SEVERE HAILSTROM AT THORI: A CASE STUDY

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ABSTRACT

During the pre-monsoon months (March-May) in Nepal, severe thunder and hailstorms cause significant property and agricultural damage in addition to loss of life from lightening. Forecasting thunderstorm severity remains a challenge even in wealthy, developed countries that have modern meteorological data gathering infrastructure, such as Doppler Radar. This study attempts to isolate the specific and unique characteristics of a hailstorm that not only might explain its severity, but also suggest forecasting techniquees for future forecasting in Nepal. The primary data sources for this investigation included Infrared Satellite images, which illustrated the sequences of convective activity, and original archived ESRL India and China upper air data, which was used for synoptic and mesoscale analyses. On May 3, 2001 between the hours of 1100pm and midnight, a severe thunderstorm accompanied by hail stones estimated at 1kg, devastated the village of Thori (Southern border to India). 800 thatched houses were destroyed, over 500 farm animals were killed and more than 200 hectares of crops lost. Many inhabitants were injured, but luckily only one death. Thori hail storm had its origins in a topographically induced lee-side convergence area in the deserts of Pakistan on May 2, 2001, from where it propagated eastwards into India and evolved into an eastward travelling Mesoscale Convective System reaching Thori near midnight on May 3. Atmospheric instability over the Gangetic Plains, fuelled by a very active surface heat low, cold temperatures and dynamic lifting mechanisms aloft, created a synoptic and mesoscale environment capable of generating a dangerous thunderstorm.

Key words: Hailstorm, infrared satellite, thunderstorm, meteorological data

INTRODUCTION

On May 3, 2001 between the hours of 1100pm and midnight, a severe thunderstorm accompanied by hail stones estimated at 1kg, devastated the

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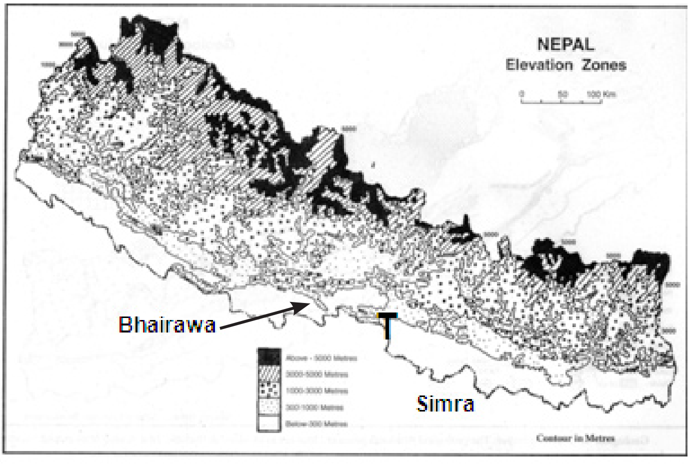
village of Thori. 800 thatched houses were destroyed, over 500 farm animals were killed and more than 200 hectare of crops lost. Many inhabitants were injured, but luckily only one death. Thori is a small village on the Nepal-India border, just south of the Chitwan National Tiger Park. It is situated at 27.3°N and 84.7°E, 70 km to the southwest of Kathmandu in the Churia Range, south of the High Himalayas at an elevation of 215m asl (Fig. 1). The area along the border with India, known as the Terai, has a sub-tropical climate. Thori is an agricultural village, and is a well-known producer of high quality mustard oil. In the Thori area and further east towards eastern Nepal, severe convective activity accompanied by large hail is a frequent occurrence especially during the pre-monsoon months of April and May.

Figure 1: Elevation Map of Nepal. Locations of Thori (T), Simra and Bhairahawa are Indicated.



Data Source

Surface synoptic weather data is collected at the airport by the Department of Hydrology and Meteorology (DHM), there was no local weather data for Thori. The DHM surface synoptic weather stations in Nepal closest to Thori are Kathmandu, 70km to the SE, Simra 45km to the NE and Bhairahawa 120km to the west. The closest North Indian upper air stations are Gorakhpur 180km to the south, Lucknow 400km to the WSW and Patna 190km to the SE. This study used Simra and Bhairahawa May 3,03UTC and 12UTC surface data and observations; 00UTC surface data was not available. Upper air weather data is from the Gorakhpur station.

Simra Observation

Table 1: Simra surface data. Temperature, dewpoint temperature, wind speed and direction, pressure and maximum temperature for 03UTC May 2, 2001 to 03UTC May 4, 2001.

	Temp	**Dewpt**	**WS (kts)**	**Direc**	**Pre (hPa)**	**Max-Temp**
May 2 03UTC	22.6C	20.6C	9	90	992.3	
May 2 12UTC	31.6C	23.2C	5	210	986.6	33.2C
May 3 03UTC	28.4C	22.6C	10	120	989.3	
May 3 12UTC	m	m	m	m	m	35.2C

Source: DHM, 2001.

May 3 synoptic reports for Simra, the station closest to Thori, at 03UTC (0845NST) indicate clear skies and a visibility of more than 10km. The surface temperature at 03UTC (0845NST) on May 3 was 28.4^{o}C, a six degree increase from the previous day, 03UTC (0845NST), May 2; the surface dewpoint temperature had increased by two degrees to 22.6^{o}C (Table 1). The maximum surface temperature for Simra on May 2 was 33.2^{o}C. The May 3 the maximum surface temperature was 35.2^{o}C, the only data available for that observation period. At 03UTC May 2, the Simra surface winds were straight easterly, from 90 degrees at 9 knots (surface winds at Gorakhpur and Patna were easterly, from 90 degrees, as well) and on May 3 at 03UTC, Simra winds were from the southeast, 120 degrees, at 10 knots. The Patna 00UTC wind direction at 00UTC May 3 was also easterly, from 90 degrees and at Gorakhpur the 925hPa winds were from a 100 degrees direction at 17 knots. The 210 degree wind direction at 12UTC (1745NST) May 2 likely reflects the diminishing up-valley mountain winds that are forced into the foothills of the Himalayan Range. Skies on May 2 at 0845NST had a 6/8 octa cloud cover for most of the day. Station surface pressure at Simra on May 3 at 03UTC was 989.3hPa, indicating a negative pressure tendency of 2.9hPa over the last 24 hours. Simra 03UTC May 4 temperature indicates a 5^{o}C degree decrease from May 3 and a dewpoint temperature decrease of 2.3°C. The surface pressure increased 0.8mb. The wind direction became westerly, from 270 degrees at 4 knots.

