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Widespread thunderstorm activity over northwest India on 26 May 1986 — Satellite and synoptic studies

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सार — एक लघुक्षेत्र दीर्घ स्थायी संवहनी सम्मिश्र की संवृद्धि और विकास को भूउपग्रह इनसेट मेघ बिम्बों द्वारा चित्रित किया गया है। उपग्रह मेघ बिम्बों और परंपरागत आंकड़ों के प्रयोग से प्रचंड संवहनी सक्रियता क्षेत्र का काफी पहले से ही पता लगाना संभव है। अवरक्त (इन्फ्रारेड) मेघ बिम्बों से तैयार किए गए मेघ शीर्ष तापमान समोच्च से सन्निकट विकास के नए क्षेत्रों का पूर्वानुमान लगाया जा सकता है। सिनॉप्टिक, गतिक और जल उष्मा गतिक विश्लेषण से यह पता चला है कि इस विकास के लिए निम्न स्तरीय अभिसरण, छोटे पैमाने पर निम्न स्तरीय भ्रमिल की उपस्थिति, विक्षुब्ध क्षेत्रों में आर्द्रता प्रभाव, प्रबल सतह तापन, तापमान और आर्द्रता विपर्यास सामान्य से कम उपरि पवन तापमान और सामान्य से अधिक उपरि-वायु उर्ध्वाधर पवन अपरूपण उत्तरदायी हैं। इनमें सततता मेघ समूह के आसपास जलवायु प्रवाह के जल गतिक प्रभाव और इसमें अंत: स्थापित चक्रवातीय प्रवाह के कारण हो सकती है। संवहनी सम्मिश्र के बनने के लिए उपरि पवन अपरूपण क्षेत्र का होना आवश्यक शर्त नहीं है।

ABSTRACT. The growth and evolution of a persistent mesoscale convective complex have been depicted by INSAT cloud imagery. Using satellite cloud imagery and conventional data, it is possible to identify the area of severe convective activity well in advance. New area of imminent development can be predicted from cloud top temperature contours prepared from infrared cloud imagery. Synoptic, dynamic and thermodynamic analysis have revealed that low-level convergence, presence of small scale low-level vortex, moisture incursion to the disturbed area, strong surface heating, temperature and moisture contrast, below normal upper air temperature and above normal upper air vertical wind shear are responsible for this development. Persistence may be due to hydrodynamical effect of the environmental flow around the cloud mass and cyclonic flow embedded in it. Upper air divergence field may not be a necessary condition for formation of convective complex.

1. Introduction

On 26 May 1986, persistent widespread thunderstorms accompanied with rain or showers, duststorm or dustraising winds were reported mainly in the afternoon/evening which extended even beyond midnight from a number of stations of Himachal Pradesh, Punjab, Haryana, Delhi, west Uttar Pradesh adjoining Madhya Pradesh and Rajasthan.

Recent studies, indicate that mesoscale convective weather systems, particularly those of meso-α, horizontal dimension of the order of 1-2 $\times$ 10^3 km are frequently responsible for widespread severe thunderstorms, and if sufficient moisture is present, they can produce widespread heavy rain and flooding (Maddox 1980). Combined use of meteorological satellite cloud imagery and conventional data yields a better assessment of the behaviour of the atmosphere than is possible with the use of the conventional data alone; these lead to more reliable and accurate warning of severe weather. Initial state of development in cumulus stage, cannot be detected by radar observations which can easily be identified in satellite cloud imagery. Development of severe thunderstorms has very significant impact on the aviation flight. 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.

It is well known that convective clouds can grow to great heights, develop vigorous updrafts, and produce heavy rain, lightning and hail when lower atmosphere is sufficiently moist and unstable. These large severe storms may occur individually or more typically in groups associated with synoptic scale fronts or mesoscale convergence zone.

Satellite visible imagery often shows disturbed areas suggestive of shooting cumulonimbus tops and their shadows. The infrared observation shows that the equivalent blackbody temperature at the top of the cloud is substantially lower tending to confirm interpretation of shooting tops. The development, evolution and persistence of the convective cloud complex as in this present study is not quite common that generally affect northwest India in hot weather season. The system in this study maintained its identity as a unit mass of cloud for more than nine hours and did not shear off inspite of strong vertical wind shear up to 250 mb level. Though the system did not produce heavy rainfall, yet it has significant impact on aviation flight and it is very important to predict such weather system. 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 analysed different features of synoptic situations and tried to find out probable dynamic and thermodynamic aspects of such widespread severe weather situations.

