	≥24 (Duraisamy *et al*., 2011)	46.1
5.	Total Totals	≥ 44.5 (Duraisamy *et al*., 2011)	54.6
6.	SWEAT Index	≥ 100 (Duraisamy *et al*., 2011)	419.6
7.	Bulk Richardson Number (BRN)	> 40 (Tyagi *et al*., 2011)	52.65
8.	Eq. Pot. temp. (°K) (850 hPa level)	> 340 (Dhawan *et al*., 2008)	377.4
9.	Dew point Temp. (°C) (850 hPa level)	≥ 13 (Dhawan *et al*., 2008)	20.8
10.	Rel. Humidity (700 hPa level)	≥ 60 (Dhawan *et al*., 2008)	63

6. Thermodynamic conditions

The thermodynamic indices and parameters such as Convective Available Potential Energy (CAPE), Lifted Index (LI), Showalter Index (SI), K Index (KI), Total Totals Index (TTI), Severe Weather Threat (SWEAT) Index, Equivalent potential temperature (θe) at 850 hPa level. Dew point temperature (Td) at 850 hPa level and Relative Humidity (RH) at 850 hPa level based on RS-RW data of 0000 UTC of 25th May, 2011 for the station Safdurjung (Delhi) have been analyzed. The computational procedure for the indices is as follows:

(*i*) *Convective Available Potential Energy*

The CAPE (Jkg^{-1}) is given by the formula

$$\int_{Zf}^{Zn} g\,\frac{(Tve-Tvp)}{Tvp}\,dz$$

where, g is the acceleration due to gravity, Z_f and Z_n are the heights of the level of free convection and neutral buoyancy respectively. *Tve* and *Tvp* are the virtual temperatures of the environment and air parcel respectively. It represents vertically integrated positive buoyancy of an adiabatically rising parcel (Moncrieff and Miller, 1976). Williams and Renno' (1993) employed CAPE to study the conditional instability in the tropical atmosphere.

(*ii*) *Lifted Index*

$$LI = T_{500} - T_{parcel}$$

where, T_{500} is the environmental temperature at 500 hPa and T_{parcel} is the parcel temperature, it is lifted with the average temperature, pressure and dew point temperature from 500 meter above the surface. It is a measure of thermal stability of the atmosphere at 500 hPa and is expressed in terms of parcel temperature and environmental temperature (Means, 1952).

(*iii*) *Showalter Index (Showalter, 1953)*

$$SI = T_{500} - T_{parcel}$$

where, T_{500} is the temperature of Environment at 500 hPa and T_{parcel} is the 500 hPa temperature which a parcel would attain if it is lifted dry-adiabatically from 850 hPa to its condensation level and then moist-adiabatically to 500 hPa level.

(*iv*) *K Index*

This index is used for determining the air mass thunderstorms. It is a combination of moisture at 850 and700 hPa level and temperature difference between 850 and 500 hPa level (George, 1960).

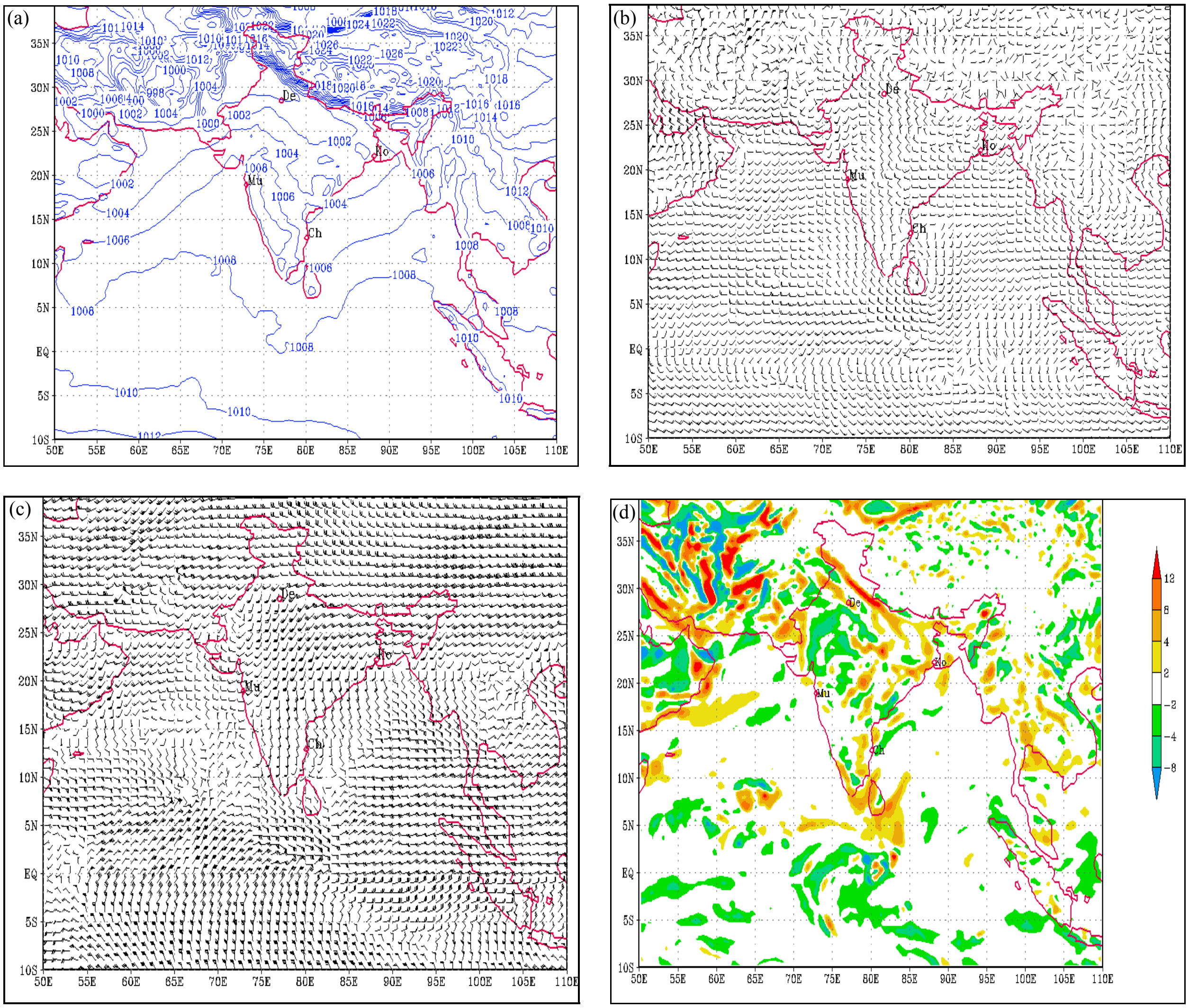
$$KI = (T_{850} - T_{500}) + Td_{850} - (T - Td)_{700}$$