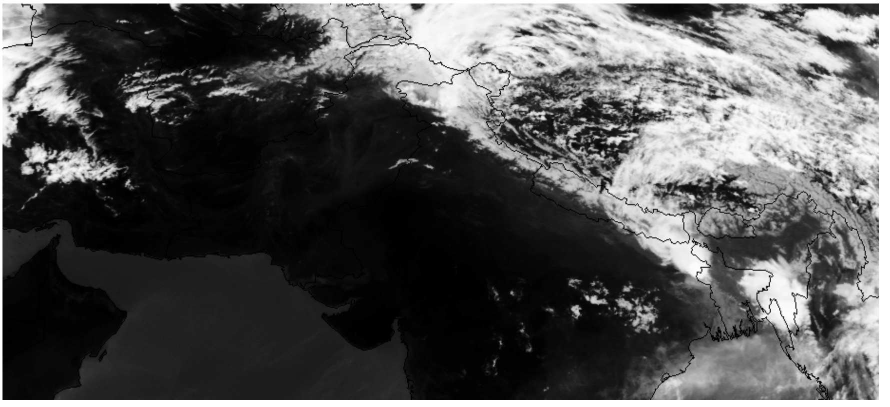
Bhairahawa Observation

Although Simra is much closer to Thori than Bhairahawa, the latter station was able to provide this study with very useful 12UTC May 3 surface data. May 3, 03UTC (0845NST) observation reports for Bhairahawa, indicate cloud cover of 1 octa (1/8), cloud type was low cumulus and visibility was also more than 10km. The surface temperature at Bhairahawa was 29.4°C, a two degrees increase from the previous day; the dewpoint temperature was 22.3°C with no increase from the previous day. Winds were also easterly, from 90 degrees, at 6 knots. Station surface pressure was 992.1hPa, exhibiting a 24 hour negative pressure tendency of 2.6hPa. At 12UTC (1745NST) May 3, Bhairahawa cloud amount was still 1 octa, but cloud type (2) had changed to low, towering cumulus. Visibility remained at more than 10km. The surface temperature was 34.2°C, with a dewpoint temperature increasing to 27.4°C by 12UTC, 1745NST. The maximum surface temperature reached 35.5°C. Winds were southeasterly from 120 degrees at 5 knots and station surface pressure dropped to 986.3hPa, a 24 hour negative surface pressure tendency of 3hPa. The 03UTC May 4 Bhairahawa surface temperature decreased 5.2°C degrees during the previous 24 hours; the dewpoint temperature decreased 2.7°C. Unlike at Simra, the winds remained easterly, from a 110 degree direction at 8 knots.

University of Dundee Archived Infrared Satellite Images

Figure 2 depicts the 630UTC (1215NST) May 2, 2001 infrared satellite image (IR) of the North Indian subcontinent. At midday the north Indian subcontinent is a deep black color, illustrating the intensely heated surface. Skies are clear and there are few signs of convective activity at this time over the plains, likely indicating insufficient moisture at the surface and at low tropospheric levels.

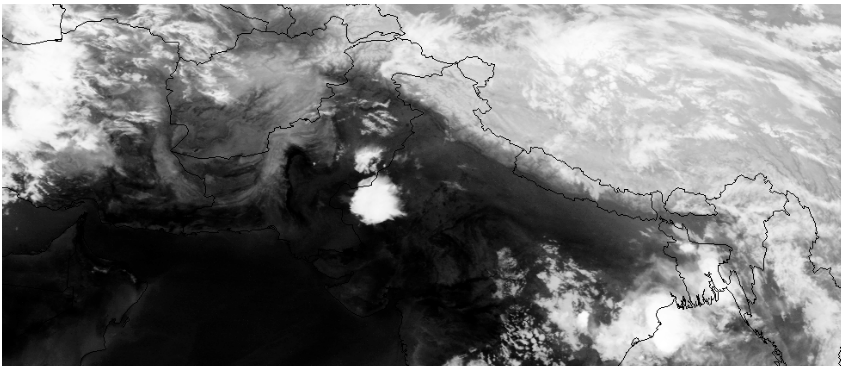
Figure 2: 630UTC (1215NST) May 2, 2001 infrared satellite (IR) image of North Indian Sub-continent and Nepal.



Source: U of dundee receiving station, 2001.

The spotty, grey patches over the high Himalayas indicate cold mountain tops as well as high clouds in the elevated valleys. The cloud shield over eastern Bangladesh is typical during the pre-monsoon months. The eastern half of Nepal is cloud covered. The hot, arid conditions of North India and Pakistan on May 2 delayed any significant convective activity until about 1545hrs NST (1000UTC) when a large cloud cluster appeared over the Thar desert, in Pakistan, near the Indian border, slightly to the west of the location of the pre-monsoon primary surface heat low. The IR images at 1345NST (08UTC) had already indicated several small areas of convection (small white spots) at the same location. At 1100UTC the cloud cluster appears to dissipate, with its edges becoming less defined, when daytime surface heating is diminishing. The cluster is also moving eastwards. At 1400UTC (1945NST) the IR image shows a very bright, white, clearly defined circle inside the same cluster over the Thar Desert, now on the India-Pakistan border, indicating the cold, high cloud tops of severe thunderstorm cells. Outflow boundaries are visible to the east of the storm cluster where future convective activity might occur.

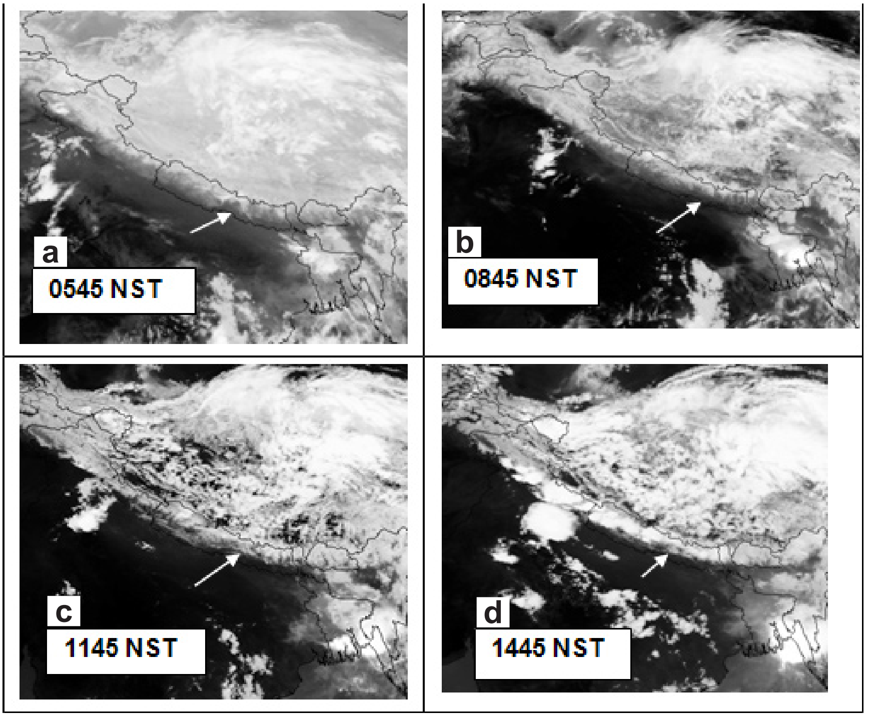
Figure 3: 19UTC May 2 (045NST) May 3, 2001 IR image of the study site.



Source: U of dundee receiving station, 2001.