2. Analysis of satellite cloud imagery

Broken, thin long cumulus lines oriented along a line from northwest to southeast, were first observed over Punjab and adjoining Pakistan in 06 GMT INSAT cloud observation (Fig. 3). These newly developed clouds

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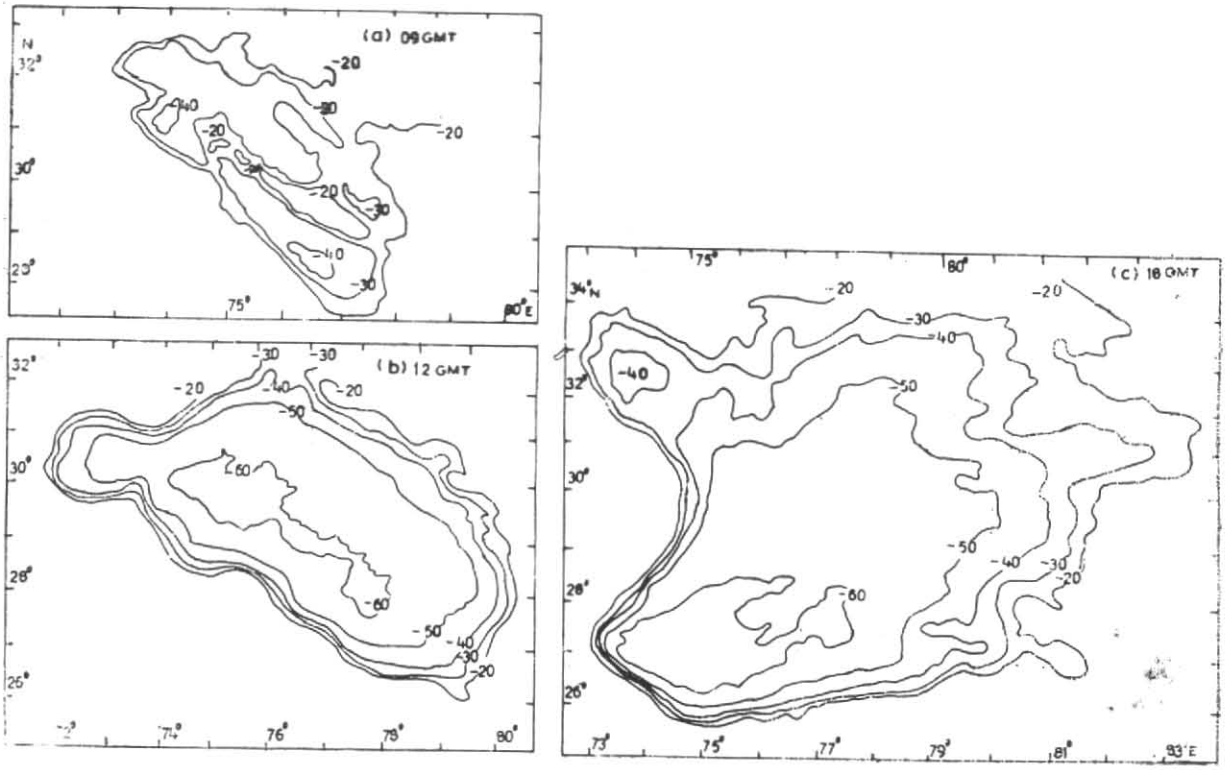


Figs. 1(a-c). Cloud top temperature contours of 26 May 1986 : (a) 09 GMT, (b) 12 GMT and (c) 18 GMT

had different form and texture and are separated by distinct clear area from the clouds over Jammu & Kashmir and Himachal Pradesh. This initial growth was not detectable in radar observation. The line along which they formed is so called "dry-line", which separates warm moist air from warm dry continental air. This is often observable up to two hours prior to the time it becomes a squall line sufficiently active to be detectable by radar (Anderson *et al*. 1974). Small areas of convective cloudiness began to form along these thin lines, organized into lines as they grew and by 09 GMT, these lines further developed as an initial stage of active squall lines and extended up to Haryana as broken convective band as seen in INSAT visible cloud imagery [Fig. 2(a)]. Delhi radar first detected this system at 0845 GMT observation in forming stage. Fig. 1(a) shows the contours of cloud top temperatures of the same observation in infrared imagery. The gradients of the contour are steeper near the edges. Minimum cloud top temperatures of the order of—44°C, were observed over southeast Haryana and adjoining Pakistan. Different convective lines are relatively identified by subsidence zones surrounding them. The edges of these convective systems are clear and sharp. As the thunderstorms complex developed further and interacted with its environment, its individual anvil clouds might overlap other clouds or they merged with one another. The cloud at 12 GMT as observed in infrared cloud imagery is shown in Fig. 2(b). It appears like a solid mass of nearly elongated elliptical shape. Thin cirrus outflows of small extent, are seen on northern and eastern parts of it. The circular convective cloud cluster over Pakistan adjacent to the main system has its own separate identity, only the cirrus outflow from it merged with the main system. In area of local severe weather, tapering V-notches are generally formed out of the parent cloud masses; there is no such indication, except one prominent bulging area on the western part of its southern edge; otherwise the southern and western edges are smooth and sharp. Cloud top temperature contours from same cloud imagery [Fig. 1(b)] show that the contours are closely packed to the southern and western edges of the storm complex. Minimum cloud top temperature at this stage was of the order of—64°C, which indicate that the cloud tops reached approximately to the height of 15.0 km. From 12 GMT onwards, the expansion of cloud mass took place on the southern side, where contour gradients were steeper; more so on the southwestern side over north Rajasthan, where warm and relatively moist air was fed into the system. The situation at 18 GMT as seen in infrared cloud imagery is shown in Fig 2 (c). By this time it covered major part of north Rajasthan. Southern and western parts of it over Rajasthan were still relatively smooth and sharp. Inspite of strong westerly flow aloft, there is no significant outflow on the eastern edge. Outflows are prominent on northern and northeastern parts. By this time the individual cloud mass over Pakistan weakened. The cloud top temperature contours for the same imagery are shown in Fig. 1(c). Here, also the contour gradients are steeper to the southwestern part of the system, where edges are sharp. Minimum cloud top temperature was of the order of—67°C. So the system did not weaken till 18 GMT. As seen from this figure —50°C temperature contour covers a large area. Afterwards, the system gradually dissipated. The main characteristics of this meso-scale convective complex are that it maintained its identity as a unit mass of clouds for pretty long time, did not shear off inspite of large environmental vertical shear flow and its later stage of development, its growths were confined to a particular area. As such, it demands detail studies of its dynamic and thermodynamic characteristics.

