PRE-MONSOON THUNDERSTORM: CASE STUDIES OF NEPAL

A THESIS SUBMITTED TO THE

CENTRAL DEPARTMENT OF HYDROLOGY AND METEOROLOGY

INSTITUTE OF SCIENCE AND TECHNOLOGY

TRIBHUVAN UNIVERSITY

NEPAL

FOR THE AWARD OF

DOCTOR OF PHILOSOPHY

IN HYDROLOGY AND METEOROLOGY

BY

DEEPAK ARYAL

JANUARY, 2016

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DECLARATION

This thesis entitled " **PRE-MONSOON THUNDERSTORM: CASE STUDIES OF NEPAL** " which is being submitted by me to the Central Department of Hydrology and Meteorology, Institute of Science and Technology (IOST), Tribhuvan University, Nepal for the award of the degree of Doctor of Philosophy (Ph.D.), is a research work carried out by me under the supervision of Prof. Dr. Lochan Prasad Devkota, Central Department of Hydrology and Meteorology, Tribhuvan University. This research is original and has not been submitted earlier in part or full in this or any university or institute, here or elsewhere for the award of any degree.

Deepak Aryal

(Researcher)

RECOMMENDATION

This is to recommend that **Mr. Deepak Aryal** has carried out research entitled "**PRE-MONSOON THINDERSTORM: CASE STUDIES OF NEPAL**" for the award of Doctor of Philosophy (Ph.D.) in **Hydrology and Meteorology** under my supervision. To my knowledge this work has not been submitted for any other degree.

He has fulfilled all the requirements laid down by the Institute of Science and Technology (IOST), Tribhuvan University, Kirtipur for the submission of the thesis for the award of Ph.D. degree.

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LETTER OF APPROVAL

Date: 26/01/2016

On the recommendation of **Prof. Dr. Lochan Prasad Devkota**, this Ph.D. thesis submitted by **Mr. Deepak Aryal** entitled **" PRE-MONSOON THUNDERSTORM: CASE STUDIES OF NEPAL "** is forwarded by Central Department Research Committee (CDCR) to the Dean, Institute of Science and Technology, Tribhuvan University, Nepal.

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(Deepak Aryal)

January, 2016

ABSTRACT

Two severe hailstorms that took place in Nepal during the pre-monsoon months of May are investigated in this study. One storm occurred close to midnight on May 3, 2001 at Thori, 215m asl, a small village on the border with India. Giant 1kg hailstones destroyed 800 dwellings, most of the villagers' livestock (over 500 oxen and goats) and 200 hectare of crops. The second storm occurred at Pokhara, 800m asl, in Central Nepal on May 18, 2005, during the middle of the afternoon. The storm lasted 15 to 20 minutes and produced 1kg hail stones that destroyed 1000 vehicles, crops, property and caused many injuries.

During the pre-monsoon months 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 the two hailstorms that not only might explain their severity, but also suggest forecasting techniques 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 were used for synoptic and mesoscale analyses.

The Thori hailstorm 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 eastwards travelling Mesoscale Convective Complex 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. Thori is known for frequent, severe hailstorms, owing to moisture convergence caused by the nature of its surroundings; an abnormally ample supply of moisture resulted in giant 1kg hailstones near midnight on May 3.

At Pokhara, late afternoon thunderstorms often accompanied by hail, are an almost daily occurrence during May. The hailstorm severity at Pokhara on May 18 was the result of enhanced convection from a sudden intrusion of extremely cold air aloft, originating over the Tibetan Plateau, to the lee-side of the Annapurna Region.

This study calculated CAPE values exceeding 7000J/kg for both hailstorms resulting in intense updraft speeds capable of sustaining giant hail growth.

Key words: CAPE, Lifting Index, hailstorm, radiosonde, geopotential height

LIST OF ACRONYMS AND ABBREVIATIONS

%	Percentage
°C	Degree Celsius
agl	above ground level
ARL	Air Resources Laboratory
asl	above sea level
AWS	Automatic Weather Station
CAPE	Convective Available Potential Energy
CCL	Convective Condensation Level
CDHM	Central Department of Hydrology and Meteorology TU
DHM	Department of Hydrology and Meteorology
cm	centimeter
ESRL	Earth System Research Laboratory
FMH	Federal Meteorological Hand Book
FMH	Federal Meteorological Handbook
hPa	Hecto-pascal
IR	Infrared
LCL	Lifting Condensation Level
LI	Lifted Index
LLJ	Low Level Jet
m/sec	meter per second
MCC	Mesoscale convective complex
MCS	Mesoscale Convective System
mm	millimeter
NOAA	National Oceanic and Atmospheric Administration
NR	NOAA Reanalysis
NST	Nepal Standard Time
RAOB	Radiosonde Observation
UTC	Coordinated Universal Time
WMO	World Meteorological Organization

TABLE OF CONTENTS

CHAPTER 5

POKHARA HAILSTROM

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

Nepal is located between China and the 4000m asl Tibetan Plateau to the north and the Gangetic plains of India to the south. The country is approximately 80% complex mountainous terrain, with the High Himalayas in the north along the China border, the near tropical lowlands, the Terai along the border with India to the south and the Churia Range in the middle. The south to north distance from the Indian border to the 8000m asl plus mountain peaks that Nepal shares with China is less than 200km. Multiple climate variations result from these topographic extremes.
During the pre-monsoon months the northeast corner of the Indian subcontinent is characterized by vigorous thunderstorm activity. These thunderstorms are the result of the establishing of a surface heat low over the North Indian state of Bihar, which draws warm, humid air from the Bay of Bengal, the intense surface heating of the subtropical sun and the superposition of the cold 500 and 200 hPa flows from the west. These surface and upper air flows combine to set up ideal conditions for thunderstorms. Deaths and injuries from severe lightening, plus the destruction of crops, livestock and in some cases, of entire villages from exceptionally large hailstones become a common occurrence during this period not only in Nepal, but also in NE India and Bangladesh.