The cloud cluster over the Thar desert continues intensifying, propagating eastwards along the storm cluster's outflow boundaries, while the rest of the northern subcontinent is slowly cooling off (Figure 3). By midnight, the cloud cluster has evolved to the size of Bhutan, at least 200km in diameter. The cloud shield is a bright white indicating cloud tops with very cold temperatures. Intense convection of such magnitude at night over the Thar desert in Pakistan and in Rajasthan (India), where the average rainfall in April and May does not exceed 4mm, suggest thunderstorm initiation mechanisms that are not immediately obvious. Cell propagation in the absence of thermodynamic (surface) lifting still requires a constant source of warm, humid air, in addition to a 'trigger' mechanism to start the lifting process, plus sufficiently cold air aloft to keep rising air buoyant. In the beginning of May, at mid and upper tropospheric levels, the westerlies still periodically sweep very cold air into the North Indian sub-continent. For thunderstorm propagation to occur at night as effectively as demonstrated in Figure 3, ESRL data for Delhi and Jodhpur indicate the presence of fast, both daytime and nocturnal low level jets on May 2; e.g., at Jodhpur on 01UTC May 2, 19 knots from 245 degrees at 925hPa with a dewpoint temperature of 16.5^{o}C. The solitary nature of the cloud cluster of figure 3, was likely due to unreliable moisture availability in the desert at low tropospheric levels, in combination with sufficiently cold temperatures aloft, plus a highly dynamic and effective lifting mechanism at upper tropospheric levels, without which organized convective activity could not have been initiated. The IR image (Figure 3) indicates convective activity along the northern region of the Bay of Bengal as well.

Figure 4: a, b, c, and d. IR images for 00UTC (0545NST) to 09UTC (1445NST) , May 3, 2001.

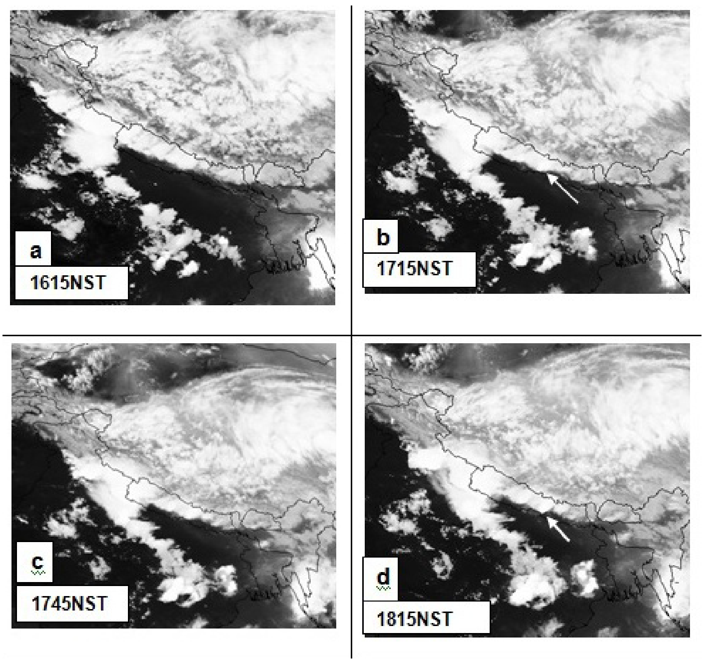


Source: U of dundee receiving station, 2001.

In the 0545 NST(00UTC) May 3 IR image, shortly after the 0523NST sunrise, the Thar Desert cloud shield has mostly dissipated, leaving a small cloud cluster, possibly the remnants of the outflow boundary from the previous' day storm, to the west of Delhi (Figure 4.a). The high Himalayas and the Tibetan Plateau are a light foggy grey colour in the IR image indicating the cold temperatures at the higher elevations. The small, white areas embedded in the grey of the high Himalayas are likely to be snow- capped peaks or high clouds attached to the mountain tops. The North Indian plains at this time have cooled to a warm, charcoal colour and are mostly clear, except for cloud cover over Bangladesh and the Bay of Bengal. The white arrow points to the location of Thori. Most noticeable in the 0845NST(03UTC) and 1145NST (06UTC) IR images is the intense heating of the sub-continent south of the Himalayan Range (black color), including the Thori area (Figure 4.b and c). By 1145NST(06UTC) the cloud cluster to the west of Delhi has moved slightly eastwards and is seen intensifying. Bright, white spots have appeared over the Himalayan range indicating early convective activity following the onset of humid air transport by the diurnal mountain-valley circulation. By midday the intensely heated sub-continent to the south of the mountains will have developed a very stable boundary layer with a strong capping inversion. At 1445NST (09UTC), what was the original May 2 Thar Desert cloud cluster has moved closer towards Delhi at 0545NST and has intensified into a very large cloud shield of at least 200km in diameter, again the size of Bhutan. Centered over Delhi (Figure 4.d), the bright, white color of the cold cloud tops is indicative of the severity created by the large cluster of propagating and intensifying thunderstorms. To the north of the Delhi cloud shield, along the Himalayan Range another high, cold cloud shield is seen forming. The latter was observed on the 1315NST IR image (1 ½ hours earlier) as a single, bright white circle (very cold cloud top) with a massive anvil pointing east. The widespread convection, including at least 10 cloud tops with anvils, seen occurring on the 1445NST IR images and confined to the High Himalayas mountain range to the west of Thori (white arrow) confirms the presence of vigorous daytime up-valley mountain flows transporting humid air to higher elevations from the plains to the south. This diurnal transport mechanism, typical of mountainous terrain, is mostly independent of the synoptic environment and occurs throughout the year. Cloud cover slows the valley wind speeds, while clear skies will increase them. Moisture content in the air being transported varies according to the season. During the pre-monsoon month of May, the Bihar surface heat low, the most significant of the pre-monsoon moisture transport mechanisms, actively transports humid air westwards from the Bay of Bengal at the lower tropospheric levels (Pant, & Rupa Kumar, 199, Rao, 1981).

The IR image does not show convective activity over the plains directly south of Nepal, in spite of the fact that ample humid air must have been available. The near solitary Delhi cloud shield, surrounded by the black, intensely heated north Indian plains suggests again an active upper level synoptic disturbance, possibly an embedded short wave at upper tropospheric levels. It is likely therefore, that the absence of anvils and therefore of severe convective activity in the eastern half of Nepal and of the Himalayan Range, highly appropriate for this time of the year, can be attributed to the synoptic or mesoscale environment. The progress of the synoptic disturbance or induced embedded low pressure short wave that travelled across Rajasthan to Delhi on May 2 and 3, accompanied by the dynamic lifting mechanisms evidenced in the IR images, may have slowed, stalled or stopped from moving eastwards altogether. Also, in the Himalayan mountain valleys, the late afternoon air mass thunderstorms, typical of the pre-monsoon period and frequently accompanied by hail, tend to occur after 1530NST.

Figure 5: a, b, c, and d**.** IR images for 1615, 1715, 1745 and 1815NST, May 3, 2001 respectively.



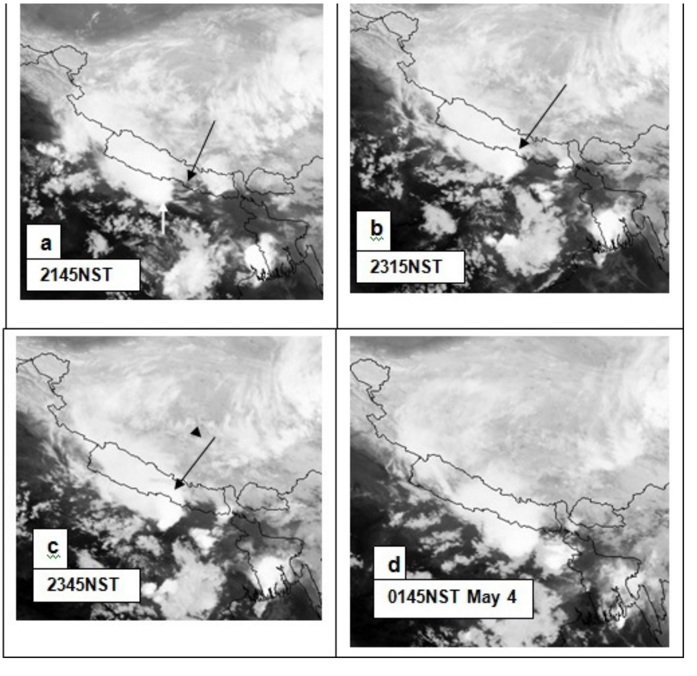
Source: U of dundee receiving station, 2001.