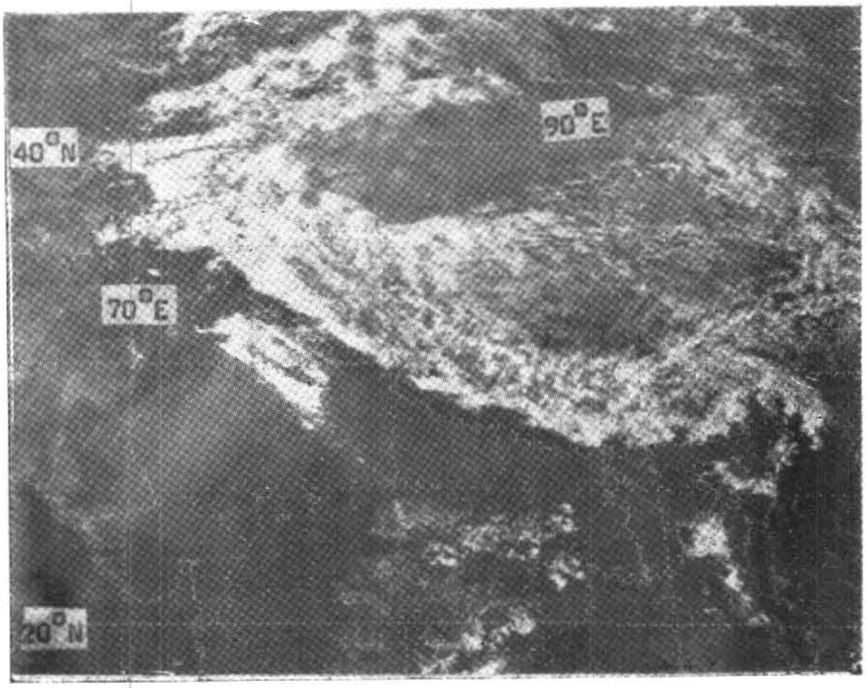


Fig. 2(a). INSAT (IR) picture of 26 May 1986 at 09 GMT

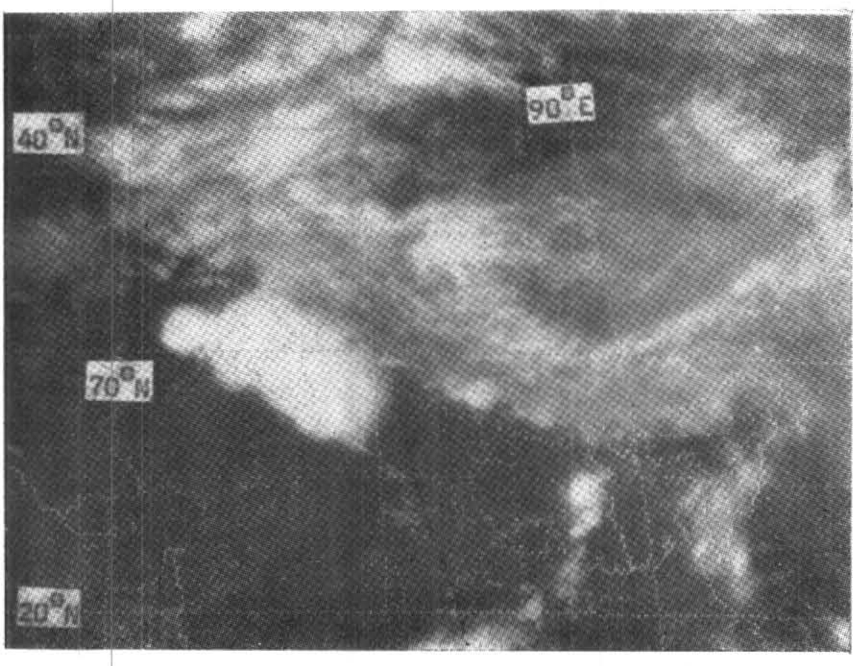


Fig. 2(b). INSAT (IR) picture of 26 May 1986 at 12 GMT

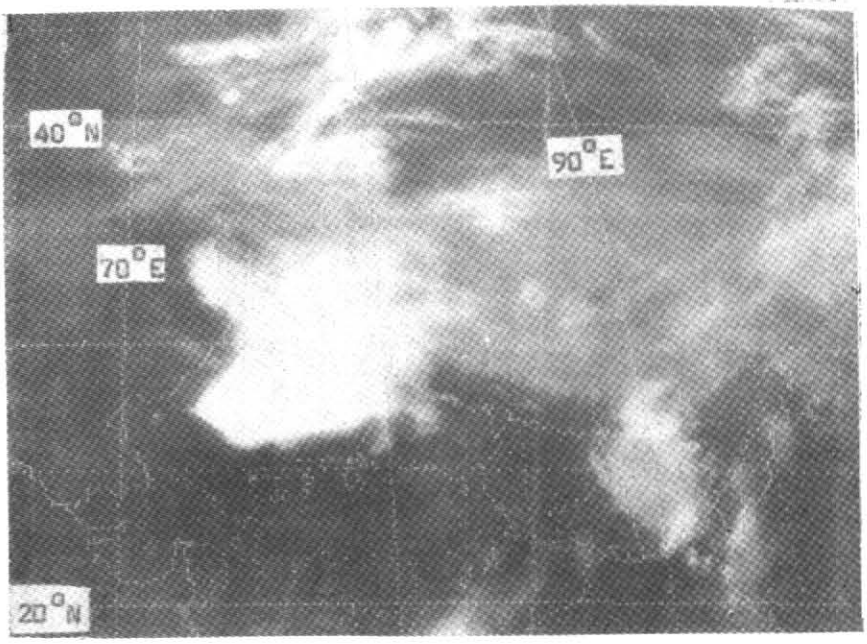


Fig. 2 (c). INSAT (IR) picture of 26 March 1986 at 18 GMT

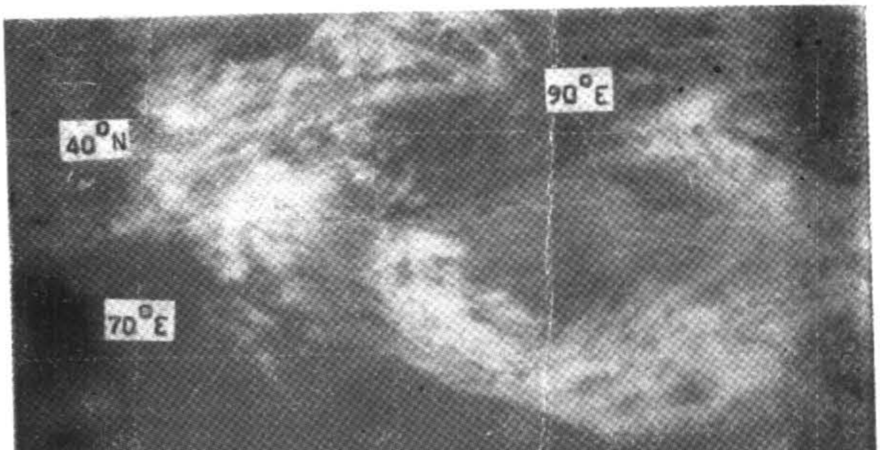


Fig. 3. INSAT (IR) picture at 06 GMT of 26 May 1986

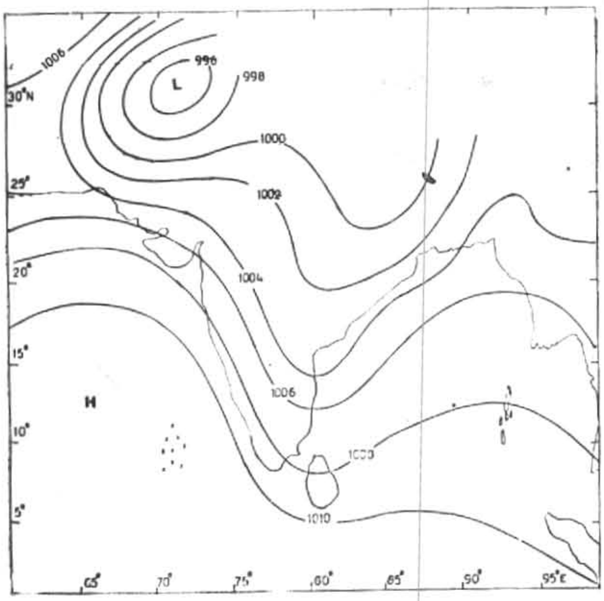


Fig. 4. Surface isobaric chart of 26 May 1986 at 06 GMT

Maddox (1980) defined meso-scale convective complex in terms of minimum areas of convective activity within certain ranges of cloud top temperatures (area $\geqslant 10^5$ km^2 with temperature $\leqslant -32$°C and area $\geqslant 5\times10^4$ km^2 with temperature $\leqslant -52$°C), persistence (duration $\geqslant 6$ hours) and eccentricity ($>.7$). The meso-scale convective complex in this study fulfills these criteria. His definition is based upon characteristics observable in satellite images, because of the wide range of atmospheric scales that may be monitored from satellite. This definition was designed so that very large and long-lived convective mesosystem could be easily identified and then studied utilising synoptic upper air and surface observations.

