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A Severe Hailstorm at Pokhara: CAPE Stability Index Calculations

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Abstract A severe hailstorm, with hail stones estimated at 1 kg, at the city of Pokhara, 800m asl in the Nepal Himalayas, on May 18, 2005 is investigated in this paper. Upper air data obtained from Gorakhpur combined with Department of Hydrology and Meteorology (DHM) surface data at Pokhara provided the basis for stability index calculations, such as convective available potential energy (CAPE). Strong updrafts in which large hail is formed are directly related to CAPE. This paper attempts to calculate CAPE values in complex terrain, where data for low tropospheric levels is not available. Temperatures and dewpoint temperatures above the surface were estimated from the DHM observations of cumulus cloud base heights at Pokhara. This proved to be a valid technique for providing essential weather data at 850hPa. The Pokhara area is a known location of moisture convergence. This, plus exceptionally cold air aloft from the northwest on May 17 and 18, resulted in extreme instability, with CAPE values reaching and possibly exceeding 6800J/Kg.

Keywords: *CAPE, lifting index, hailstorm, radiosonde, geopotential height*

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1. Introduction

On May 18, 2005 at approximately 1530 a severe thunderstorm struck Pokhara. Hailstones, estimated at 1kg caused extensive destruction in the city within a period of about 15 to 20 minutes. Hundreds of vehicles were damaged and one person was killed. (local newspapers [15]). Eyewitnesses near Phewa lake report seeing "the blackest cloud they had ever seen" behind Sarangkot, before powerful horizontal wind gusts blew open doors and sent tennis ball size hail stones rolling across their floors. According to witnesses, the giant hail was confined to a swath across the northern section of Pokhara only. The hailstones that landed first, near the lake were perfectly spherical. As the storm moved further east, the hailstones became more varied and irregular in shape, with many reported to weigh 1kg. There was no rain during this brief storm and the southern half of the sky remained clear and blue. DHM staff in charge of weather data collection at the Pokhara Airport, 2 km southeast of the storm location, did not observe the storm and the storm is not in the their records.

Pokhara, 28°N and 84°E, is situated in the hilly region at about 800m asl. It is directly 25km south of the Annapurna Massif and the High Himalayas. Thunderstorms without hail had occurred on the afternoons of May 16 and 17. Inhabitants of Nepal's rural areas have become accustomed to almost daily thunderstorms during the month of May [9], with accompanying lightening and often hail. Still, the destruction of the May 18 afternoon storm was completely unexpected. Forecasting the severity of thunderstorms requires advance technology which Nepal simply does not have. Thunderstorm intensity is always difficult to forecast [4]. Even in highly developed and industrialized countries around the world, weather forecasters with Doppler radar, portable Radiosonde equipment and unlimited computer power at their fingertips, are easily taken by surprise. Forecasters in Nepal do the best they can, given the very limited resources.

This study aims to analyze the Pokhara storm and find characteristics unique to this severe event. It is likely that several severe storm enhancers were in place, that could deviate the usual mid-afternoon convective activity towards such instability that record breaking 1 kg hail stones would result [3,5,8]. Factors such as the sudden arrival of very cold, dry air aloft, near super-adiabatic lapse rates, the presence of an embedded short wave trough plus perhaps unusually warm and moist air to the south are investigated.

This paper focuses on the CAPE calculations for the Pokhara storm. This effort was complicated by the fact that upper air data from the Indian city of Gorakhpur, 200km to the south of Pokhara and the closest synoptic upper air station to Pokhara, was missing for May 18, 2005.

2. Data Sources

2.1 Synoptic Surface Data

The Department of Hydrology and Meteorology (DHM) maintains 16 synoptic surface weather stations throughout Nepal. In 2005, the weather station at the Pokhara Airport was a manned synoptic station, with observations and measurements of weather data limited to daytime only.

The DHM synoptic Pokhara Airport data reports during this period, including May 18, were limited to five daytime standard observation hours, 00UTC, 03UTC, 06UTC, 09UTC, and 12UTC, corresponding to 0545, 0845, 1145, 1445 and 1745NST (local time) respectively. DHM staff at the Pokhara Airport recorded synoptic observations for each daytime observation period these include surface temperature, minimum and maximum surface temperatures (recorded twice daily at 0845and 1745 NST for the period preceding the hour of observation), surface dewpoint temperatures, surface station pressure, humidity, wet and dry-bulb temperatures, visibility, cloud cover and cloud types, precipitation, past and present weather and sunshine duration. Automatic Weather Station (AWS) was not installed in 2005 at Pokhara Airport so we have not surface wind data. However, in 2012, an AWS was installed at the Pokhara Airport. It is assumed that the diurnal, thermally generated mountain-valley circulation of the elevated, complex terrain here has not experienced radical changes in wind direction and speed over a period of seven years. This study, therefore, completed an analysis of wind speed and direction for May 2012. The results of these May 2012 analyses were then used for the May 2005 study.

2.2. Satellite Images

Satellite images for the Pokhara storm analyses were obtained from the Dundee Satellite Receiving Station at Dundee University, UK (www.sat.dundee.ac.uk). The receiving station provides an up-to-date archive of images from NOAA, Seastar, Terra and Aqua polar orbiting satellites in addition to images from geostationary satellites covering the whole earth such as SEVIRI, VISSR, GOES and MTSA.

2.3. NOAA/ESRL Rawinsonde Database (Upper Air Data)

The upper air data that are collected include air pressure, air temperature and humidity measured continuously by the instruments aboard the rawinsonde. These observations ‘Rawinsonde observation program for windows’ (RAOB) are directly transmitted by the radio transmitter for various levels in the free atmosphere. The wind speed and direction are determined from the ground-based radio tracking antenna that tracks the rawinsonde as it is carried by the wind during its ascent.By international convention, the mandatory or standard, specific pressure levels that must be reported in the RAOB message are; the surface, 1000, 925, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, 50, and 10 hPa.

Significant pressure levels report significant, abrupt or extreme changes in the vertical temperature and/or dewpoint temperature profile. Upper air data from both mandatory and significant levels are essential for investigating synoptic weather patterns and they are vital for constructing stability indicators calculated from rawinsonde soundings originating in India.

The present study of pre-monsoon thunderstorms in Nepal relies heavily on potential thunderstorm indicators calculated from rawinsonde soundings originating in India. Many of these soundings, however, have much missing data. This might be a technical issue but, it is not impossible that at this time of the year, during the late afternoon, a 12UTC (1745NST and 1800 IST in India) rawinsonde flight could be headed straight into either thunderstorm or pre-thunderstorm conditions, with lightening, strong up and downdrafts and high electric fields interfering with data transmission as in below.

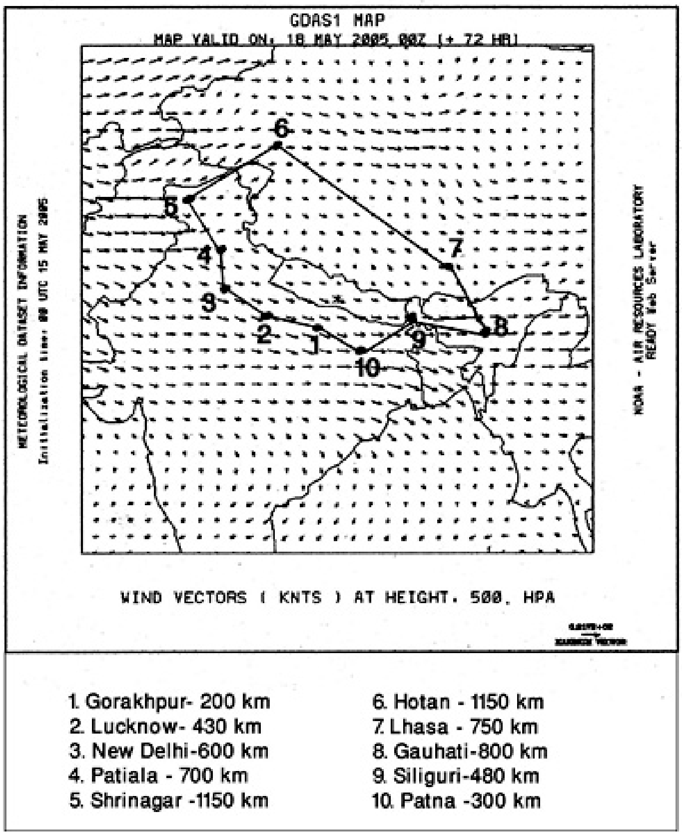


Figure 1. Map indicating locations of closest upper air stations in India and China plus their distances from the storm locations

There are no upper air stations in Nepal. Upper air data for the Pokhara storms was obtained from the closest WMO upper air stations in India and China (Figure 1). Figure 1 emphasizes the fact that the area for which there is no upper air data available is not only immense, but also contains possibly the most complex terrain on the globe. The arrow indicates the approximate location in Central Nepal of Pokhara.