One and a half hours later at 1615NST (1030UTC) the Delhi cloud shield and the shield just to the north in the Himalayan foothills appear to be merging, the Delhi section moving further east (Figure 5a) towards

Lucknow. The anvils of the combined storm cluster are reaching into the far southwest of Tibet. The North Indian Plains south of Nepal are still clear. Anvils of the thunderstorms in the foothills of the western half of Nepal are indicating upper air winds from the southwest, 225 degrees; the anvils are massive, all reaching across Nepal into Tibet. At 1715NST (1130UTC), the entire original Delhi shield has moved further east, partially into western Nepal and as far as Lucknow in India (Figure 5b). The anvils of the thunderstorms in the foothills and mountains of Nepal are now pointing eastwards, indicating a change in direction of the upper tropospheric wind from the west. The 1715NST IR image still indicates a deep, black color, intensely heated surfaces, over the Himalayan foothills in the eastern half of Nepal. Most of the gangetic plains to the south of Nepal indicate intense surface heating as well, establishing a stable, deep, boundary layer where convective activity is unlikely unless the stability is disturbed by strong and effective dynamic processes. There is a line of convective activity, south of the clear gangetic plains, reaching from the Delhi cloud shield in a southeast direction to Calcutta. Close inspection of the Thori area reveals cold cloud tops directly to the west (white arrow). Half an hour later, at 1745NST (12UTC), Bhairahawa, 120km to the west of Thori, reported low, cumulonimbus over 1/8th of the sky. Two anvils, originating near the Nepal/India border, possibly the Thori/Bhairahawa area, are visible on the IR image (Figure 5c). The1815NST (1230UTC) IR image indicates a thunderstorm, a bright, white circle (white arrow), occurring very close to Thori (Figure 5d). Southwesterly upper tropospheric winds are directing the thunderstorm anvil as far as Tibet in China, suggesting this storm was severe, with a strong likelihood of hail. Nevertheless, this storm would have been reported in the Nepal media had there been loss of life and injuries. The cloud cluster covering western Nepal has remained stationary. The IR images indicate no convective activity at Gorakhpur and Patna.

An hour and a half later, at 1915NST (1330UTC), the IR images show the large cluster of organized thunderstorm cells beginning to travel eastwards at speeds of up to 70km/hour. At this time the resemblance of the large cloud cluster to a Mesoscale Convective System (MCS) is increasing. The organized system does not meet all the criteria of a Mesoscale Convective Complex (MCC),which requires a substantially larger (50,000km^2) extremely cold cloud shield of less than -52^{o}C (*Houze,* *1993*). However, its behavior does appear to follow the less stringent guidelines for a MCS, such as overall size, cell propagation and intensifying long after sunset, during the night when surface based convection can no longer occur. Elevated convection replaces surface based convection. Studies show that elevated convection at night is sustained by the warm, humid air of a nocturnal low-level jet. MCSs and MCCs normally begin travelling eastwards (propagating) when the nocturnal low-level jet has reached maximum speeds, sometimes up to 20 or 30 knots, usually around midnight. The MCS in the above IR images started travelling several hours before midnight, before a nocturnal low-level jet could have been fully established.

Figure 6: a, b, c and d**.** IR images for 2145, 2315, 2345, NST, May 3, 2001 and 0145NST May 4, 2001 respectively.



Source: U of dundee receiving station, 2001.

The 2145NST (16UTC) IR imageof Figure 6a, indicates the enlarged, travelling Mesoscale Convective System (MCS). The MCS continued eastwards, its northern edge covering the Himalayan Range, a large section of southwestern Tibet, all of western Nepal, as well as a 200km swath to the south, of the north Indian gangetic plains. There appears to be a leading convex convective line from the Nepal/India border near Thori to the city of Gorakhpur (short white arrow). The whitest section of the system, therefore the coldest, highest cloud tops, is behind the convective line. By 2315NST (1730UTC) the cloud arc over Gorakhpur, appears to be dissipating, but further north, sections inside the cloud shield over the Thori area (long black arrow), have become a very bright, white color, indicating the high, cold tops of severe thunderstorms (Figure 6b). The cold Thori cloud tops (Figure 6c) are still visible in the 2345NST (18UTC) IR image, confirming the Thori villagers' reports of the time of the hailstorm, very late at night on May 3. The leading convective line has moved further east towards Patna and by 0145NST May 4 (20UTC) is seen approaching Bangladesh (Figure 6d). The system begins dissipating two hours later.

Thori Stability Indices

This study was fortunate in having both 00UTC and 11UTC, May 3, 2001 Gorakhpur upper air data sets. The IR images indicate two thunderstorms for Thori on May 3, one at approximately 1815NST and one near midnight that devastated the village. Stability indices for Thori, May 3 were calculated for 00UTC and for 11UTC, using Gorakhpur ESRL upper air data sets and substituting surface data from Bhairahawa and Simra. The Gorakhpur surface data, 77m asl for both soundings was replaced with a surface data level beginning at 215m asl, 970hpa, assigned for Thori. The elevation of Thori is approximately 500m below the 925hPa tropospheric level.It is not known whether the second, late night thunderstorm storm was accompanied by rain. Nothing was documented about the earlier 1815NST thunderstorm, which judging by the high, cold cloud tops in the IR images, may have been fierce as well. The IR images indicate storm clusters, or a possible Mesoscale Convective System (MCS) that began travelling across the North Indian subcontinent after sunset on May 3. At that time, convective activity initiated by surface heating is no longer a factor in the destabilization of the atmosphere. Other causes of lift need to be considered such as elevated convection in the presence of a low level nocturnal jet, upper tropospheric disturbances or strong and efficient cell propagation within a well-organized thunderstorm cluster. Additional stability index calculations beginning not at the surface, but at 925hPa, approximately 700m asl a likely height of the nocturnal low level jet, were done, to determine atmospheric instability in the case of elevated convection.

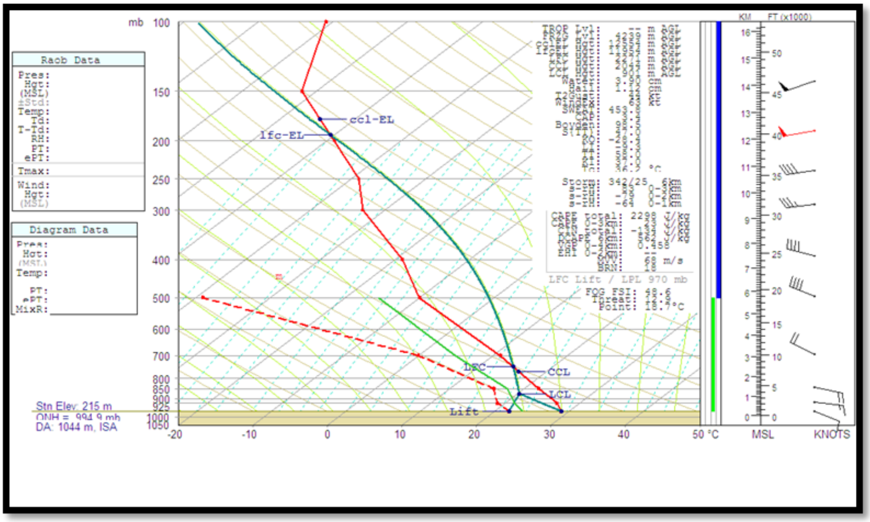
Table 2: Original 00UTC May 3, 2001 Gorakhpur upper air radiosonde data with 03UTC Simra and Bhairahawa surface data that was loaded into the RAOB ERS program.