3. Synoptic situations

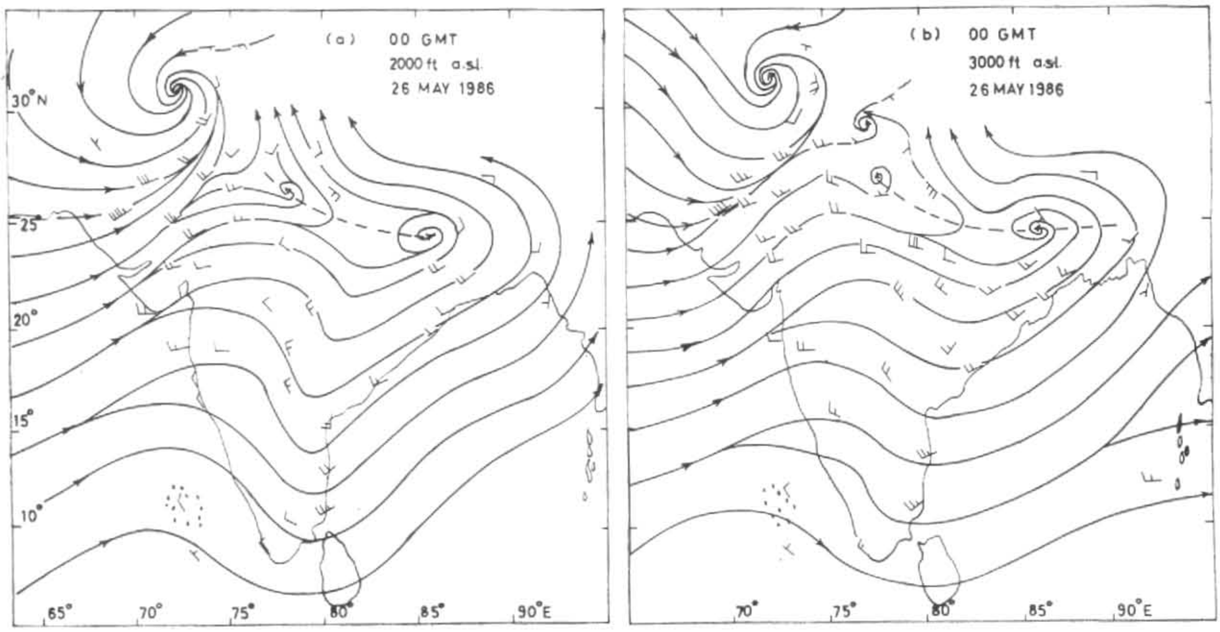
3.1. *Surface and upper air conditions*

Looking into the causes of this severe activity, it is observed that a western disturbance, which was located over central Pakistan and adjoining Afghanistan on 25 May 1986, had moved northeastwards and was over central Pakistan and adjoining Rajasthan and Punjab on 26 May. The pressure distribution on sea level chart at 06 GMT on 26 May '86 is shown in Fig. 4. It indicates that the system is quite strong with two closed isobars and central pressure less than 996 mb. Associated cyclonic circulation at 00 GMT extends up to 3000 ft a.s.l. and trough up to 700 mb level. Another cyclonic circulation lies over Bihar plateau and adjoining Gangetic West Bengal and Orissa up to 850 mb level. A trough in the lower level up to 3000 ft extends from southeast Haryana to northeast India. A small vortex can be identified southeast of Delhi imbedded in the trough. The flow pattern on 00 GMT chart at 2000 ft [Fig. 5(a)] shows quite strong flow from Arabian Sea to the southeast sector of the cyclonic circulation, the wind speed at Chhor being southwesterly/45 kt, which is conducive to moisture incursion to the system. Isopleths of dew point temperature at 00 GMT of 26 May have been drawn and shown in Fig. 5(c). This figure confirms that moisture incursion was taking place in tapering narrow zone towards Haryana, Delhi and southwest U.P. Here, 16°C isopleth passes through the region of thunderstorm activity. Rhea (1966) identified 10°C isopleth of screen dew point temperature as dry line for the greater plains of United States. Weston (1972) suggested 15°C isopleth as the so called dry line for north India for convective activity. It has also been observed that the dew point temperature over Delhi and Jodhpur started increasing from 24 May, and maintained this trend up to 26th. The streamlines at 2000 ft converge down stream. The asymptotes of the convergence lines can be treated as a low level jet-let. The low level jet has long been considered to be an important factor for convective activity. Decreasing of wind speed down stream along the stream lines is indicative of vertical motions. Bonner (1966) and Pitchford and London (1962) show that thunderstorms tend to develop in down stream portion of low level jet, where velocity convergence can lead to synoptic scale ascent of 1 to 10 cm/sec