Other locations on the globe that experience very severe thunderstorms include Bangladesh, South East China, and “tornado alley” in the USA. The destructive thunderstorms that occur in Nepal have similar and frequently more potential energy than the tornadic storms in the US, however apart from some reported, but undocumented tornado sightings in Nepal’s SE corner on May 10 1996, Nepal’s complex topography does not allow for tornado genesis.

This study was inspired originally by the giant hailstone size, 1kg, in two thunderstorms, that occurred in Nepal in May 2001 and in May 2005. However, apart from both hailstorms occurring in the foothills of the High Himalayas during the pre-monsoon month of May, accompanied by giant hailstones (*Makela et al., 2013*), further research indicated almost immediately that several significant differences existed as well. Both of the hailstorms were extremely destructive and neither had been forecast.

Close to midnight on May 3, 2001, Thori at 215m asl, a village in the Terai, 80km southwest of Kathmandu and close to the border with India, was completely devastated by giant hailstones weighing up to 1 kg. 800 houses were destroyed, most of the villagers' livestock killed and more than 200 hectare of crops lost. News of the disastrous event did not reach Kathmandu until 10 days later (Appendix).

On May 18, 2005, during the mid-afternoon, hailstones weighing up to 1 kg fell on Pokhara, a popular tourist resort at 800m asl and about 25 km south of the Annapurna Massif (Daily newspapers). Within a period of 15 to 20 minutes, the hailstorm destroyed 1000 vehicles plus property and field crops. One person was killed (Local Newspapers). There had been thunderstorms on the 16th and 17th of May as well, but not 1 kg hailstones. 1 kg hailstones are a rare occurrence, anywhere.

The basic requirements for thunderstorm generation are warm, humid air at the surface, sufficiently cold air aloft and a "trigger" or lifting mechanism to release the potential atmospheric instability. Lifting mechanisms include daytime heating, low level moisture increase, dynamic lifting resulting from vorticity ahead of an approaching upper level short wave trough and divergence occurring in the jet maximum of the subtropical Jetstream at high tropospheric levels. Severe thunderstorms result when in addition to the basic requirements, some or all of the lifting mechanisms are present to enhance the convection process. Favorable giant hail growth environments require strong, tilted updrafts. The latter are dependent upon the convective available potential energy (CAPE) of the thunderstorm cell. Very large CAPE values require high dewpoint temperatures at the surface and low tropospheric levels and sufficiently high convective temperatures; cold temperatures aloft allow the rising air to remain buoyant. Both Thori and Pokhara are well known locations of moisture convergence. The severe convective activity that occurred at Thori and Pokhara was the result of highly supportive synoptic and mesoscale environments that provided almost all documented severe "thunderstorm enhancers" in May 2001 and in May 2005.

The hailstorm that struck the village of Thori during the night of May 3, 2001, was generated within an eastward travelling Mesoscale Convective System (MCS). At this time the stable planetary boundary layer, the nighttime inversion, had been established in the Thori area. Consequently, instead of surface or thermodynamic initiated convection, elevated convection, assisted by warm, humid air supplied by a nocturnal low level jet, was initiated above the stable nighttime layer.

Guided by Infrared Satellite images, this study traces the formation of a Mesoscale Convective System (MCS) from its origins of topographically induced lee-side convergence on May 2 in the intensely heated Pakistan deserts, to its eastwards path into the Thar Desert of India and towards Delhi, where by late afternoon of May 3, the MCS had further increased in size to at least 600km in diameter. The MCS continued propagating and intensifying in the early evening of May 3, ample, surface and low tropospheric level, warm, humid air likely supplied by a nocturnal low level jet and moving in an easterly direction at speeds of up to 70km/hr towards Thori, so that elevated convection could be initiated. Synoptic data analyses indicated in addition to pervasive low pressure over the entire Gangetic Plains area, a travelling embedded short-wave trough at 500hPa that reached the Gorakhpur area by 11UTC May 3. A south-north, slightly easterly oriented trough axis was in place west of Thori. Colder temperatures aloft had arrived in the area between 11UTC May 3 and 00UTC May 4. More than sufficient surface and low-level moisture was supplied by both a nocturnal low level jet and by the very active Bihar surface heat low circulation. When the convective line of propagating thunderstorms of the MCS reached the extreme potential atmospheric instability of the Thori area and giant hail growth was being generated in the updraft, the 1kg hailstones that landed on Thori close to midnight, may well have been considerably larger high in the storm cell, before melting on the way down.