Both 00UTC and 12UTC upper air data sets for Gorakhpur, the station closest to both Pokhara and Thori were missing for May 18, 2005. So here we are not able to calculate Stability Indices for Pokhara with original upper air data. Instead, the study interpolated from the original May 17 and May 19 upper air data, which fortunately was available. There was no missing upper air data from the China stations, enabling this study to complete several significant upper air analyses.

2.4. NOAA Ready Archived Point and Click Internet Site

This helpful and informative site can be found at http://ready.arl.noaa.gov/ready. In addition to many other features, the point and click capabilities enable the user to create both forecast and archived weather maps for many meteorological requirements. The studies undertaken here concentrate mostly on rawinsonde calculations for soundings or Skew T log P charts and on upper air synoptic charts at low, mid and high tropospheric levels, illustrating wind speed and direction, temperature and atmospheric humidity and geopotential heights.

The NOAA computer programmers face considerable challenges when creating the computer models that best calculate synoptic analysis charts from both existing and missing weather data in the area outlined in Figure 2. In addition to the problems of incomplete and missing data, the model needs to include the complex terrain of the High Himalayas (many mountain peaks are over 6500m asl) and that of the rest of Nepal's mountainous surface.

2.5. Data Management

This study's calculations of Stability Indices and potential thunderstorm severity, such as CAPE values and Lifted Indices were complicated due to missing original data. In these cases it was necessary to refer to the NOAA ARL archived data. When necessary, original observed and archived temperatures, dewpoint temperatures and wind data for the storm location or from the closest surface weather station were combined with the NOAA ARL vertical profile data. Soundings or Skew T log p charts were constructed using the RAOB program created by Environmental Research Services, http://www.raob.com The program calculated all potential thunderstorm severity indicators, including Convective Available Potential Energy (CAPE), Lifted Index (LI), hail size, and maximum vertical velocity.

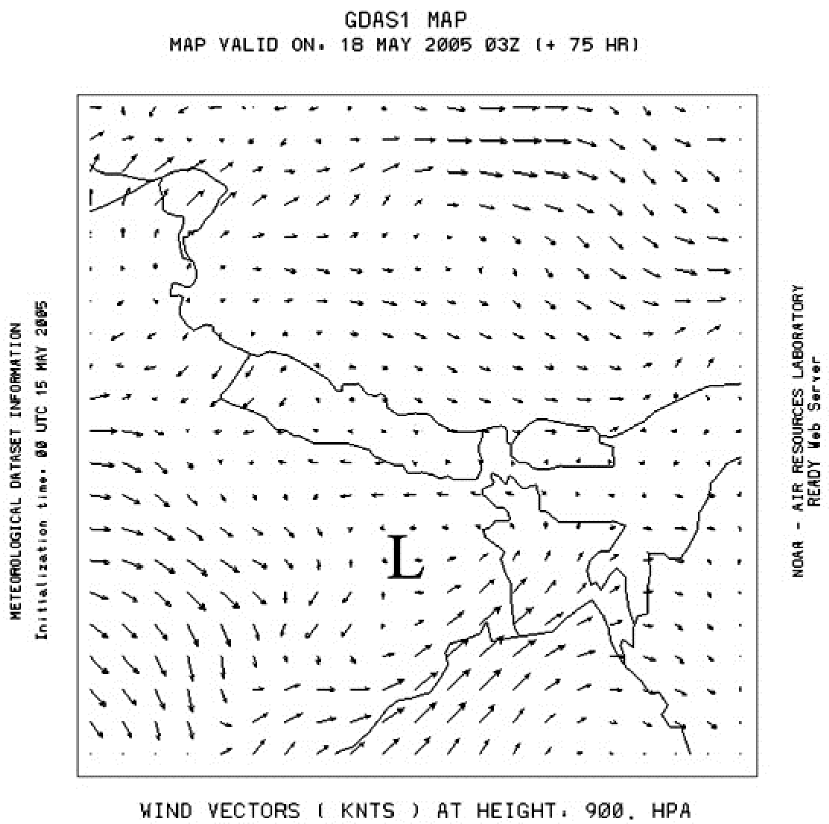


Figure 2. The 900hPa wind vectors for 03UTC, 0845NST May 18 and the heat low just south of Patna. Source NOAA ARL Archives

3. Synoptic Environment

Several thermally induced surface or heat lows start establishing during April and May. These stretch across northern India into Pakistan and form the monsoon trough that eventually brings in the monsoon in June. By early May these become very active. During the pre-monsoon months, the northeast corner of the Indian subcontinent is characterized by vigorous thunderstorm activity [10,12,13]. Colder than normal temperatures from mid- tropospheric

"Western Disturbances" combined with intense surface daytime solar radiation at these sub-tropical latitudes and high dewpoints result in almost daily thunderstorms. The most significant source of moisture that initiates the deep, moist convection along the Himalayas and the Tarai area of Nepal is the Bay of Bengal. The transport mechanism for this moisture is the surface heat low in the Patna region of Bihar. The counter clockwise circulation of the surface heat low enables moist air advection towards the west as well as towards the mountainous areas of Nepal.

The heat low in Bihar, just to the south of Patna (Figure 2) is instrumental in transporting moisture from the Bay of Bengal not only to the regions further to the west, such as Gorakhpur and Lucknow in Uttar Pradesh but also to the Terai and foothills of the Himalayas in Nepal. The wind vectors for 03UTC, 0845NST May 18 are at 900 hPa, approximately 980m asl (Figure 2).

4. Study Site

Pokhara is located approximately 25km to the south of the Annapurna Massif (Figure 3). The Pokhara valley is surrounded in the east, north and northwest by high mountains. These act as barriers and induce precipitation in orographically lifted humid air as well as precipitation from mountain-valley flows that are drawn into the area each day. These features explain why Pokhara is a moisture convergence zone that receives some of the highest precipitation in Nepal.