PRESS HPA	HGT(MSL) M	TEMP C	DEW PT C	WND DIR DEG	WND SPD M/S
970.	215.	29.0	22.6	120.0	5.0
925.	705.	27.2	19.2	100.0	8.5
850.	1448.	22.0	16.0	105.0	11.0
700.	3107.	11.8	-0.2	305.0	11.5
500.	5800.	-10.1	-39.1	300.0	21.0
400.	7490.	-19.3	-273.1	290.0	19.5
300.	9560.	-33.3	-273.1	260.0	17.0
250.	10830.	-39.9	-273.1	260.0	19.5
200.	12320.	-49.7	-273.1	255.0	25.0
150.	14140.	-62.3	-273.1	245.0	24.5
100.	16580.	-71.9	-273.1	235.0	19.5

Source: ESRL and DHM, 2001.

The 00UTC May 3 Gorakhpur upper air data plus the averaged 03UTC Bhairahawa and Simra surface data (00UTC May 3 Bhairahawa or Simra data not available). Surface and dew point temperatures for Thori (Simra/Bhairahawa) were 29^{o}C and 22.6^{o}C respectively; surface winds were 5 m/sec from a 120 degree direction. Dewpoint values of -273.1^{o}C at 400hPa and higher indicate levels of extremely dry air that the radiosonde does not record (Table 2).

Figure 7: Skew-T log P chart for Thori, 00UTC May 3, 2001 including Stabilit Index calculations.



Source: ESRL and DHM, 2001.

The Skew-T log P chart for Thori calculated with the RAOB.ERS computer program for 00UTC May 3 using the data in Table 2 is shown in Figure 7. The results of the Thori calculations indicate a potentially dangerous hailstorm with positive Convective Available Potential Energy (CAPE) of 2298 J/kg, a Lifted Index (LI) of -9.3, hail size of 1.17cm (5cm before melting) and a potential updraft velocity of 68 m/sec, capable of sustaining very large hailstones. Downdraft CAPE (DCAPE) in the lower 6km was weak, 562J/kg. The Lifting Condensation Level (LCL) and the Convective Condensation Level (CCL) were 901 and 2044m agl respectively, the freezing level was at 4239m agl, 518m above the wet bulb zero height of 3721m agl (650hPa). A highly unstable lapse rate of 8.2°C between 700 and 500hPa contributed to the potentially severe atmospheric instability. The Skew-T chart indicates a stable, early morning layer, a capping inversion at about 500m above the surface (925hPa) inhibiting convection. 925hPa temperature at Gorakhpur was 27.2°C. negative CAPE (CIN) is -134J/kg and the convective temperature (Tc) is 36.2°C. The maximum surface temperature for Simra on May 2 was 33.2°C (maximum surface temperature data missing for May 3) and for Bhairahawa the maximum temperatures for May 2 and May 3 were 34.2°C and 35.5°C respectively. A 00UTC (0545NST) capping inversion resulting from nighttime radiational cooling usually weakens with daytime surface heating and with increasing dewpoint temperatures. However given the maximum Simra and Bhairahawa surface temperatures for May 2 and 3, a Tc of 36.2°C at Thori seems unlikely. The above sounding using 0845NST surface data indicates between approximately 500hPa and 300hPa, near ideal hail generating conditions: a large, wide CAPE area between -10°C and -30°C, the location of the maximum updraft and the favored location of hail formation.

The IR images indicate two thunderstorms at Thori; one, a late afternoon thunderstorm visible on the 1230UTC (1815NST) IR image and a second one, the destructive hailstorm close to midnight. At 12UTC (1745NST) the synoptic Bhairahawa observations detail towering cumulonimbus clouds with low ceilings, indicating the disappearance of the early morning cap and allowing convection to initiate. There are no photographs of the 1kg Thori hailstones. The reports of the storm's devastation lead this study to accept that the hailstones were very large and probably varied in shape. It is likely that some hailstones were perfectly round and some were conglomerates of different size hailstones glued together with super cooled water droplets at high elevations in both the updraft and the downdraft (*Knight and Knight 2001*)

Table 3: Original 11UTC May 3 Gorakhpur ESRL upper air and 12UTC Bhairahawa DHM surface data.

PRESS HPA	HGT(MSL) M	TEMP C	DEW PT C	WND DIR DEG	WND SPD M/S
970.	200.	35.5	27.4	120.0	2.5
925.	700.	27.2	24.2	30.0	4.0
850.	1441.	21.0	14.0	330.0	3.5
700.	3096.	11.6	-0.4	290.0	8.0
500.	5790.	-8.9	-24.9	295.0	20.0
400.	7490.	-19.1	-273.1	295.0	20.5
300.	9570.	-33.5	-273.1	290.0	17.5
250.	10820.	-41.1	-273.1	290.0	18.0
200.	12310.	-52.3	-273.1	290.0	17.0
150.	14100.	-65.3	-273.1	260.0	10.5
100.	16490.	-77.9	-273.1	245.0	11.0

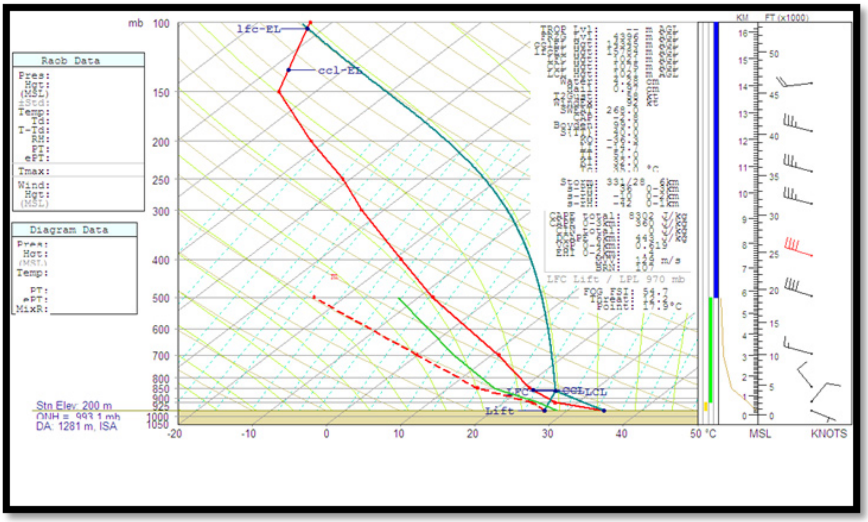
Source: ESRL and DHM, 2001.