at approximately 700 mb. The isotherms at 00 GMT on sea level chart [Fig. 5 (c)] indicate southwest to northeast temperature contrast along low level trough. The convergence of air masses of contrasting thermal and humid characteristics is a potential region for cyclogenesis, where marked instability frequently develop. Active thunderstorms often develop in this front like zone located mostly in the moist air masses (Roy 1949). The axis of the weak Sub-Tropical Jet (STJ) at 250 mb runs from southern part of Caspian Sea to southwest U.P. adjacent to southeast Haryana [Fig. 5 (d)]. Though the initial area of convective activity lies in the left exit zone of STJ, its diverging effect appears not to be strong. In the later stage of development, it was extended to the south of the jet axis.

3.1.2. *Thermodynamic conditions*

Fig. 6 shows the upper air soundings over Delhi at 00 GMT on 26 May 1986, which was within the convective cloud complex. Near the ground, there is a shallow inversion layer, thereafter the lapse rate is nearly dry adiabatic up to 700 mb. After 270 mb, the lapse rate decreases and between 215 and 190 mb, there is an isothermal layer of —46°C. The tropopause level is situated at 104 mb, where temperature is —70°C. At 09 GMT, the surface temperature over Delhi rose to 39°C, which is sufficient for free convection.

Table 1 shows the comparison of upper air wind, temperature, and vertical wind shear at 00 GMT over Delhi and Lucknow (Jodhpur misda) with their normals in May. The temperature up to 300 mb for both the stations are below normal. For Delhi, the wind speed at 500 mb and 300 mb are much more than normal; but that at 200 mb it is much below normal. The wind shear between 850 and 300 mb is twice that of normal; but that between 850 and 200 mb it is much below normal. For Lucknow, the wind shear between 850 and 200 mb is fairly high. Rapid decrease of wind speed above 250 mb (for Delhi) and 200 mb (for Lucknow) may be one of the reasons that the outflow did not confine to one sector. For energy liberated at higher levels by ascending parcel to be more than that supplied during its initial lifting, *i.e.,* the parcel to possess real latent instability, it is necessary that the troposphere should be cooler. This has been observed in both stations up to 300 mb level.



Figs. 5 (a&b). Wind flow chart of 26 May 1986 at 00 GMT : (a) 2000 ft and (b) 3000 ft a.s.l.