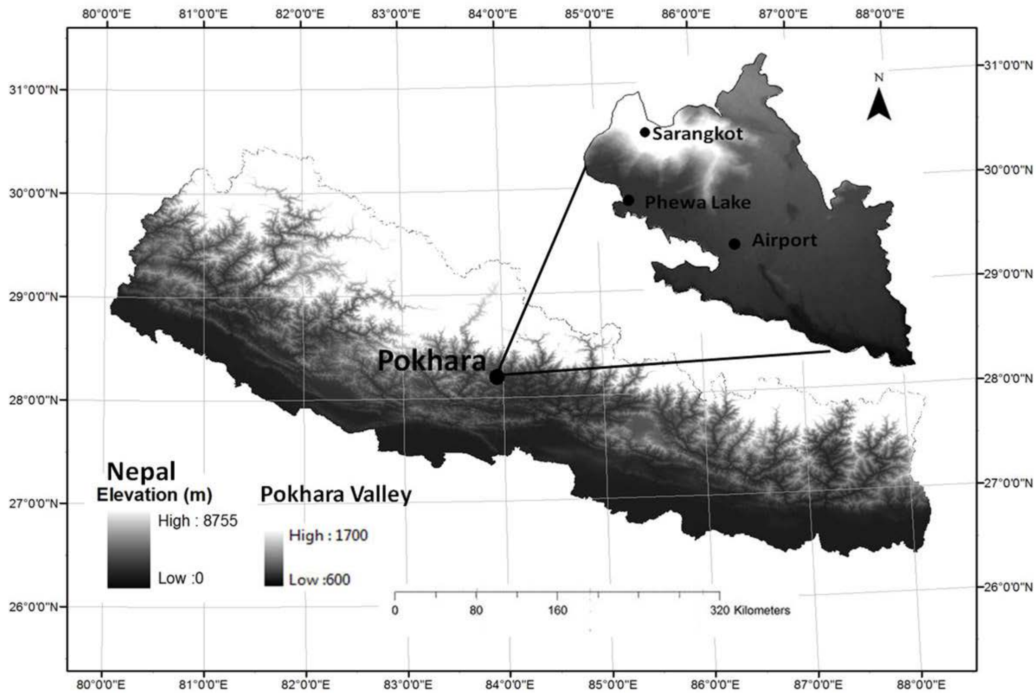


Figure 3. Map of Nepal showing the study site

5. Synoptic Surface Weather Data for May 18, 2005

5.1. Surface and Surface Dewpoint Temperatures

At 0545NST the surface temperature was 18.4°C, with a dewpoint temperature of 17.8°C. Temperature and dewpoint at 0845NST were 22.3 and 19.5°C respectively although a surface temperature of 30°C was briefly reached at some point before 0845NST. At 1145NST the surface temperature and dewpoint were 26.4°C and 20°C respectively, while at 1445NST the surface temperature climbed to 28°C and the surface dewpoint dropped slightly to 19.9°C. At 1745NST, the surface temperature dropped to 26°C, but during the preceding three hours, the surface temperature again reached 30°C. The dewpoint temperature at this time had decreased to 19.2°C.

5.2. Station Pressure

Station pressure varied very little, ranging from 916.6 hPa at 0545NST to a maximum of 917.7 hPa at 1145NST and falling to 914.4 hPa by 1745NST.

5.3. Wind Data

There are unfortunately no wind measurements for this period. However, wind data from May 1 to May 25, 2012 obtained from a newly established automatic weather station at Pokhara Airport were available for analysis. These analyses indicate that at 0545NST wind direction was northwesterly, ranging between 290 and 340 degrees, at average speeds of 0.3 to 2 m/sec. At 0845NST the surface wind direction ranged between 90 and 180 degrees, at speeds averaging between 0.5 and 2.7 m/sec. At 1145NST surface winds settle in a more southerly direction, between 90 and 140 degrees, at speeds of 1.8 to 3.7 m/sec. By 1445NST the wind direction is unchanged and wind speeds average between 2.0 and 4.8 m/sec. At 1745NST, the last DHM observation of the day in May 2005, daytime winds have already begun the transition to northerly and northwesterly at speeds ranging from 1 to 8 m/sec. Since the paper now explains earlier how we handled the missing May 2005 wind data by using 2012 instead, The May 2012 analyses indicate that at 0545NST wind direction was northwesterly, ranging between 290 and 340 degrees, at average speeds of 0.3 to 2 m/sec. At

0845NST the surface wind direction ranged between 90 and 180 degrees, at speeds averaging between 0.5 and 2.7 m/sec. At 1145NST surface winds settle in a more southerly direction, between 90 and 140 degrees, at speeds of 1.8 to 3.7 m/sec. At 1445NST the wind direction is unchanged and wind speeds average between 2.0 and 4.8 m/sec. By 1745NST daytime winds have already begun the transition to northerly and northwesterly at speeds ranging from 1 to 8 m/sec.

5.4. Cloud Types and Cover, Cloud Base and Visibility

Convective activity was noted as follows. At 0545NST the observed total cloud amount was 2, WMO code for sky cover of 2 oktas or 2/8th, with cloud types consisting of mostly cumulus but also some thin stratocumulus and high cirrus clouds. The observed cloud base height above the surface for the cumulus clouds was 300 to 600 m agl (code 4) and visibility was 8km.

At 0845NST the observed total cloud amount was 1/8th, consisting only of fair-weather cumulus with an observed cloud base at 600 – 1000 m agl (Code 5); visibility was 10km. From 0845NST to 1145NST, the total cloud amount remained at 1/8th and the cloud base height remained at 600 to 1000 m agl (code 5). Convective activity within the observation range consisted of fair-weather-type cumulus clouds only(WMO code 1) and visibility reached 15km.

By 1445NST (45 minutes before the hailstorm), the cloud base height had decreased to 300 to 600m agl (Code 4); a combined cumulus and stratocumulus cloud cover had increased to 6/8ths and visibility remained 15km. At 1745NST, two hours after the hailstorm, the sky cover was recorded at code 8 (i.e completely covered) with cloud types mostly cumulus and stratocumulus and a cloud base height between 200 and 300m agl (code 3).

5.5. Present and Past Weather

At 0545NST both present and past weather were noted as Code 0, defined in the WMO handbook as “cloud covering ½ or less of the sky throughout the preceding three hours”. At 0845NST present weather was Code 3, “Clouds generally forming or developing” and past weather remained at 0. At 1145NST present weather was Code 2,”State of the sky on the whole unchanged” and past weather remained at 0. And at 1445NST, present weather was noted at Code 1 “Clouds generally dissolving or becoming less developed”, while past weather was 0. At 1745NST Code 0, “Cloud covering ½ or less of the sky throughout the appropriate period”, was noted for both present and past weather.

6. Archived Satellite Images for May 18, 2005

Several satellite images are included in this paper, confirming the severe convective activity at Pokhara at 1530NST on May 18.

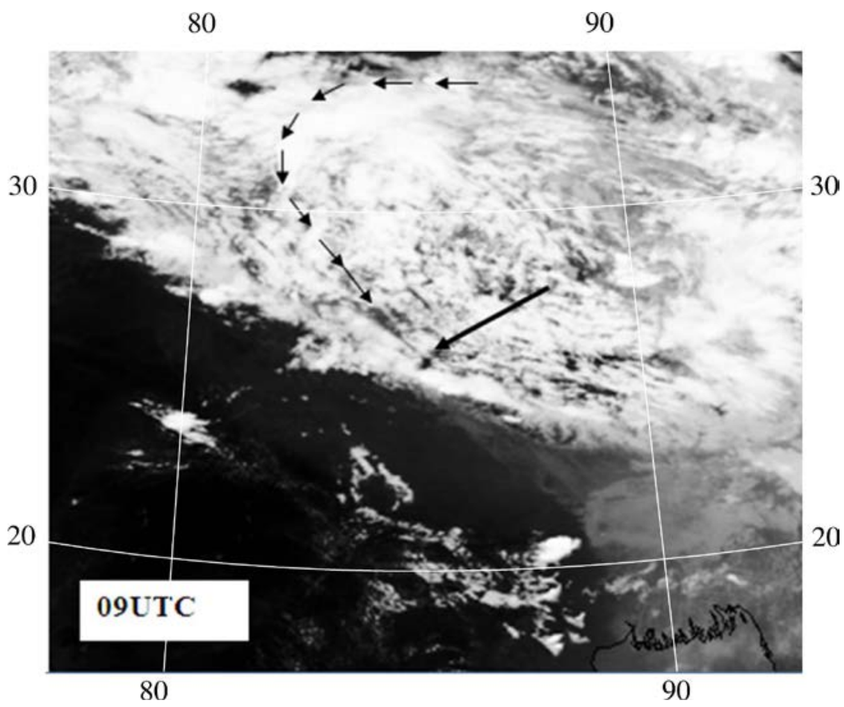


Figure 4. 09UTC (1445NST), May 18, 2005. Archived Infrared Satellite Image. Source: University of Dundee

This infrared image (Figure 4) of 09UTC May 18, is centered over Northern India, Nepal, the Himalayas, Tibet (China), Bangladesh and the northern tip of the Bay of Bengal, including the delta of the Ganges. The arrow points to the Kali Gandhaki Valley, frequently clearly visible from space and making it easier to identify the location of Nepal on the satellite maps. The valley cuts through Nepal from North (Tibet, China) to South (India) and is also an easy reference point for the location of Pokhara, which in the IR image above is located slightly to the lower right of the Kali Gandaki Valley.