Estimating temperature and dewpoint temperature values for the low-tropospheric levels, e.g. 925hPa at Thori is complicated by the complex terrain of the Himalayan foothills surrounding Thori along its west, east and northern boundaries. Original 12 UTC May 3 Thori/ Bhairahawa surface, 215m asl, temperature was 35.5°C and the dewpoint temperature was 27.4°C. The ESRL 925hPa Gorakhpur temperature and dewpoint temperatures were 26.2°C and 18.2°C respectively, values this study adjusted with the aid of a Skew-T logP chart to reflect the almost 200m elevation difference between Thori and Gorakhpur. The 925hPa temperature for the Thori sounding was increased 1°C to 27.2°C and given the very high surface dewpoint temperature at Thori of 27.4°C, the 925hPa dewpoint temperature was increased to 24.2°C.

The 11UTC May 3 Gorakhpur upper air data combined with the 12UTC (1745NST) Bhairahawa maximum May 3 surface temperature of 35.5°C, (Table 3) when loaded into the RAOB program yielded the unexpected result of 0 CAPE. No CAPE means no updraft, no vertical velocity and no hail growth. RAOB program did calculate a Lifted Index of -14.7, a critically high value, hail before melting was estimated at 8cm and the convective temperature (Tc) was 35°C. Data verifying and manipulation within the model, revealed that the RAOB computer program rejected the exceptionally cold 100hPa temperature of -77.9°C (Table 3). Substituting lesser values -77°C, -76°C and -75°C into the 100hPa level continued yielding 0 CAPE. The 100hPa temperature, -77.9°C would have placed the cloud and its overshooting top caused by the extremely strong updraft, far above the anvil, above 17000m asl and outside the Skew-T diagram.

Figure 8 shows the Skew-T log P chart and stability index calculations for Thori, 11 UTC May 3, using the data of Table 4.8, except for the 100hPa temperature, which this study was forced to increase by 4°C from -77.9°C to -73.9°C. CAPE at 11UTC resulted in a value of 8320J/kg, the LI was -14.9, maximum vertical velocity increased to an unbelievable 129m/sec, the convective temperature remained 35°C, predicted hail size was 0.97cm, 8cm before melting and precipitable water was 4.28cm.

Figure 8: Stability Index calculations for Thori, 11UTC May 3, 2001.



Source: ESRL and DHM, 2001.

Daytime surface heating erased the 00UTC cap and consequently negative CAPE was 0. DCAPE from the surface to 6km was 443J/kg. The LCL increased by 120m to 1021m agl and the CCL decreased to 1075 m agl from 2044m agl at 00UTC. The freezing level rose 157m to 4396m agl and the wet bulb zero level increased as well to 3788m agl, both values reflecting the Gorakhpur temperature increase at 500hPa of 1.2^{o}C. At 11UTC, the lapse rate between 700 and 500hPa remained conditionally unstable, 7.6^{o}C; the 6.5^{o}C surface temperature increase resulted in a super-adiabatic lapse rate between the surface and 925hPa. The hail growth zone, between -10^{o}C and -30^{o}C, is located approximately between 500hPa and 300hPa and coincides on the above Skew-T diagram with the area where the most intense CAPE and therefore the strongest updraft are located.

Apart from a higher, 6.5^{o}C surface temperature at 11UTC, the 925, 850, and 700hPa temperatures changed little between 00UTC and 11UTC (Table 4). The 500hPa temperature actually increased from -10.1^{o}C to -8.9^{o}C from 00UTC to 11UTC, while the 400 and 300hPa temperatures remained approximately the same.

Table 4: 00UTC and 11UTC May 3temperature and dewpoint temperature comparisons in Centigrade for Thori.

HPA	Temperature in C		Dewpoint in C	
	00UTC	11UTC	00UTC	11UTC
970	29.0	35.5	22.6	27.4
925	27.2	27.2	19.2	24.2
850	22.0	21.0	16.0	14.0
700	11.8	11.6	-0.2	-0.4
500	-10.1	- 8.9	-39.1	-24.9
400	-19.3	-19.1	-273.1	-273.1
300	-33.3	-33.5	-273.1	-273.1
250	-39.9	-41.1	-273.1	-273.1
200	-49.7	-52.3	-273.1	-273.1
150	-62.3	-65.3	-273.1	-273.1
100	-71.9	-77.9	-273.1	-273.1

Source: ESRL and DHM, 2001.

The data show a gradual temperature decrease at the upper tropospheric levels, beginning at 250hPa with a small temperature decrease, 1.2°C, from -39.9°C to -41.1°C. The 200hPa temperature fell 2.6°C from -49.7°C to -52.3°C and the 150hPa temperature dropped 3°C to -65.3°C. At 100hPa the temperature decrease was 6°C, to -77.9°C. At 00UTC, the 500hPa dewpoint temperature was low, -39.1°C; the atmosphere above 500hPa was too dry to be recorded. But by 11UTC, slightly warmer and more humid air had been advected into the Thori area, causing the 500hPa dewpoint temperature to rise 14.2°C to -24.9°C. Again, the data indicate the higher tropospheric levels to be extremely dry and therefore not recorded. The 100 to 120 degree surface wind direction during the pre-monsoon period is a result of the surface heat low usually centered near Patna in Bihar. This direction is maintained at the lower tropospheric levels up to 925hPa and frequently up to the 850hPa level (Table 5). The northerly oriented Gorakhpur wind directions at 925Pa and 850hPa at 11UTC on May 3 interrupted this pattern, although dewpoint temperatures remained the same. Surface winds at Bhairahawa/Thori at 12UTC May 3 were 5 knots from a 120 degree direction, with a dewpoint temperature of 27.4°C, undoubtedly enhancing existing moisture convergence at Thori.

Table 5: 00UTC and 11UTC May 3, 2001 wind speed and wind direction comparisons for Thori / Gorakhpur.

HPA	Wind Speed m/sec		Wind Direction Degrees	
	00UTC	11UTC	00UTC	11UTC
970	5.0	2.5	120	120
925	8.5	4.0	100	30
850	11.0	3.5	105	330
700	11.5	8.0	305	290
500	21.0	20.0	300	295
400	19.5	20.5	290	295
300	17.0	17.5	260	290
250	19.5	18.0	260	290
200	25.0	17.0	255	290
150	24.5	10.5	245	260
100	19.5	11.0	235	245

Source: ESRL and DHM, 2001.

Surface winds at Gorakhpur on May 3 were also from a northerly 45 degree direction at 00UTC and 11UTC. The latter abrupt changes were accompanied by a 4mb drop in surface pressure from the previous day, 00UTC May 2. The embedded short wave low pressure trough that is indicated in the 12UTC 500hPa synoptic charts and that had been travelling eastwards and lowering geopotential heights across northern India, likely signified its arrival in the Gorakhpur area with the wind change direction. Lower tropospheric wind speeds decreased by half on May 3 between 00UTC and 11UTC: at the surface from 5m/sec to 2.5m/sec, at 925hPa from 8.5 m/sec to 4 m/sec and at 850hPa from 11m/sec to 3.5 m/sec. Gorakhpur surface winds returned to their usual pre-monsoon easterly/southeasterly direction on May 4. Winds at upper tropospheric levels were mostly westerly on May 3, with speeds from 20 to 25m/sec between 500 and 150hPa at 00UTC and from 20 to 17 m/sec at 11UTC between 500 and 200hPa. Wind direction at 100hPa was southwesterly, as documented also in the IR images. The extreme instability indicated for 11UTC resulted in severe weather twice, at 1230UTC (1815NST) as indicated in the IR images and about 5 hours later when Thori was devastated by a hailstorm that occurred probably between 1730 UTC and 18UTC (1115NST and 1145NST).