The May 18 Pokhara hailstorm occurred very suddenly during the day, between 1530NST and 1550NST. The thunderstorm happened at least two hours before the usual pre-monsoon late afternoon thunderstorms the residents of Pokhara had become accustomed to. There had been late in the day thunderstorms on the 16th and 17th of

May as well. Pokhara is located at 800m asl in a valley where the diurnal mountain-valley circulation sends warm, humid air from the Gangetic Plains into the mountain valleys at speeds of up to 6 to 10 m/sec, resulting in high dewpoint temperatures at the surface. Pokhara is surrounded by highly complex terrain, including many south facing slopes. By May 18, when the onset of the monsoon is not far away, the monsoon trough which stretches across the North Indian sub-continent is close to being established. But synoptic disturbances, accompanied by very cold air aloft from Central Asia to the northwest can still cause severe weather events in Nepal.

The most significant source of upper air data for both Thori and Pokhara hailstorms was from the Indian city of Gorakhpur, south of Nepal. Gorakhpur May 18 upper air data was missing and this study consequently interpolated for May 18 from May 17 and May 19 upper air data. Synoptic analyses and upper air temperature calculations for Pokhara, using the interpolated May 18 upper air data indicate that on 00UTC May 3, a deep, low pressure trough was situated from 700hPa to 200hPa over Delhi and another low pressure trough with a negatively northwest-southeast tilted axis was situated over Gorakhpur. Wind data from NOAA indicates the subtropical jet stream directly over Nepal. Upper air temperatures at Gorakhpur on May 19 were exceptionally cold for mid-May, e.g., -15.9^{o}C at 500hPa dropping 3.4^{o}C from May 17. Witnesses described the initial hail that reached the ground outside the main city of Pokhara as having, “tennis ball size”.

This study assumes that convective activity had been initiated already by early afternoon. In addition to the dynamic lifting mechanisms provided by the synoptic environment, the sudden arrival of unseasonably very cold air at upper tropospheric levels, led to the generation of a single, violent thunderstorm cell, much like a supercell, with a wide updraft, sufficiently intense and of long duration so that giant hail growth could occur. The thunderstorm cell then continued slightly eastwards towards the northeast edge of Pokhara, where the high speed, moisture filled, southeast valley winds advected additional humid air into the hailstorm, increasing updraft speeds and moisture content. The added moisture changed the hail growth processes within the cell, resulting in an increase of the number of hailstones, a decrease in hail stone size, followed by hail stone collisions and the forming of conglomerates glued together with super cooled water droplets. The hail conglomerates continued increasing in size as long as the updraft speed remained fast enough to keep them aloft. The cold, dry air of the Pokhara storm likely allowed very little melting to occur before the hail stones hit the ground.

Although there was much missing upper air data, almost all the synoptic geopotential heights analyses charts in this study were hand drawn with original available ESRL data. It was found that the computer calculated archived geopotential heights charts from the //ready.arl.noaa.gov/ internet site resembled the original geopotential heights data very little and significant meteorological details such as the locations of embedded short wave troughs were lost. The NOAA site also consistently underestimated dewpoint temperatures across the North Indian sub-continent, which for this study was vital information. Wind data from the site was helpful.

This study used the computer program RAOB.ERS to create SkewT logP charts and calculate the Stability Indices (SI). Gorakhpur upper air data was used for both Thori and Pokhara. Surface data and observations for Pokhara was obtained from the DHM at Pokhara Airport. DHM surface data and observations for both Simara and Bhairahawa were substituted for Thori. Calculating temperature and dewpoint values for the lower tropospheric levels at Thori, such as 925hPa and 850hPa, that would reflect the elevation, as well as the complex terrain, presented an additional challenge. Pokhara is at 800m asl and above the 925hPa tropospheric level. The 850hPa level is approximately 600m agl. For the May 18 SkewT logP diagrams, the cloud base heights were used to calculate the 850hPa temperature and dewpoint temperature values.

The SI calculations indicate a highly potentially unstable atmosphere for both Thori and Pokhara, with Convective Available Potential Energy (CAPE) values exceeding 8000J/kg at 11UTC May 3, 2001 for Thori and 7000J/kg for Pokhara at 00UTC May 18, 2005, with updraft velocities exceeding 100m/sec, allowing for giant hail growth. Assuming elevated convection from 925hPa (700m asl), the Thori SI calculations for 1730UTC May 3 derived from 11UTC May 3 and 00UTC May 4 upper air data, still yielded very large CAPE, 4193J/kg, and a potential updraft velocity of 92m/sec. Such values would have indicated intense tornadogenesis from supercells in the severe thunderstorm prone areas in Bangladesh or the USA.

Satellite images, Infrared, Visible and Water Vapour provided by the University of Dundee were important tools for this study. The Infrared Images (IR) in particular indicated not only areas of well-developed convective activity. The IR also were sufficiently clear to indicate the small, but significant images of outflow boundaries, areas of moisture convergence and occasionally the tiny, white dots of convective cell initiation. Most importantly, the IR of the northern Indian sub-continent, Tibet (China), Pakistan and Central Asia provided this study with a constant snapshot of where convective activity was occurring and when.