While the subcontinent to the south of the high mountains was heating (dark areas on the IR indicate warm surfaces), convective activity, consisting of a string of individual cells all along the foothills of the High Himalayas, was occurring rapidly. At least five cells, small, bright white circular areas, have developed and are clearly visible. Three are located to the east of the Kali Gandaki Valley and two to the west. The cell east of and closest to the Kali Gandaki Valley is directly over the Pokhara area. At this point, the Pokhara hailstorm is 45 minutes away. Cyclonic circulation is visible over the Tibetan Plateau (arrows). Synoptic DHM Pokhara Airport observations indicate the total cloud cover at 7 okta, 7/8th of the sky covered with mostly cumulus clouds, at a cloud base height of 300- 600 m agl (Manual on codes, WMO-No.306) and visibility still at 15km

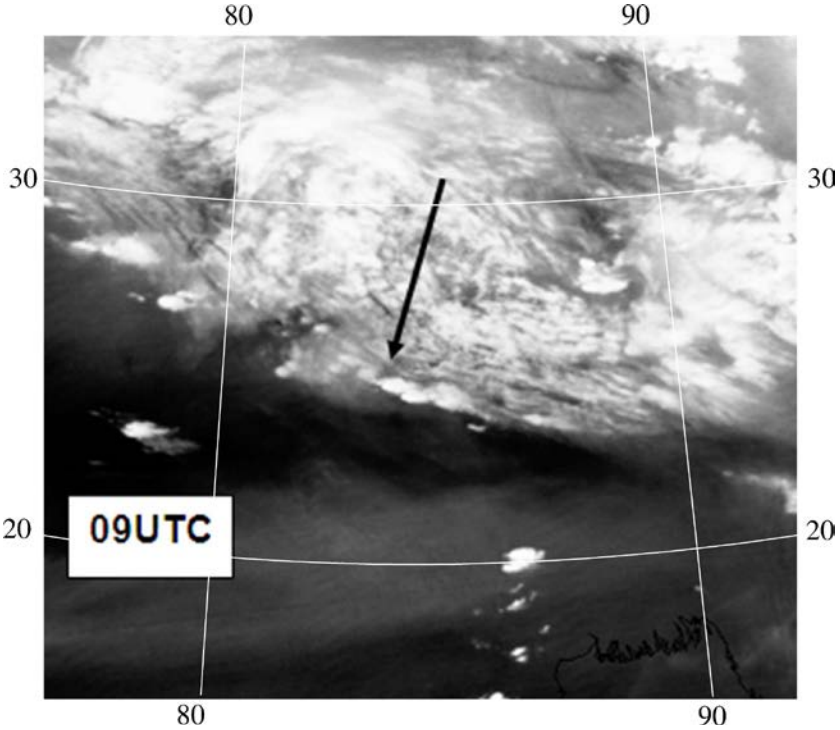


Figure 5. 09UTC (1445NST), May 18, 2005. Archived Water Vapour Satellite Image. Source: University of Dundee

In this Water Vapour Image for 1445NST (Figure 5), we see additional evidence of the deep moist convection that is essential to the formation of severe thunderstorms. Close inspection indicates again the clear northern half of the Kali Gandaki Valley (arrow). On this image, the number of potentially severe storms is reduced to two, possibly three; one directly over Pokhara, the next one further east over the Tarai, possibly Birgunj. All the anvils are clearly indicated and are pointing east indicating an upper air wind direction from the west. The Pokhara anvil is estimated to be 130km long; the anvil of the cell to its southeast, 80km.

The low pressure field over Tibet is visible on the above the water vapor image as well.

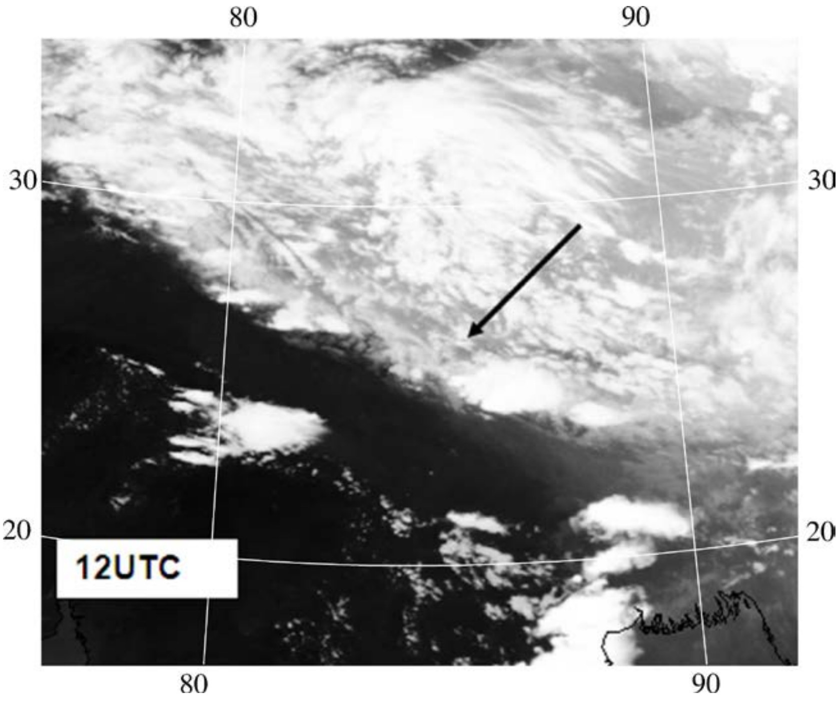


Figure 6. 12UTC (1745NST), May 18, 2005. Archived Infrared Satellite Image. Source: University of Dundee

This IR image of 12UTC, 1745NST now indicates a large cluster of cells just east of the Kali Gandaki where at least 4 individual thunderstorms have clearly defined edges along their southern flanks; anvils are pointing eastward. Propagation of the thunderstorm cells towards the southeast is indicated. The combined length of the cloud shield from west to east is at least 400km. In far eastern Nepal, a large single cell storm is dissipating, its anvil extending approximately 260km. 80 to 90 knot westerly winds at 150hPa, approximately 14000m asl, determine the direction of the anvil.

Two hours after Pokhara's hailstorm, the new storm cell clusters that have formed southeast of Pokhara, are making it difficult to detect traces in the IR image of the earlier, by now dissipating Pokhara hail storm. Synoptic DHM Pokhara Airport observations now indicate the total cloud cover at 8 okta, all of the sky covered with mostly cumulus at a cloud base height of 200- 300 m agl and some stratocumulus clouds at a different height (code 8); cloud base of the latter was not noted. Visibility is 12 km.

7. Determining Stability Indices

In spite of the fact that the DHM personnel had not observed the May 18 hailstorm, the infrared satellite images of the event, daily newspaper articles[1], plus witnesses in Pokhara clearly establish its occurrence. The India upper air station closest to Pokhara is Gorakhpur, 77m asl, approximately 200km to the south. Stability indices for Pokhara, 800m asl (918hPa), were calculated from Gorakhpur May 18 ESRL sounding data beginning at 800m asl and substituting the DHM surface data. Unfortunately Gorakhpur rawinsonde data for both 00UTC and 12UTC May 18, 2005 is missing. There is existing 05UTC May 18 wind data from the surface to 2000m, but this is a wind profile only.

Complete upper air data is required to construct SkewT log P charts, which present an atmospheric profile for all parameters, temperature, dewpoint temperature, wind speed and direction, pressure and geopotential heights. More importantly for this study, the SkewT log P chart provides the basis for stability indices calculations for convective storms, such as CAPE, Lifted Indices, hail possibility and hail size. CAPE determines the updraft strength and large values are essential for giant hail formation.