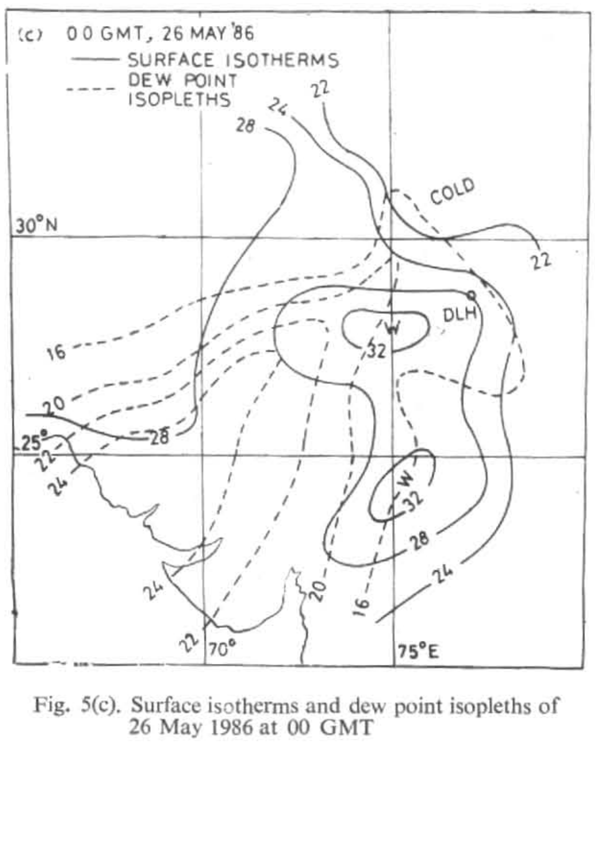


Fig. 5(c). Surface isotherms and dew point isopleths of 26 May 1986 at 00 GMT

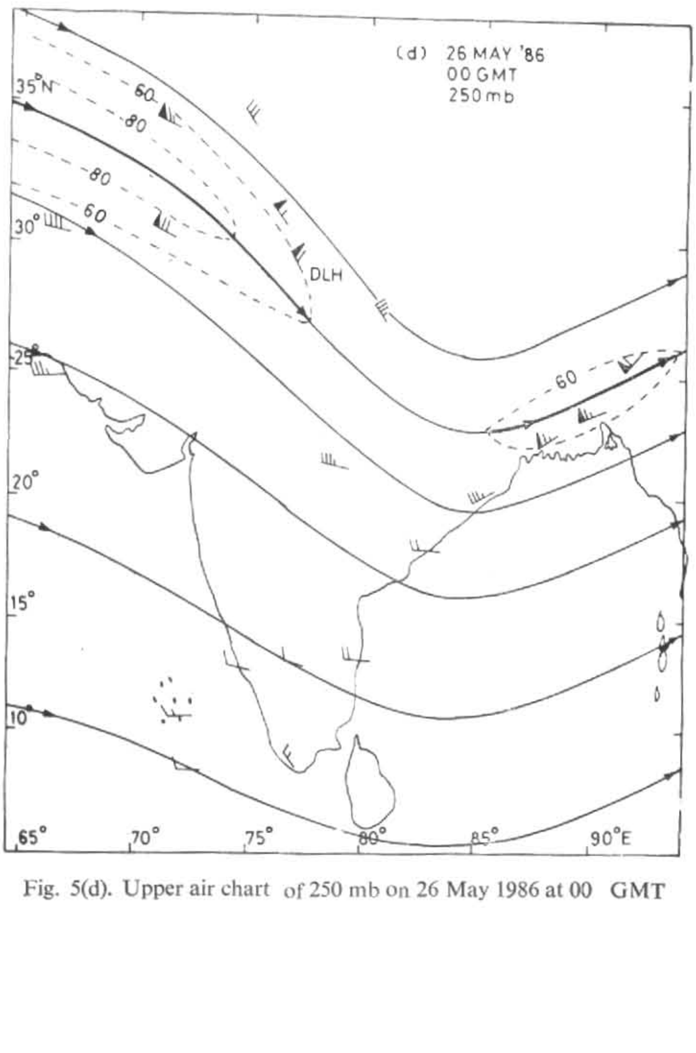


Fig. 5(d). Upper air chart of 250 mb on 26 May 1986 at 00 GMT

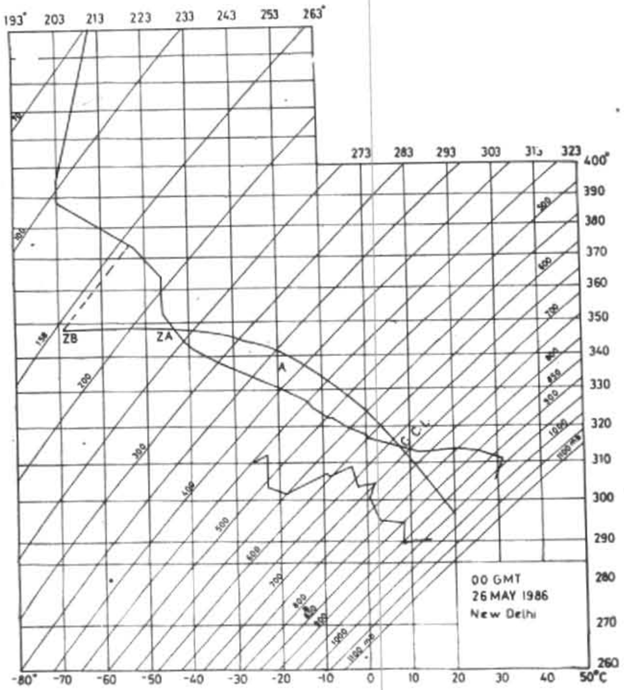


Fig. 6. Tephigram of New Delhi at 00 GMT of 26 May 1986

4. Discussions

As mentioned earlier, a cyclonic circulation of limited extent over Pakistan and adjoining Punjab along with prominent convergence zone and small vortex to the southeast sector of the circulation was present. Such meso-scale systems often have predominant influence on the development of convective clouds. Leichter (1974) found that significant convection over the Black Hills of South Dakota was associated with convergence due to motion of meso-scale vortices in lower boundary. Rai Sircar (1957) observed presence of convergence of cyclonic nature in lower levels in many nor'wester situations. Role of meso-scale circulation in the genesis of severe thunderstorms and hailstorms in central India was emphasised by Chowdhury *et al.* (1973).