Both Pokhara and Thori are known areas of convergence and prone to severe weather. Pokhara is surrounded by high mountains to the west, north and east, including the Annapurnas to the north and receives some of the most precipitation in Nepal. The terrain surrounding Thori, small mountain ridges to the southwest and southeast and a higher ridge directly north created a moisture convergence zone that at midnight of May 3, 2001 contributed significantly to one of Thori's most severe hailstorms.

Eye witness accounts proved to be valuable information for the Pokhara hailstorm. Statements such as, "the blackest cloud I've ever seen, suddenly appeared behind Sarangkot", or " the winds blew open all the doors and tennis ball size hailstones were rolling into the bedroom" and " the southern half of the sky remained blue throughout the whole storm," relayed very significant information. The accounts describe a tennis ball size and 1kg giant hailstone producing thunderstorm that resembled a surface convection initiated supercell that briefly affected only the northern half of the city while the southern half of the sky remained clear. The Pokhara storm is not in the DHM Airport records, because the west to east storm path occurred at least 2km to the north of the airport, along Pokhara's northern edge and the airport staff did not see it.

This study found that the most significant meteorological parameters contributing to the severity and high Stability Indices of the Thori midnight hailstorm were its propagation and elevated convection along the convective line of a MCS, plentiful warm, humid air from a fast nocturnal low level jet that sent a continuous supply of moisture directly into the updraft (this study has no way of knowing the temperature and dewpoint temperatures here and it is likely the true values exceed those used for SI calculations) , steep lapse rates between 700hPa and 500hPa, and between 300hPa and 250hPa, dry mid-level air that increased evaporative cooling and lowered the freezing level, plus the dynamic lifting created east of the trough axis of an embedded short wave trough. Feeder cells, visible in the IR images, likely generated hail embryos and perhaps smaller hail stones that continued growing in the deep, 14430m asl high thunderstorm.

Convective activity on May 18 in the complex terrain surrounding Pokhara that resulted in the mid- afternoon 1kg hail stones was likely the result (*Das 1962, Foote 1984, Browning 1977*) of the sudden extreme decrease of temperatures at mid and upper tropospheric levels, combined with dynamic lifting from a low pressure trough located over central Nepal. The perfectly formed tennis ball size hailstones attest to the likelihood that the Pokhara storm initially was a Low Precipitation hailstorm. When the storm moved eastwards, where the Pokhara valley widens and considerably more moisture was drawn into the updraft, hail stone growth was affected. Maximum downward velocity of the hail stone occurs closest to the surface and consequently the falling hail stone spends the least time in warmer surroundings that would cause melting. At 800m asl, the Pokhara hail stones probably landed reasonably intact.

The analyses of both storms are indicating that some meteorological conditions were very similar, while others were not, thereby outlining new directions of study likely to assist future severe weather forecasting in Nepal.