In order for a computer program process these calculations (this study used RAOB by the ERS) there cannot be any missing input data.

8. Archived NOAA ARL Computer Calculation for Pokhara

Faced with missing 00UTC Gorakhpur upper data with which to construct an atmospheric profile for Pokhara , this study turned first to the convenient archived NOAA ARL data base. RAOB ERS, the computer program that this study uses to calculate the atmospheric stability indices from SkewT-log p charts, requires the input of all meteorological data at all mandatory and significant levels that the NOAA ARL data base provides. The following steps were followed.

1. The co-ordinates for Pokhara are 28.13°N and 84.0°E. The NOAA ARL computers place this location at 1100m asl and not at 800m asl (DHM Pokhara station elevation). To correct this, Pokhara was assigned slightly different coordinates, 27.6° N latitude and 84°E longitude, that matched the NOAA ARL 800m asl location. The NOAA computers then calculated vertical atmospheric profiles for Pokhara beginning at 800m (918hPa) for both 00UTC (0545NST) and for 09UTC (1445NST) of May 18; the storm occurred at 1530NST. The necessary parameters calculated were at 918hPa (surface), 900, 875, 850, 800, 750, 700, 650, 600, 550, 500, 450, 400, 350, 300, 250, 200, 150, 100, 50 and 20hPa.

2. DHM observations (and IR satellite images) indicate late afternoon thunderstorms at Pokhara on May 16, 17 and 19. For comparison purposes, atmospheric profiles for those days were obtained as well.

3. Next, all data for each of the eight NOAA profiles was fed into the RAOB program to calculate Stability Indices.

Table 1. indicates Stability Indices for Pokhara, 00 and 09UTC for May 16, 17, 18 and 19, calculated by RAOB ERS. Source, NOAA ARL

	CAPE J/Kg	Lifted Index	Hail
May 16 00UTC	0	+12.4	no
May 16 09UTC	0	+3.7	no
May 17 00UTC	0	+7.2	no
May 17 09UTC	0	+0.7	no
May 18 00UTC	0	+10.2	no
May 18 09UTC	0	+2.1	no
May 19 00UTC	0	+10.0	no
May 19 09UTC	0	+1.3	no

The results of these calculations are shown in Table 1. The NOAA ARL archived data do not indicate a potentially unstable atmosphere for May 16, 17, 18 and 19 at Pokhara CAPE was 0, the Lifted Indices all positive and there was no forecast for hail.

4. Therefore, in the next step, the NOAA surface data, temperature and dewpoint temperature, were replaced with the original DHM surface data plus the wind data calculated for the eight atmospheric profiles that had just been calculated.

5. The altered eight Pokhara vertical profiles were then fed into the RAOB program which calculated all stability indices.

Table 2. Indicating both NOAA ARL and original DHM Pokhara 800m asl surface temperatures and dewpoint temperatures in Centigrade for 00UTC and 09UTC May 16, 17, 18 and 19. Sources; DHM and NOAA ARL

	Surface T in C		Surface Dewpoint in C	
	NOAA	DHM	NOAA	DHM
May 16 00UTC	19.4	18.1	0.1	16.3
May 16 09UTC	34.8	30.0	1.3	18.9
May 17 00UTC	21.2	17.1	3.1	15.9
May 17 09UTC	35.8	29.0	4.9	18.4
May 18 00UTC	20.9	18.4	1.8	17.8
May 18 09UTC	34.9	28.0	4.5	19.9
May 19 00UTC	21.3	16.3	2.1	14.9
May 19 09UTC	35.2	30.0	1.6	18.9

The DHM surface temperatures and dewpoint temperatures that were substituted into the Pokhara NOAA ARL profiles are indicated in Table 2. Most striking are the differences in dewpoint temperatures between the DHM data and the values calculated by NOAA; the DHM values are on average 15.1C higher.

Table 3. Stability Indices after substituting DHM surface data into the NOAA ARL computed vertical profiles for 00UTC and 09UTC May 16, 17, 18 and 19. Sources; DHM and NOAA ARL

	CAPE J/Kg	Lifted Index	Tc	Hail
May 16 00UTC	50	+0.3	40.1	no
May 16 09UTC	2503	- 6.5	40.5	no
May 17 00UTC	7	-0.3	36.1	no
May 17 09UTC	2258	-7.0	36.7	no
May 18 00UTC	191	-1.8	37.0	no
May 18 09UTC	2550	-6.7	37.9	no
May 19 00UTC	0	+3.4	38.8	no
May 19 09UTC	2764	-8.4	38.6	no

Table 3 shows markedly different outcomes with the DHM surface data substitutions. CAPE values increase considerably by 09UTC, as have the Lifted Indices. CAPE values, such as 2550 J/Kg and 2764J/Kg for 09UTC May 18 and 19 respectively indicate high potential for atmospheric instability for all four afternoons. Similarly, 09UTC Lifted Indices, such as -6.8 for May 18 and -8.4 for May 19 are extremely high. However, the Tc's (convective temperatures) ranging between 36.1°C and 40.5°C are very high and not realistic for initiating severe convective activity at 800m. The maximum daytime temperatures recorded by the DHM for May 16 to May 19 did not exceed 30°C. The calculations shown in Table 3 indicate no predictions for hail formation.

9. NOAA/ESRL Radiosonde Database for Gorakhpur

Following the unsatisfactory results in the previous section, another solution to the lack of original upper air Gorakhpur data for the 18th of May was to simply average the original existing Gorakhpur 00UTC data of May 17 and 19.

The original ESRL rawinsonde data for Gorakhpur, 00UTC May 17 included the geopotential heights at all mandatory and significant levels. Temperature plus dewpoint temperatures only were recorded at 613, 607, 600 and 599Pa. Temperature data only were recorded at nine additional levels above 500hPa up to 157hPa. Wind speed and direction was recorded at two significant levels, 683 and 509hPa.

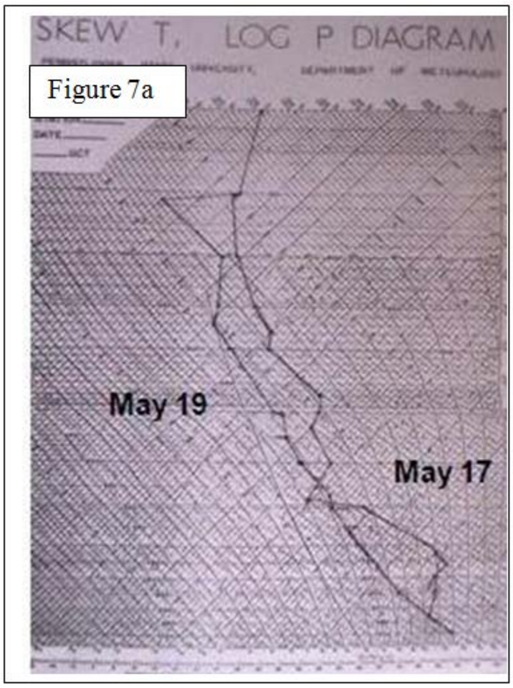
For May 19th we have most mandatory levels: the surface data, plus complete data for 925, 850,700, 500, 400, 300 and 250 hPa. Significant levels for temperature and dewpoint only were recorded at 727, 660, 584, 532, 453, 413hPa and for temperature only at 268 and 155hPa.

9.1. Temperature, Dewpoint Temperatures and Geopotential Heights for Gorakhpur

First, on one chart (Figure 7) the two separate temperature profiles were hand drawn, one for May 17 and one for May 19. All data points, both mandatory and significant levels were noted, even though many of the geopotential heights of the significant levels differed from each other. On the SkewT- log p chart both profiles were started at 900hPa and reached to 38hPa for May 19 and to 157hPa for May 17. Once both temperature profiles were drawn, deducing average temperatures for May 18 at similar geopotential heights became a simple procedure.