CAPE values of both 00UTC and 11UTC soundings were more than adequate to sustain large hail growth. The 11UTC surface and 925hPa dewpoint temperatures provided ample moisture to destabilize the atmosphere, initiate severe convective activity and to generate hail. It is very likely that Thori's first thunderstorm produced hail, but not of a noteworthy size after falling to the surface. Thori's second storm, 5 hours later found its way into the media, with 500 oxen, buffaloes and goats killed, 800 thatched houses destroyed, tin roofs shredded and 300 bighas, more than 200 hectare, of crops completely destroyed by hailstones estimated to weigh up to 1kg (*Local Newspaper*). Gorakhpur upper air data for 00UTC May 4 was mostly incomplete; wind data, except for the surface and 925hPa, is missing. All remaining temperature and dewpoint temperatures had been recorded at odd tropospheric levels instead of at the usual mandatory levels. To perform a comparison between the 11UTC May 3 and 00UTC May 4 Thori/Gorakhpur vertical atmospheric profiles, all data had to be at the same mandatory levels. When the existing 00UTC May 4 temperature and dewpoint temperature values were plotted manually on a Skew-T logP chart and the profiles drawn, the mandatory level values were easily located (Table 6b).

Significantly colder air had arrived by 00UTC May 4 at mid- and upper tropospheric levels, between 700hPa and 300hPa (Table 6 a and b). Temperatures at 500hPa had decreased 3.1^{o}C from -8.9^{o}C to -12^{o}C and at 300hPa the temperatures dropped 1.6^{o}C to -35.1^{o}C. A warming trend, however, was indicated at the higher tropospheric levels, beginning at 250hPa, where the temperature increased 1.1^{o}C. At 200hPa the temperature increased by 3^{o}C to -49.3^{o}C from – 52.3^{o}C, at 150hPa by 3.1^{o}C to -62.2^{o}C and at 100hPa, the 11UTC May 3 temperature of -77.9^{o}C increased a surprising 13.9^{o}C to -64^{o}C. Dewpoint temperatures were missing above 400hPa for both datasets indicating extremely dry air at high tropospheric levels. At 500hPa and 700hPa the atmosphere became significantly more humid, increasing from -24.9^{o}C to -15^{o}C and -0.4^{o}C to 2.1^{o}C respectively. Surface, 925hPa and 850hPa dewpoint temperatures for 11UTC May 3 were higher than those of May 4, indicating the expected humid air increases at lower tropospheric levels at the end of the day. Surface winds at Simra had become westerly by 00UTC May 4. The rest of the wind data for 00UTC May 4 was missing. Gorakhpur ESRL data for May 5 was missing as well.

Table 6: a and b. Thori/Gorakhpur 11UTC May 3 and 00UTC May 4 2001 surface and upper air data.

PRESS HPA	**HGT(MSL) M**	**TEMP C**	**DEW PT C**	**WND DIR DEG**	**WND SPD M/S**
970.	200.	35.5	27.4	120.0	2.5
925.	700.	27.2	24.2	30.0	4.0
850.	1441.	21.0	14.0	330.0	3.5
700.	3096.	11.6	-0.4	290.0	8.0
500.	5790.	-8.9	-24.9	295.0	20.0
400.	7490.	-19.1	-273.1	295.0	20.5
300.	9570.	-33.5	-273.1	290.0	17.5
250.	10820.	-41.1	-273.1	290.0	18.0
200.	12310.	-52.3	-273.1	290.0	17.0
150.	14100.	-65.3	-273.1	260.0	10.5
100.	16490.	-77.9	-273.1	245.0	11.0

(a)

PRESS HPA	**HGT(MSL) M**	**TEMP C**	**DEW PT C**	**WND DIR DEG**	**WND SPD M/S**
970.	200.	23.8	20.0	270.0	2.0
925.	700.	25.2	22.2	120.0	7.0
850.	1470.	20.0	12.7	m	m
700.	3078.	8.9	2.1	m	m
500.	5770.	-12.0	-15.3	m	m
400.	7420.	-21.8	-30.7	m	m
300.	9468.	-35.1	-273.1	m	m
250.	10705.	-40.0	-273.1	m	m
200.	12124.	-49.3	-273.1	m	m
150.	13961.	-62.2	-273.1	m	m
120.	15460.	-64.0	-273.1	m	m
(b)					

Source: ESRL, 2001.

The Thori midnight storm occurred about 6.5 hours after the 11UTC May 3 upper air data set and 6.5 hours before the one at 00UTC May 4. This study averaged the two data sets, so that stability indices that might match existing atmospheric conditions could be calculated. Also, as described in the previous section, the Thori midnight hailstorm was not an isolated event, but occurred when an eastward propagating and travelling MCS engulfed a large area in Central Nepal and in the Gangetic Plains, directly to the south. Convection at midnight is not likely to be diurnal surface-heating based. The previous two sets of stability index calculations, for 00UTC and 11UTC May 3 were calculated with Skew-T logP profiles that were surface based. Convection along the convective line of an MCS, close to midnight is likely to occur only when a constant source of warm, humid air is available above the surface and usually above the stable nighttime boundary layer.

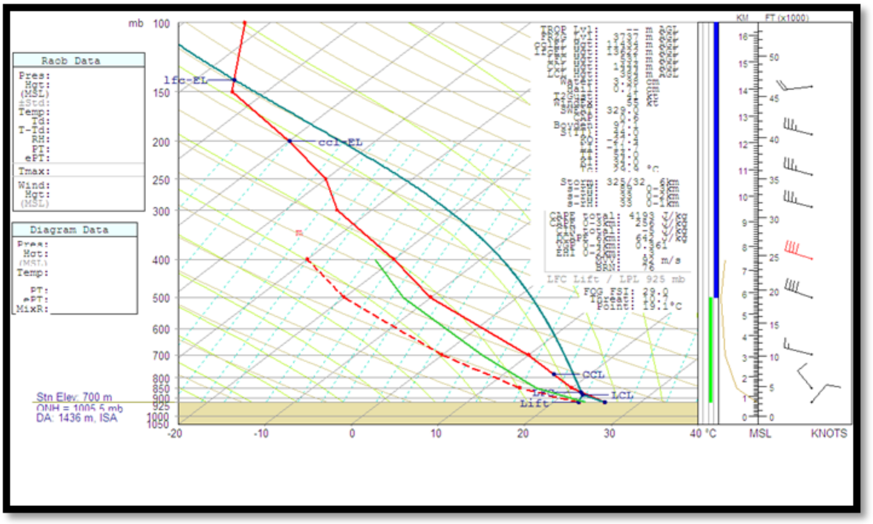
Table 7 indicates the averaged Thori/Gorakhpur vertical atmospheric profile values of 11UTC May 3 and 00UTC May 4, that were used to calculate stability indices for 1730UTC May 3 at Thori. The profile begins at 925hPa, approximately 500m above the elevation of Thori. Wind data was missing for May 4. The wind data for 11UTC May 3 was used to complete the profile.

Table 7 Upper air data for Thori averaged from 11UTC May 3 and 00UTC May 4 Gorakhpur.