CHAPTER 2

DATA SOURCES

2.1 DHM Synoptic Surface Data

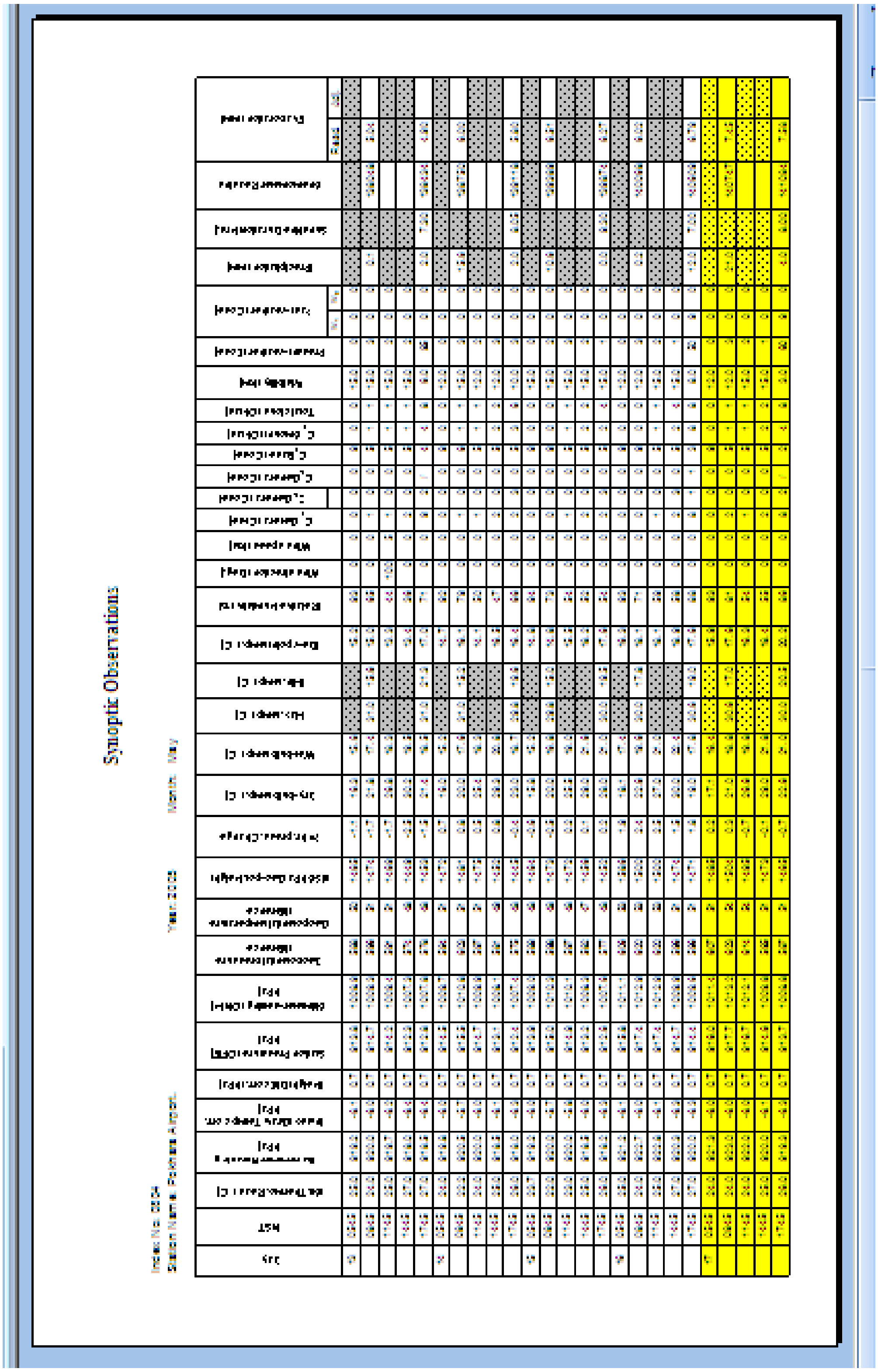
2.1.1 Pokhara

Today the Nepal Department of Hydrology and Meteorology (DHM) maintains 16 synoptic surface weather stations throughout Nepal, including an Automatic Weather Station at the Pokhara Airport. In 2005, the weather station at the Pokhara Airport was a manned station, with observations and measurements of weather data limited to daytime only. The notation format for observations and measurements follows the WMO guidelines and codes found in the Land Station Surface Synoptic Code FM 12-IX from the Federal Meteorological Handbook (FMH) number 2 (Appendix).

The DHM synoptic Pokhara Airport data reports during this period, including May 18, combined both primary and intermediate synoptic reports, but 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.

In May 2005, the DHM staff at the Pokhara Airport recorded a total of thirty one synoptic observations for each daytime observation period. (Table 2. 1). 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. Unfortunately there is no Pokhara Airport DHM surface wind data at all for May 2005. However, in 2012, an automatic weather station (AWS) was installed at the Pokhara Airport. This study assumes 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. Therefore, an analysis of wind speed and direction for May 2012 was performed and the daytime results of these May 2012 analyses were used for the May 2005 study. See Appendix.

Table 2. 1. All 3-hourly daytime 0545 to 1745NST synoptic observations at the Pokhara Airport for May 13, 14, 15, 16, 17 and 18, 2005. Source DHM.



The DHM parameters of Table 2.1 used for the Pokhara storm analyses include surface temperatures in degrees centigrade, surface station pressure in hPa, maximum and minimum temperatures in degrees Centigrade, surface dewpoint temperatures in degrees Centigrade, relative humidity (%), cloud genera (3 categories in WMO code, Tables 2.2, 2.3 and 2.4), cloud base (in WMO code, Table 2.5), CL cloud amount (cumulus category in oktas, Table 2.6), total cloud amount in oktas (Table 2.6) visibility (Km), present weather (in WMO code, Table 2.7), past weather (in WMO code, table 2.8) and precipitation (mm).

Table 2.2. Code table 0513 CL, listing clouds of the genera Stratocumulus, Stratus, Cumulus, and Cumulonimbus. (Source. Land Station Surface Synoptic Code FM 12- IX from the Federal Meteorological Handbook (FMH) number 2)

Code table 0513 C_L — Clouds of the genera stratocumulus, stratus, cumulus, and cumulonimbus

Code figure	Technical specifications
0	No C_L clouds
1	Cumulus humilis or cumulus fractus other than of bad weather,* or both.
2	Cumulus mediocris or congestus, with or without cumulus of species fractus or humilis or stratocumulus, all having their bases at the same level.
3	Cumulonimbus calvus, with or without cumulus, stratocumulus or stratus.
4	Stratocumulus cumulogenitus.
5	Stratocumulus other than stratocumulus cumulogenitus.
6	Stratus nebulosus or stratus fractus other than of bad weather,* or both.
7	Stratus fractus or cumulus fractus of bad weather,* or both (pannus), usually below altostratus or nimbostratus.
8	Cumulus and stratocumulus other than stratocumulus cumulogenitus, with bases at different levels.
9	Cumulonimbus capillatus (often with an anvil), with or without cumulonimbus calvus, cumulus, stratocumulus, stratus or pannus.
/	C_L clouds invisible owing to darkness, fog, blowing dust or sand, or other similar phenomena.

* "Bad weather" denotes the conditions which generally exist during precipitation and a short time before and after.