Initial area of convective cloud growth was detected in satellite picture at 06 GMT by long thin cumulus lines. The convective clouds first appeared as broken lines or band instead of convective cloud clusters along these lines as seen in 0900 GMT satellite imagery, which we thought should a rise in the region of pronounced low level wind and moisture discontinuities or strong wind shear and pronounced curvature of the wind profile in low-level jet. Though the above factors were present to some extent, what were other factors, which could have contributed to the formation of bands? In laboratory experiments (Brunt 1951) longitudinal rolls develop in heated flows with vertical shear. Kuo (1963) has shown analytically that unstable mode of perturbations exists with negative stability and uniform wind shear. Over land areas, there is almost always shear within the boundary layer and more critical parameter for band formation may be heating of the air to the point where free convection occurs. When this happens thermal may originate from near the ground extending through the region of boundary layer wind shear. The rising air will then follow a helical path along the flow and cloud forms, if the height of the eddy extends above the condensation level. In this case study, above a thin inversion layer, deep unstable leyar was present; surface air was heated from below and temperature reached to a high value during afternoon. So above process might have taken part for such development.

The necessity of strong vertical wind shear in upper troposphere for the development of thunderstorm/hailstorm has been emphasised by Fawbush and Miller (1953), Dessens (1960) & others. According to Ludlam (1963) in absence of wind shear, the updraft is up right and precipitation falls through it and thereby decelerates the updraft. But when the shear is strong the updraft becomes tilted and the outflow from the anvil occurs predominately on one side and does not interfere with updraft. Chowdhury and Banerjee (1983) showed that in case of hailstorm over northeast India in pre-monsoon season, the vertical wind shear between 850 and 300 mb is nearly four times the normal. The shear between 850 and 200 mb is about twice the normal. In this study, the wind shear over Delhi between 850 and 300 mb is twice the normal which might have favoured the development. In this case wind speed above 250 mb decreased sharply (Table 1) and it may be one of the causes that the clouds top did not reach to a very high altitude.

The mesoscale convective complex in this study developed and persisted for more than 9 hours in presence of strong vertical wind shear without being sheared off or deformed. Observations of the persistence and growth of large cumulonimbus system in presence of strong vertical shear and that these storms resist deformation in presence of strong shear have been recorded by Hitschfeld (1960), Ludlam (1966) and others. Newton and Newton (1959) postulated that the environmental air is forced to diverge and flow around a well developed cumulonimbus. This idea has been substantiated by observations by Fujita and Grandoso (1968). Alberty (1969) mentioned that for vertically oriented, steady state storm imbedded in shear environmental flow, vertical gradients of hydrodynamic pressure leading to vertical motion around the updraft core, would cause the updraft to be shielded from erosive effect of environment. From analytical considerations, he has shown that the vertical shear produce an enhancement of vertical motions on the perimeter of the updrafts core characteristics of severe storm. The intensified vertical motion would allow the updrafts to be less adversely affected by shearing forces and may explain the persistence or growth of such storms. He has also shown that the vertical gradient of hydrodynamic pressure is proportional to the vertical shear itself. A persistent cumulonimbus is a result of very delicate balance between dynamical and thermodynamical interactions. As discussed earlier that in the mature stage cirrus outflow was seen in satellite picture to the north and northeast side of cloud mass. This may be due to the interaction of the cyclonic flow present in the storm complex with the westerly environmental flow. Long persistence of the system can partially be attributed to the presence of cyclonic flow in the convective complex. Another important feature is that for formation of convective complex upper air divergence field may not be a necessary condition, the outflow may spread side ways.

TABLE 1

Comparison of upper air wind and temperature with their normals at 00 GMT on 26 May 1986

		850 mb	700 mb	500 mb	300 mb	250 mb	200 mb	150 mb	100 mb	Wind shear between 850 and 300 mb	Wind shear between 850 and 200 mb
					New Delhi						
Wind speed (kt)	Actual	5	15	30	60	60	15	20	20	55	10
	Normal in May	11	16	20	38	—	49	—	24	27	38
Temperature (°C)	Actual	25.5	10.0	—9.5	—33.5	—41.5	—46.5	—55.5	—70.0		
	Normal in May	27.8	12.9	—7.6	—31.2	—	—47.3	—	—68.7		
					Lucknow						
Wind speed (kt)	Actual	10	15	25	25	35	50	25	25	15	40
	Normal in May	15	20	22	37	—	—	—	—	22	—
Temperature (°C)	Actual	25.0	11.0	—9.0	—34.0	—42.0	—50.0	—61.0	—71.0		
	Normal in May	27.2	12.3	—6.6	—31.5	—	—49.7	—61.8	—72.5		

5. Conclusions

This study has been made using three hourly INSAT data. If hourly data were available, the evolution of the system could be represented in a better way. The type and form of the convective complex studied here is not a common occurrence. In our day to day working in practical field, it has been found that inspite 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 values of them which are necessary for such widespread development. To understand it properly, it requires number of case studies. Though this is a case study, in operational work, it may be helpful to some extent.

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