The same procedure was followed for the dewpoint temperatures, although there were far fewer data points (Figure 7). Recording of dewpoint temperature data stops at 599hPa on May 17, at 28.5°C and at 400hPa at 39.3°C on May 19. It is quite usual for the radiosonde equipment to stop recording dewpoint temperatures at the higher elevations when the air is extremely dry.

Calculations for geopotential heights were again straightforward arithmetic when both May 17 and 19 mandatory levels were available, but required additional computing in order to arrive at the values for the significant levels.



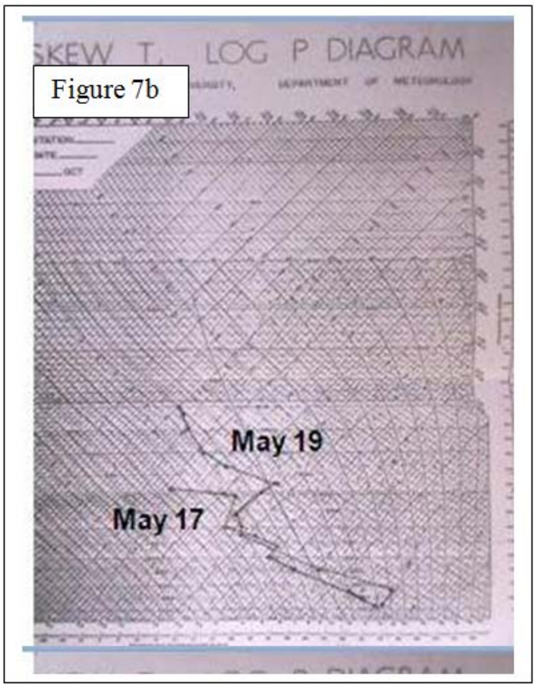


Figure 7. SkewT log P Temperature and Dewpoint Temperature diagrams for Gorakhpur 00UTC, May 17 and 19, 2005. Source: NOAA/ESRL Radiosonde Data base

Figure 7a and Figure 7b show a significant intrusion of colder and drier air at Gorakhpur just above 600hPa on May 17, which is where the dewpoint data end. On May 19, much colder air had arrived from 925 to 150hPa; the temperature decrease is nearly completely dry adiabatic between the surface and 700hPa. Between 400 and 250hPa, on May 19, temperatures had dropped by an average of 5.8C, for example at 370hPa temperature decreased from -24.5°C on May 17 to -32°C on May 19.

Figure 8 traces the Gorakhpur 500 and 400hPa temperatures in centigrade for 00UTC May 1 to 31 2005, using the original ESRL archived data. There was missing data, but the data still show distinct cold air intrusions on May 13- 14, on May 18-19 and on May 28.

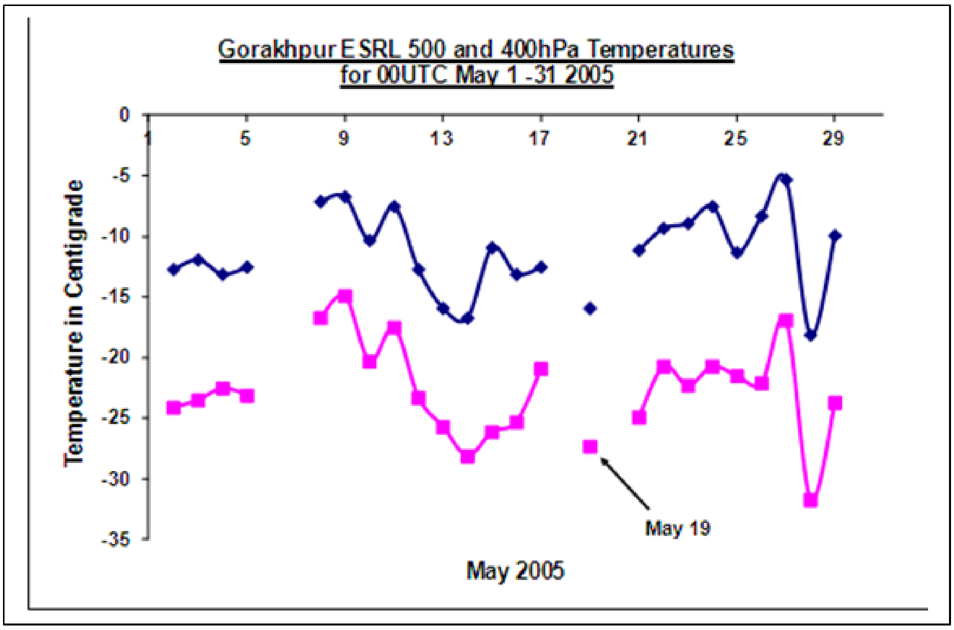


Figure 8. Gorakhpur 500 (top line) and 400hPa (bottom line) temperatures for 00UTC May 1- 31, 2005. Source: NOAA/ESRL Radiosonde Database

Original ESRL temperature data in Table 4 indicate a cold air intrusion over much of north India just to the south of the Himalayan Range. Beginning at 00UTC May 16 at Shrinagar, the 500hPa temperature drops 4.0°C by 00UTC May 18. At Delhi the 500hPa temperature dropped 5°C between May 16 12UTC and 00UTC May 18. The 500hPa temperature began decreasing at Lucknow between 00UTC May 17 and 18, falling 4.6°C; at 400hPa at Lucknow the temperature change was small, decreasing only 1.2°C by 00UTC May 18. The 500 and 400hPa temperatures at Gorakhpur dropped to -15.9°C and -27.3°C respectively by 00UTC May 19, a total drop of 9.8°C, the coldest of these four stations after Shrinagar. At 34.08°N and 74.83°E Shrinagar is considerably further north. 19 May data was missing at Delhi and Shrinagar.

Table 4. 500 and 400hPa temperatures at North Indian stations. Source NOAA/ESRL Radiosonde Database

500 and 400hPa Temperatures		
Gorakhpur ESRL	500hPa	400hPa
May 17 00UTC	-12.5C	-20.9C
May 18 Estimated	-14.2C	-24.1C
May 19 00UTC	-15.9C	-27.3C
Lucknow ESRL	500hPa	400hPa
May 17 00UTC	-9.5C	-21.5C
May 18 00UTC	-14.1C	-22.7C
May 19 00UTC	-11.1C	-23.9C
Delhi ESRL	500hPa	400hPa
May 16 12 UTC	-9.9C	-20.1C
May 17 12UTC	-14.1C	-24.1C
May 18 00UTC	-14.9C	-25.1C
Shrinagar ESRL	500hPa	400hPa
May 16 00UTC	-14.5C	-29.1C
May 17 00UTC	-14.1C	-25.3C
May 17 12UTC	-16.9C	-25.1C
May 18 00UTC	-18.5C	-32.3C

9.2. Wind Data for Gorakhpur

Wind speed and direction calculations were similarly based on the May 17 and 19 data, although 05UTC May 18 data were actually available at the surface, at 304m, 609m, 914m and at2133m asl from the Gorakhpur station (Table 5). 05UTC or 6UTC radiosonde launchings for wind data only, were done frequently in May at Gorakhpur as well as at other north Indian stations, such as Delhi, Lucknow and Patna. The only rawinsonde wind data for 00UTC May 17 is at 887hPa, 1070m asl, at 850hPa, 1439m asl, at 700hPa, 3073m asl, at 683hPa, 3270m asl and at 509hPa, 5628m asl. For May 19th, wind data was available for mandatory levels up to 250hPa. In order to compensate for the considerable missing wind data, this study turned to the data provided by the NOAA ARL point and click internet site. The data base for the NOAA ARL archives includes measurements and observations from aircraft. Such information is valuable for normally inaccessible locations like the Himalayan Range.