Table 2.3. Code table 0515 CM, listing clouds of the genera Altocumulus, Altostratus and Nimbostratus. (Source. Land Station Surface Synoptic Code FM 12- IX from the Federal Meteorological Handbook (FMH) number 2)

Code table 0515 C_M — Clouds of the genera altocumulus, altostratus, and nimbostratus	
Code figure	Technical specifications
0	No C_M clouds
1	Altostratus translucidus
2	Altostratus opacus or nimbostratus
3	Altocumulus translucidus at a single level.
4	Patches (often lenticular) of altocumulus translucidus, continually changing and occurring at one or more levels.
5	Altocumulus translucidus in bands, or one or more layers of altocumulus translucidus or opacus, progressively invading the sky; these altocumulus clouds generally thicken as a whole.
6	Altocumulus cumulogenitus (or cumulonimbogenitus)
7	Altocumulus translucidus or opacus in two or more layers, or altocumulus opacus in a single layer, not progressively invading the sky, or altocumulus with altostratus or nimbostratus.
8	Altocumulus castellanus or floccus.
9	Altocumulus of a chaotic sky, generally at several levels.
/	C_M clouds invisible owing to darkness, fog, blowing dust or sand, or other similar phenomena, or because of continuous layer of lower clouds.

Table 2.4. Code table 0509 CH, listing clouds of the genera Cirrus, Cirrocumulus and Cirrostratus. (Source. Land Station Surface Synoptic Code FM 12- IX from the Federal Meteorological Handbook (FMH) number 2)

Code table 0509 C_H — Clouds of the genera cirrus, cirrocumulus, and cirrostratus	
Code figure	Technical specifications
0	No C_H clouds.
1	Cirrus fibratus, sometimes uncinus, not progressively invading the sky.
2	Cirrus spissatus, in patches or entangled sheaves, which usually do not increase and sometimes seem to be the remains of the upper part of a cumulonimbus; or cirrus castellanus or floccus.
3	Cirrus spissatus cumulonimbogenitus.
4	Cirrus uncinus or fibratus, or both, progressively invading the sky; they generally thicken as a whole.
5	Cirrus (often in bands) and cirrostratus, or cirrostratus alone, progressively invading the sky; they generally thicken as a whole, but the continuous veil does not reach 45 degrees above the horizon.
6	Cirrus (often in bands) and cirrostratus, or cirrostratus alone, progressively invading the sky; they generally thicken as a whole; the continuous veil extends more than 45 degrees above the horizon, without the sky being totally covered.
7	Cirrostratus covering the whole sky.
8	Cirrostratus not progressively invading the sky and not entirely covering it.
9	Cirrocumulus alone, or cirrocumulus predominant among the C_H clouds.
/	C_H clouds invisible owing to darkness, fog, blowing dust or sand, or other similar phenomena, or because of a continuous layer of lower clouds.

Table 2.5. Code table 1600 h.Lists the height above the surface of the base of the lowest cloud seen. If the height is, for example, 300 feet, then the higher code figure (in this case 2) will be reported. (Source. Land Station Surface Synoptic Code FM 12- IX from the Federal Meteorological Handbook (FMH) number 2)

Code table 1600 h — Height above surface of the base of the lowest cloud seen		
Code Figure	Feet	Meters
0	0-100	0-50
1	100-300	50-100
2	300-600	100-200
3	600-900	200-300
4	900-1,900	300- 600
5	1,900-3,200	600-1,000
6	3,200-4,900	1,000-1,500
7	4,900-6,500	1,500-2,000
8	6,500-8,000	2,000-2,500
9	8,000 or higher or no clouds	2,500 or higher or no clouds
/	Height of base of cloud is not known.	

Table 2.6. Code Cloud table 2700. Lists codes for total cloud cover in oktas (1/8ths). (Source. Land Station Surface Synoptic Code FM 12- IX from the Federal Meteorological Handbook (FMH) number 2)

Cloud table 2700 N — Amount of cloud cover		
Code figure	Cloud amount (oktas)	Cloud amount (tenths)
0	0	0
1	1/8 or less, not zero	1/10 or less, not zero
2	2/8	2/10 - 3/10
3	3/8	4/10
4	4/8	5/10
5	5/8	6/10
6	6/8	7/10 - 8/10
7	7/8 or more, but not 8/8	9/10 or more, but not 10/10
8	8/8	10/10
9	Sky obscured, or cannot be estimated.	Sky obscured, or cannot be estimated.
/	No measurement made; (automatic stations only)	No measurement made; (automatic stations only)

There are currently 99 codes in the Federal Meteorological handbook for present and past weather from manned weather stations such as the one at Pokhara Airport. However, for the sake of simplicity only the listings of the most frequently used codes will be noted here. The codes refer to significant present and past weather phenomena as well as weather at the time of observation. For past weather the most significant (Figure 2.1, Past Weather W1) and the second most significant past weather (Figure 1, Past Weather W2) during the period are reported. Together this period covers a maximum of either three or six hours. Here, the intermediate synoptic reports cover the last three hours.