(*v*) *Total Totals Index*

This index is useful to assess the storm strength but fails to consider the latent instability below 850 hPa (Miller, 1972)

$$TTI = T_{850} + Td_{850} - 2\,T_{500}$$

where, *T* and *T*d are the dry bulb and dew point temperatures at the indicated pressure levels.



Figs. 4(a-d). ECMWF model analysis based on 0000 UTC 25 May 2011 of (a) Mean sea level pressure (b) 850 hPa level wind (c) Wind shear between 200 and 850 hPa level and (d) Vorticity ($\times 10^{-5}$ s^{-1}) at 850 hPa level

(*vi*) *Severe Weather Threat Index (SWEAT)*

This index is proposed by Miller (1972) for determining the severe weather.

$$SWEAT = 12\ T_{d850} + 20(TTI - 49) + 2f_{850} + f_{500} + 125[\sin(d_{500} - d_{850})] + 0.2$$

where, f_{850}, f_{500} are the wind speed in knots at 850 and 500 hPa level respectively and d_{500}, d_{850} are the wind direction in 0-360° at 500 and 850 hPa respectively.

(*vii*) *Bulk Richardson Number (BRN)*

It is the ratio of the CAPE to vertical wind shear of the environment of the lifted parcel. It indicates the type of the thunderstorm single, multi-cell and super cell. (Weisman and Klemp, 1982 and 1984),

$$BRN = CAPE/(0.5 \times U^2)$$

where, U is the magnitude of shear.

From Table 1, it is seen that all the selected ten indices and parameters satisfy the critical value criteria. These indices indicate that the atmosphere in an around Delhi was unstable and had favourable conditions for development of severe thunderstorm cells.

7. Numerical weather prediction models

To study the characteristics of severe thunderstorm dynamically, we have considered some of the analysis products of European Centre for Medium-range Weather Forecasts (ECMWF) model on a domain 10 °S - 50 °N; 50 °E - 110 °E with 0.25° × 0.25° latitude - longitude horizontal resolution.

ECMWF model analysis of mean sea level pressure and wind analysis at 850 hPa level based on 0000 UTC of 25th May, 2011 [Figs. 4(a-d)] indicate that a trough of low pressure runs from Punjab to Bihar across Uttarakhand and Uttar Pradesh and extending up to 1.5 km above sea level with wind shear between 200 and 850 hPa levels of about 40-60 knots over Delhi and surrounding areas. ECMWF model also shows very high positive vorticity at 850 hPa level, *i.e.*, in the order of 12×10^{-5} S^{-1} or more over Uttarakhand and west Uttar Pradesh.

Thus, analysis of various products of ECMWF model based on 0000 UTC of 25th May, 2011 indicate that there was a possibility of thunderstorm over Delhi and surrounding areas on 25th May 2011.

8. Conclusions

Thunderstorm development can be spotted in satellite images and Doppler Weather Radar pictures by continuous monitoring especially when the synoptic situation is known to be favourable, but otherwise they can be missed because of their short life.

The synoptic condition was favorable for lifting mechanism and most of the thermodynamic indices over Delhi were also favourable for occurrence of the thunderstorm in and around Delhi on 25th May 2011.

In our day to day working in practical field, it has been found that in spite of the presence of most of the criteria for thunderstorm development sometimes nothing significant comes into existence. It is felt that there exist some well balanced relations in amplitudes or extent of different criteria or some threshold value of them which are necessary for such wide spread development. To understand it properly, it requires number of case studies.

It is essential to investigate the occurrence of severe thunderstorm with the available observational data so as to have a better insight into the conditions that lead to these highly localized devastating events and also to test the capabilities of high resolution meso scale models in simulating them.

The understanding of the dynamical/physical mechanisms of these thunderstorms is essential for improving the forecast of such meso scale systems.

There is a need of integration of all inputs such as synoptic charts, satellite images, thermodynamic indices, Numerical Weather Prediction (NWP) model outputs and Doppler Weather Radar products in the understanding of such meso scale severe weather phenomena.

Development of new observation technologies and installation of finer spatial and temporal resolution observation networks will definitely increase understanding and better prediction of such meso-scale disaster weather events.

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