Table 5. Gorakhpur 05UTC May 18 wind data up to 2133m asl. Wind speed is in knots. Source: NOAA/ESRL Radiosonde Database

254	5	18	MAY	2005		
1	99999	42379	26.75N	83.37E	77	99999
2	99999	99999	99999	9	99999	3
3		VEGK		99999	kt	
6	99999	77	99999	99999	90	4
6	99999	304	99999	99999	100	11
6	99999	609	99999	99999	90	6
6	99999	914	99999	99999	90	5
6	99999	2133	99999	99999	300	17

Table 6. Geopotential Heights, Temperature, Dewpoint Temperature, Wind speed and Wind direction calculations for May 18 00UTC at Gorakhpur. Source: NOAA/ESRL Radiosonde Database and NOAA ARL

hPa	Meters asl	Temp °C	Td °C	Wind Dir Degr	Wind Spd M/S
993	77	26.8	19.7	90	2.0
950	500	22.5	19.9	100	5.5
925	710	22.2	16.2	90	3.0
900	957	20.8	13.0	90	2.5
850	1444	17.5	2.7	297	5.3
800	2020	14.5	-2.0	300	8.5
760	2359	13.0	-5.0	300 est	9.3 est
730	2740	10.0	-10.0	295 est	11.3 est
700	3064	7.9	-13.6	287	16.8
660	3536	4.0	-14.5	290 est	16.8 est
610	4134	-2.5	-16.5	298 N	17.1 est
600	4302	-3.9	-16.9	298 N	17.2 est
599	4315	-8.5	-21.8	298 N	17.4 est
580	4497	-8.8	-22.0	298 N	17.4 est
530	5238	-11.7	-24.0 (19)	297 N	17.6 est
500	5725	-14.2	-28.9 (19)	297.5	17.8
450	6443	-20.0	-34.9 (19)	283 N	17.8 est
400	7390	-24.1	-40.5 (19)	282 N	20.9 N
350	8469	-31.5	-64.2 N	279 N	27.2 N
300	9415	-40.3	-65.1 N	275 N	33.5 N
270	9900	-45.4	-65.1 N	270 (19)	32.0 N
250	10640	-48.2	-64.3 N	271 (19)	38.0 N
200	12075	-57.0	- 67.0 N	267 N	42.7 N
155	13593	-69.4	-73.6 N	267 N	40.0 N
150	13740	-70.7	-73.6 N	264 N	39.7 N
100	16130	-74.3	-77.7 N	265 N	25.2 N
50	20470	-52.6	-273.1 N	73 N	5.8 N
20	26456	-49.3	-273.1 N	97 N	10.9 N

The completed Gorakhpur upper air profile for 00UTC May 18 from the surface, 77m asl (993hPa) to 26456m asl (20hPa) is shown in Table 6.

9.3. Gorakhpur Profile Adjusted for Pokhara

To calculate the Stability Indices for Pokhara the above profile (Table 7) was shortened to start at 918hPa. At the surface, the original 09UTC DHM surface pressure, 918hPa, maximum temperature, 30°C, and dewpoint temperature, 20°C, were substituted, plus, because no DHM wind data in May 2005, the surface wind values based on DHM wind observations done in May 2012. At 09UTC diurnal valley winds are likely to be from the south or southeast with wind speeds somewhat faster at 900hPa, 5 m/sec, than at the 918hPa surface, 3.8 m/sec. Gorakhpur 850hPa winds had taken on a more north westerly direction, 297 degrees at 5.3 m/sec (Table 7). Pokhara is situated in a valley and 850hPa is 600m agl. Keeping the wind speed at 5.3 m/sec and changing the direction to 210 degrees seems appropriate.

Table 7. 09UTC May 18 Pokhara surface, 900hPa and 850hPa data. Source: DHM

PRESS HPA	HGT(MSL) M	TEMP DEW °C	PT °C	WND IR DEG	WND SPD M/S
918.	779.	30.0	20.0	120.0	3.8
850.	1444.	23.0	18.0	210.0	5.3

Following the dry adiabat from the surface temperature of 30°C on the SkewT- log P chart, the 850hPa temperature was changed to 23°C from 17.5°C. From the surface dewpoint temperature of 20°C, along the mixing ratio, the 850hPa dewpoint temperature was changed to 18°C from 2.7°C(Table 7).

However, Stability Indices calculated with the newly created Pokhara SkewT profile, which included the original DHM surface data, were disappointing. Convective temperature of 30°C, Lifted Index of -14.5, hail size 4.78cm all point to a potentially very unstable atmosphere, but a CAPE of 0 indicates no potential thermal instability, no potential convective activity, no updraft and therefore no hail.

High dewpoint temperatures at and near the surface are essential in producing the deep, moist convection that will result in potentially severe thunderstorms [6]. It is important to remember that an extremely violent storm producing 1kg hailstones (source: Daily local news papers and interview of local people) did occur mid-afternoon on May 18, between 1530 and 1550NST and that all the necessary conditions for thunderstorm initiation, including a deep layer of humid air must have been in place at least an hour before then, to allow for giant hail to grow.

In spite of the fact that there was no upper air data at Pokhara, **1**. what moisture was available for deep, moist convection in the Pokhara area at the surface and at higher levels so that severe atmospheric instability could occur and **2**. at the same time determine a procedure for forecasting these severe events in the future.

10. Observed Cloud Base Heights Verses 09utc May 18 Surface Dewpoint Temperature And Moisture Convergence Areas Near Pokhara

Using a SkewT- log P chart to analyze the DHM Pokhara surface data and synoptic observations for May 18, the following results were noted:

1. An observed cloud base height of 600 to 1000m agl (code 5) at 0845NST is a reasonable estimate when a buoyant parcel of air is lifted from 918hPa to its CCL (cloud condensation level) with a surface temperature of 22.3°C and dewpoint temperature of 19.5°C. The SkewT cloud base height is actually closer to 600m than to 1000m agl.

2. At 1145NST, with a surface temperature of 26.4°C and dewpoint temperature of 20°C, cloud base height was still code 5 (600 to 1000m agl), a close estimate. On the SkewT chart, the 4.1 degree increase of the surface temperature puts the cloud base height at 1000m agl.

3. At 1445NST, 45 minutes before the arrival of 1kg hailstones, the surface temperature increased to 28°C and the dewpoint temperature dropped slightly to 19.9°C. The maximum surface temperature of 30°C for that day had occurred twice, once between 0545NST and 0845NST and again between 1445NST and 1745NST. The cloud base height, agl, using the surface temperature of 28°C and the surface dewpoint temperature of 19.9°C, calculated with the SkewT chart is 2000m (SkewT height m asl) which minus the 800m Pokhara elevation becomes 1200m agl. The observed cloud base height at 1445NST was Code 4, 300 to 600m agl, at least 600 to 900m lower. With a higher surface temperature and the same surface dewpoint, the cloud base heights should not have come down, unless there was considerable humid air above the surface from another source.

Such a discrepancy can be explained by the knowledge that by the mid-afternoons a layer of warm, humid air of considerable depth, originating in the much hotter regions to the south, arrives in the mountains each day following the onset of the up-valley circulation in the morning [7,11,14]. The clouds that result from this orographic lifting tend to cling to preferred areas of convergence such as mountain sides or they will continue along the direction of a valley [1,2]. Moisture convergence above the surface means that surface dewpoint temperature measurements here cannot determine cloud base heights and conversely, determining surface dewpoints using saturation levels aloft is not likely to be accurate.

However, the deep moist convection that occurred in Pokhara could not have been initiated without sufficient moisture at or near the surface. When stability indices are calculated using the Pokhara May 18 maximum afternoon surface temperature of 30°C and dewpoint temperature of 20°C plus the previously calculated vertical profile, atmospheric instability is not indicated. But a severe thunderstorm did occur, therefore the initiation for convective activity may have been at a location very close to the Pokhara airport, a mountain slope, for instance, where both the surface temperature and dewpoint temperature were sufficiently high.

11. Tracing Warm, Humid Air

By mid-May, the surface heat low in Bihar has become very active, and warm, humid air from the Bay of Bengal is moved westwards towards the foothills of the Himalayan Range. Table 8 for 00UTC May 17, the day before the May 18 hail storm, shows a layer at least 700m deep of humid air with an average dewpoint temperature of 22.9°C at Patna; the average dewpoint here increased to 25.2°C by 12UTC May 17. Surface winds from the east, then southeast and south by 645m asl at speeds of up to 15 knots demonstrate the cyclonic circulation of this surface heat low.