Table 2.7. Present weather codes for manned synoptic land station. (Source: Land Station Surface Synoptic Code FM 12- IX from the Federal Meteorological Handbook (FMH) number 2)

Table 4677. ww — Present weather reported from a manned weather station (for this study has been abbreviated and limited to actual observations only)

00 Cloud development not observed or not observable

01 Clouds generally dissolving or becoming lessdeveloped

02 State of sky on the whole unchanged

03 Clouds generally forming or developing

Table 2. 8. Past weather codes for manned synoptic land station. (Source. Land Station Surface Synoptic Code FM 12- IX from the Federal Meteorological Handbook (FMH) number 2)

Code table 4561 Past weather

Code figure	Description
0	Cloud covering 1/2 or less of the sky throughout the appropriate period.
1	Cloud covering more than 1/2 of the sky during part of the appropriate period and covering 1/2 or less during part of the period.
2	Cloud covering more than 1/2 of the sky throughout the appropriate period.
3	Sandstorm, duststorm, or blowing snow.
4	Fog or ice fog or thick haze.
5	Drizzle.
6	Rain.
7	Snow, or rain and snow mixed.
8	Shower(s).
9	Thunderstorm(s) with or without precipitation.

The above DHM cloud observations were essential in analyzing the convective activity and cloud characteristics at Pokhara on May 18, 2005. Upper air data from the Indian station of Gorakhpur which this study used most extensively, was missing for May 18. This study's thunderstorm Stability Index calculations for Pokhara used the DHM observations of cloud base heights and cloud types to complete temperature profiles at the lower tropospheric levels.

2.1.2 Thori

Unlike the manned synoptic weather station at the Pokhara Airport, the DHM does not maintain a weather station at the small village of Thori. The 1kg hailstorm occurred in the middle of the night, when all villagers were sleeping. There are, therefore, no Thori weather observations at all. For the Stability Indices calculations, this study relied on the surface data collected by the DHM stations closest to Thori. These are are Simra, a small airport, 45km to the NE and Bhairahawa, also an airport, 120km to the west, close to the border with India. At 1400m asl and 70km to the NE, the Kathmandu airport surface weather data and observations were not useful for this study.

In May 2001 at the Simra and Bhairahawa airports synoptic weather data was collected at 03UTC (0845NST) and at 12UTC (1745NST). The recorded parameters included surface temperature and dewpoint temperature in centigrade, cloud amount in octa, cloud type, visibility in km, wind speed in knots and direction in degrees true, precipitation amounts in mm, station pressure in mb/hPa and negative and positive pressure tendencies in mb. Maximum surface temperature for the whole day was recorded at 12UTC and the minimum at 03UTC. The 12UTC Simra data was missing for May 3.

This study constructed vertical profiles (Skew T log P charts) and calculated Stability Indices for Thori on May 3, 2001 at 00UTC (0545NST), by combining the averaged 03UTC Simra and Bhairahawa surface data with 00UTC upper air Gorakhpur data. For the May 3, 12UTC (1745NST) vertical profile, only the 12UTC Bhairahawa surface was available. It was combined with the 11UTC (no 12 UTC upper air data) Gorakhpur upper air data to construct SkewT charts and calculate Stability Indices.

2.2 Satellite Images

Satellite images for both Pokhara and Thori storm analyses were obtained from the Dundee Satellite Receiving Station at Dundee University, 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 MTSAT (Appendix).

Table 2.9. A description of the available Meteosat VISSR (Visible/ Infrared Spin Scan- Radiometer) geostationary satellite images over IODC (Indian Ocean Data Coverage) 057.0E . Source: Website of the Dundee Satellite Receiving Station at Dundee University, UK

Meteosat VISSR (IODC) 057.0E Quicklooks for 12 March 2014 at 0600 UTC

Channel	Image (without grid)	Image (grid overlay)	Approx. Range	Description
1	small | medium | large	small | medium | large	0.45 - 1.00 µm	Panchromatic Visible
2	small | medium | large	small | medium | large	10.5 - 12.5 µm	Thermal Infrared
3	small | medium | large	small | medium | large	5.7 - 7.1 µm	Mid-IR / Water Vapour

The Thori and Pokhara analyses in this study relied on the Meteosat (Visible and InfraRed Imager (MVIRI)) VISSR (IODC) 057.E geostationary images for May 16, 17, 18 and 19, 2005, supplied by the Dundee Satellite Receiving Station at Dundee University, UK (Table 2.9). The following is taken from the University of Dundee website, www.sat.dundee.ac.uk/

“The VISSR provides high-resolution images of Earth and its cloud cover every 30 minutes. It acquires imagery as it spins west to east at 100 rpm aboard a spin-stabilized spacecraft, step scanning north to south on each spin to provide cloud imagery and data for determining cloud and surface temperatures and wind fields.”

2.3 NOAA/ESRL Radiosonde Database (Upper Air Data)

This radiosonde data archive is provided by NOAA's Earth System Research Laboratory (ESRL) and is composed of two distinct data sets; the Archived Dataset which is available on DVD and the Real-time Dataset, which is available online at www.esrl.noaa.gov/raobs This study used the latter option, because the site provides immediate access to archived global radiosonde data via the simple point and click process. Of the several formats available, this study used the real-time Datasets in ASCII format.

The radiosonde reports consist of data taken at mandatory, significant and WMO regional and significant (PPBB) wind levels as outlined in the Federal Meteorological Handbook (FMH) No. 3.

The radiosondes are released twice daily, at 00UTC and at 12UTC.

The upper air data that are collected include air pressure, air temperature and humidity measured continuously by the instruments aboard the radiosonde. These observations (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 radiosonde 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 determining stability indicators calculated from rawinsonde soundings originating in India.