PRESS HPA	HGT(MSL) M	TEMP C	DEW PT C	WND DIR DEG	WND SPD M/S
925.	700.	26.2	23.2	30.0	4.0
850.	1441.	20.5	14.0	330.0	5.5
700.	3096.	10.2	0.7	290.0	8.0
500.	5790.	-10.5	-20.2	295.0	20.0
400.	7490.	-20.5	-30.1	295.0	20.5
300.	9570.	-34.4	-273.1	290.0	17.5
250.	10820.	-40.7	-273.1	290.0	18.5
200.	12310.	-50.8	-273.1	290.0	17.0
150.	14100.	-64.4	-273.1	260.0	10.5
100.	16490.	-73.9	-273.1	245.0	11.0

Source: ESRL, 2001.

Figure 9: Skew-T logP chart and Stability Index calculations for Thori elevated convection from 925hPa at 1730UTC May 3, 2001.



Source: ESRL and RAOB ERS, 2001.

The Stability Indices calculated by the RAOB program for Thori for 1730UTC May 3 from the Skew-T logP chart in Figure 9 indicate again extreme atmospheric instability. This study assumes elevated convection was likely and the profile starts at 925hPa, 500m above the elevation of Thori. CAPE value is 4193J/kg with negative CAPE only -5J/kg, ensuring an intense updraft of 92m/sec, capable of sustaining large hail growth. Calculated hail size before melting was 6.5cm and 0.71cm after melting. The steepest lapse rates were between 700hPa and 500hPa, 7.7°C and 400hPa to 300hPa, 7°C respectively, somewhat steeper than the lapse rates calculated for 11UTC. The wet bulb zero level lowered the freezing level, 0°C, by approximately 500m. The top of the Thori hailstorm was at 14430m asl, a massive convective system, but, in theory, according to the ROAB stability index calculations not as potentially severe as Thori's first storm in the late afternoon of the same day, which did not make the news.

It is probable that the first storm on May 3 did have hail, but was not destructive enough to be noteworthy. The environmental conditions conveyed by the IR images suggest that a strong capping inversion existed in the Thori area, a highly stable atmosphere, inhibiting convective activity, even when high daytime maximum surface temperatures must have coincided with sufficiently high dewpoint temperatures resulting from the

Bihar heat low circulation, plus likely convectivity enhancing mid and upper tropospheric dynamic mechanisms. The first Thori storm occurred about 25 minutes before sunset. At 12UTC, 1745NST, the Thori area is still dark in color in the IR images and to the west of Thori stretches a line of thunderstorm in the Himalaya foothills into NW India. Half an hour later, at 1230UTC, 25 minutes before sunset, the Thori area is covered with a large, round, cold cloud shield with the appearance of a supercell, at least 15km across and an anvil floating over Tibet. The thunderstorm had mostly dissipated by 13UTC (1845NST).

It is very likely, therefore, that Thori's first storm was the product of cell propagation from the eastern flank of a parent storm directly to the west of Thori, visible in the IR images that explosively broke through the capping inversion. The first Thori storm exhibits clearly defined edges along its southern boundary and is seen in the IR images propagating eastwards towards higher terrain of east Nepal. The IR images indicate several outflow boundaries across the border in India, south of the thunderstorm cell. In all likelihood, hail growth did occur in the earlier thunderstorm. Unlike the second, later storm, the short duration of the first Thori storm, albeit with considerably more potentially dangerous stability index values, may have inhibited very large hail growth. The second, destructive Thori storm did not propagate along the foothills of the high Himalayas, but had its origins within a MCS` which travelled from the west, near Delhi across the Gangetic Plains, covering all of western Nepal and an equally large area to the south over India. The MCS was travelling eastwards at close to 70km/hour, towards the direction of the Bihar surface heat low and towards a constant moisture supply. The IR images indicate several supercells embedded behind the convective line south of Thori by 1700UTC (2245NST). Feeder cells west and south of Thori had appeared half an hour earlier, generating hail embryos and small hail stones to be deposited into the tilted, intense updraft of the Thori storm where hail growth continued until the large hail stones, some still weighing 1kg after falling all the way through the storm cloud, landed on Thori.

CONCLUSION

When the Thori villagers were awakened by 1kg hailstones during the night of May 3, 2001, they were unaware that the storm which devastated their village and destroyed their livelihood had its origins at least 34 hours earlier, more than 1600km to the west, over the Thar desert in

Pakistan. The sequence of IR images illustrates the evolving of clusters of organized thunderstorm cells into Mesoscale Convective Systems between the afternoon of May 2 and the early hours of May 4, during which many episodes of violent weather occurred. Initial topographically induced lee-side convergence over the intensely heated deserts of Pakistan generated a massive storm visible in the 1400UTC May 2 IR image. To the east of the storm cluster, the distinct traces of outflow boundaries are visible where future convective activity might occur. The location of the storm cluster is also the location of the pre-monsoon primary surface heat low on the subcontinent. The solitary nature of the cell cluster testified not only to the lack of moisture in the extremely dry desert environment but also to the likely existence of a strong lifting mechanism at mid or upper tropospheric levels, such as an embedded short-wave trough. The system continued intensifying and had moved eastwards by early morning of May 3, when it dissipated somewhat, leaving a smaller cloud cluster, possibly remnants of outflow boundaries. The heavy, cold air of the latter radiate away from the parent storm and given the appropriate thunderstorm initiation conditions will generate new cells.

Propagating slowly eastwards towards Delhi and towards areas of warm, humid air (at 01UTC Delhi surface dewpoint temperature was 18^{o}C and 925hPa was 10.8^{o}C) was the most logical direction. By 1445NST (09UTC) May 3, the large cloud shield, the size of Bhutan, was located directly over Delhi. Within two hours, multiple thunderstorm anvils are visible on the IR images over the foothills and the high Himalayas. The original Delhi cloud shield has intensified further and by 1715NST had reached into western Nepal. Continued propagation of the large cluster of organized thunderstorm cells, a likely Mesoscale Convective System, although not a Mesoscale Convective Complex exhibiting a convective line with trailing stratiform clouds, appeared to have stalled. The IR images indicate convection leading to Thori's first storm on May 3 has been initiated. Two hours later, at 1915NST (sunset is at 1835NST), the IR images show the MCS, propagating and intensifying eastwards at speeds of up to70km/hour, its eastern boundaries becoming very defined and reaching close to the Thori area by 2145NST. Feeder cells were visible half an hour later. The Thori hailstorm, resembling in the IR images an embedded supercell, occurred late at night and the villagers would only have been able to estimate the size of the hail stones that fell close to their dwellings. Because of the availability of ample moisture in the form of minute supercooled water droplets in the cloud, plus the likelihood of high intense velocity in a tilted updraft enabling the very large hailstones to be kept aloft, this study assumes that the 1kg hailstones were conglomerates, a collection of hailstones of varied sizes that collided and were glued together by the supercooled water droplets. In addition to the 1kg hailstones, it is likely there were smaller, maybe golf or tennis ball size hailstones that contributed to the devastation of the villagers' livelihood. The MCS dissipated at approximately 0345NST (22UTC) on May 4.

On 00UTC May 3, 2001, a synoptic and mesoscale environment highly supportive of severe atmospheric instability existed across the entire length of the North Indian subcontinent. The geopotential heights charts indicate a deep low pressure trough at 200hPa, 300hPa and 500hPa, with positively tilted trough axes positioned over the Delhi area, the latter providing the dynamic lifting mechanisms leading to the Delhi cloud cluster visible in the IR images.

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