Table 8. Original Patna upper air data for 00UTC May 17, 2005. Source: NOAA/ESRL Radiosonde Databas

254	0	17	MAY	2005		
1	99999	42492	25.60N	85.10E	60	0
2	9250	3260	1390	54	99999	3
3		VEPT		99999	kt	
9	9970	60	276	249	90	4
4	10000	33	99999	99999	99999	99999
5	9820	193	258	99999	99999	99999
6	9710	290	99999	99999	110	15
5	9690	309	246	241	99999	99999
5	9620	372	250	248	99999	99999
6	9580	408	99999	99999	140	14
6	9450	526	99999	99999	170	15
6	9320	645	99999	99999	190	11
4	9250	711	266	176	195	9
6	9060	889	99999	99999	295	2

With increased, moisture laden easterly winds during May, the Gorakhpur surface and 925hPa, 720m asl, dewpoint temperatures begin climbing. The data indicate that from May 16 to 19 (Table 9), the surface dewpoint temperatures at Gorakhpur averaged 19.8°C; at 925hPa, the average was 15.8°C. It is this at least 700m deep layer of humid air that is drawn in a north and northeasterly direction into the mountains each day by the mountain – valley circulation. Areas of significant moisture convergence result in the mountains from both mechanisms, the mountain-valley circulation and orographic lifting.

Table 9. Gorakhpur surface, 946hPa and 925hPa dewpoint temperatures for 00TC May 16-19, 2005. Source: NOAA/ESRL Radiosonde Database

Gorakhpur Original ERSL Dewpoint Temperatures for Surface (77m) to 925hPa (719m), 00UTC			
	Surface 77m asl	499m asl	719m asl
	993hPa	946hPa	925hPa
May 16	19.8°C	missing	14.4°C
May 17	19.4°C	15.8°C	13.2°C
May 18	19.7°C est.	19.9°C est	16.2°C est
May 19	20.2°C	missing	19.2°C

12. Re-Calculating Pokhara Dewpoint Temperatures Using Cloud Base Heights

The DHM cloud base heights observations for May 18 at 1445NST where T = Td, provide temperatures and dewpoint temperatures at 300, 400, 500 and 600m agl or 890, 880, 860 and 850hPa . Using a SkewT-log P chart, and the surface temperature of 30°C (maximum reached between 1445NST and 1745NST), an air parcel lifted along the dry adiabat from the surface to 850hPa reaches a temperature of 24°C, which is also its dewpoint temperature. Similarly, the 500m agl cloud base is 25°C, the 400m agl cloud base is 27°C and the 300m agl cloud base is 28°C. It is not possible however, to calculate a new more practical atmospheric instability inducing surface dewpoint temperature with the above calculated cloud condensation temperatures, because the DHM staff were observing clouds at a known location of moisture convergence, which was not necessarily directly above the airport. Visibility at the airport at this time (1445NST) was 15km; present weather was code 01, "clouds generally dissolving or becoming less developed".

Tracing the DHM 300, 400, 500 and 600m asl saturated cloud base temperatures back down along the mixing ratio line yields surface dewpoint temperatures of 28, 26, 26 and 25°C respectively.

This study assumes that the cloud base height (CCL) was at 600m asl, 850hPa, with a temperature of 24°C, resulting in a surface dewpoint temperature of 25°C. Substituting these values into the Pokhara profile and calculating stability indices yields a staggering CAPE of 10354J/Kg, with giant hail size predicted at 6.17cm in diameter.

Knowing that very close to the surface, the dewpoint temperature of the unsaturated air must have been higher than 20°C, higher trial surface Tds were substituted into the stability indices calculations. A one degree increase in the surface dewpoint temperature, from 20 to 21°C, while keeping the surface temperature at 30°C, is sufficient to destabilize the atmosphere, initiate convective activity, with an updraft strength of 117 m/sec, possible hail size of 5.99cm, a Lifted Index of -15.4,CAPE of 6800 J/Kg and no negative CAPE (Figure 9). Further Stability Indices calculations were made, using surface dewpoint temperatures of 22, 23, and 24°C. All are extremely high.

For each additional degree of surface dewpoint temperature, CAPE increases approximately 800J/Kg.

Therefore, is spite of seemingly exaggerated, extremely high Stability Indices, this study has to assume that CAPE values for the Pokhara area on May 18 fall somewhere between 6800 and 10000J/Kg. Extreme variations in stability index values can be expected in the complex terrain surrounding Pokhara.

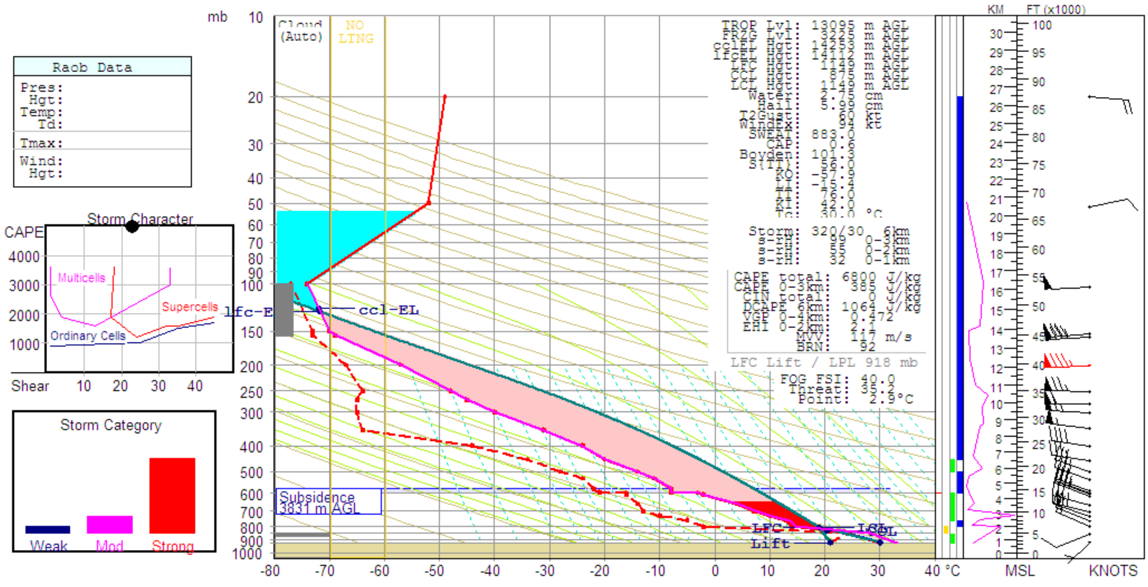


Figure 9. RAOB diagram indicating Stability Indices for Pokhara, May 18. Source: NOAA/ESRL Radiosonde Database, DHM and NOAA ARL

13. Conclusion

This paper attempts to calculate the CAPE values for a severely destructive hailstorm that occurred in Pokhara on May 18, 2005. Upper air data from Gorakhpur, the closest upper air station in India, was missing for May 18. DHM surface data was available, but not the synoptic data for the lower tropospheric levels needed to complete a full atmospheric profile. The CAPE calculations executed in this paper were based on the following. 1. Gorakhpur upper air data that was interpolated from May 17 and 19. 2. 850hPa dewpoint temperatures obtained from observed cloud base heights at Pokhara. 3. Pokhara is a known location of moisture convergence. The recorded DHM surface dewpoint temperatures did not yield the CAPE values needed to produce an updraft necessary to sustain 1 kg hailstones. When the Pokhara surface dewpoint temperatures were allowed to vary in the CAPE calculations in order to reflect the existing severe atmospheric instability on May 18, an increase of just 1 degree centigrade resulted in CAPE of 6800J/Kg. 4. Upper air wind data from NOAA ARL.

Under favourable synoptic conditions, CAPE predictions of such magnitude are very likely to result in extremely dangerous weather.

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