The present study of pre-monsoon thunderstorms in Nepal relies heavily on potential atmospheric instability and thunderstorm indicators calculated from the rawinsonde soundings of the Indian cities of Gorakhpur, Lucknow and Patna.

Table 2.10. Description of data validity during thunderstorms of Radiosonde flights. Source: Federal Meteorological Handbook #3

> **4.5.3.4 Flights Near and Into Thunderstorms**. Thunderstorms may affect the validity of the flight position data. Typically, wind speed and direction change abruptly in and near thunderstorms, causing unusual wind profiles to appear. With RDF systems, erratic angles may also result from lightning causing radiosonde signals to drop out. High electric fields in and near the storms may cause NAVAID
>
> signals to drop out as well. If the observer determines that the flight train is in or near a thunderstorm, individual agency guidelines for processing the wind data ***shall*** be followed.

These soundings, (mostly India ones) 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 afternoons in the pre-monsoon months, a 12UTC (1745NST) radiosonde flight could be headed straight into either thunderstorm or pre-thunderstorm conditions, with strong up and downdrafts, lightening and electric fields interfering with data transmission (Table 2.10)

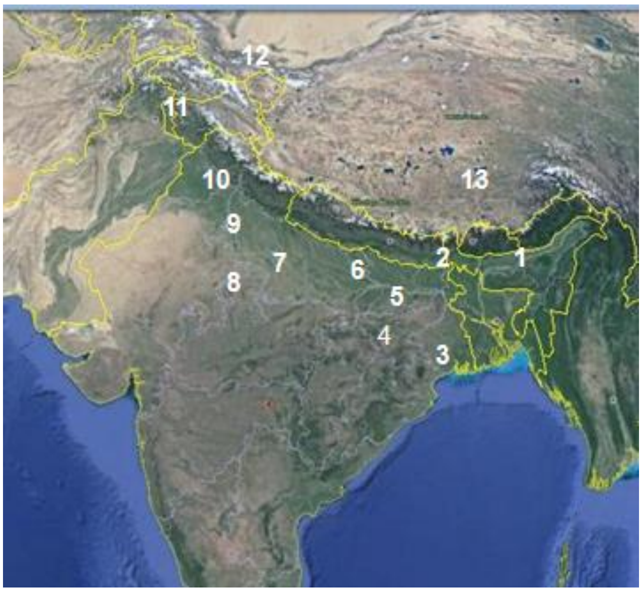
Table 2.11. Gorakhpur radiosonde data for 00UTC May 4 2001, illustrating the extent of missing and incomplete upper air data. Source: ESRL

254	0	4	MAY	2001		
1	99999	42379	26.75	83.37	77	99999
2	9250	7450	99999	20	99999	3
3	VEGK		99999	kt		
9	9940	77	212	193	135	6
4	10000	39	99999	99999	99999	99999
5	9570	406	270	269	99999	99999
4	9250	726	252	222	120	14
5	9110	858	244	198	99999	99999
5	8100	1919	478	478	99999	99999
5	7450	2661	132	52	99999	99999
5	6590	3673	56	-14	99999	99999
5	6140	4243	0	-38	99999	99999
5	6000	4426	-19	-46	99999	99999
5	5400	5249	-95	-97	99999	99999
5	4560	6537	-151	-211	99999	99999
5	3130	9267	-343	-453	99999	99999
5	2390	11121	-413	99999	99999	99999

Table 2.11 illustrates a sample Gorakhpur sounding with incomplete and missing data. 99999 indicates missing data. The incomplete upper air data for 00UTC May 4, 2001 as shown here can still be used to construct SkewT charts. Missing wind data can often, but not always, be managed using interpolation from other sources such as Lucknow and Patna. Internet sites such as http://ready.arl.noaa.gov/ready are an additional resource when there are no primary data sources at all.

Typically, the 12 or 11UTC upper air data is missing from the India Radiosonde database in the ESRL archives. This study was fortunate in having both 00UTC and 11UTC upper air data for the Thori hailstorm on May 3, 2001.

Upper air data for the Pokhara and Thori synoptic hand drawn analyses, such as pressure and temperature charts was obtained from the closest WMO upper air stations in both India and China (Figure 2.1). The latter figure demonstrates 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. Pokhara and Thori are both located in Central Nepal.



1. Guwahati	5. Patna	9. Delhi	13. Lhasa
2. Siliguri	6. Gorakhpur	10. Patiala	
3. Calcutta	7.Lucknow	11. Shrinagar	
4.Ranchi	8. Gwalior	5.Patna	12.Hotan

Figure 2.1 Map indicating locations of closest upper air stations in India and China plus their distances from the storm locations.

Missing data was a serious and complicated issue for the Pokhara analysis, because both 00UTC and 12UTC upper air data sets for Gorakhpur, the station closest to both Pokhara and Thori were missing for May 18, 2005.

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. This study's analyses made use of the NOAA READY site to create synoptic charts for comparison purposes as well as acquiring wind speed and direction information that was frequently missing from the ESRL database. This study also used the NOAA READY features to create upper air profiles and SkewT charts with which to calculate Stability Indices.

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 2.1 In addition to the problems of incomplete and missing weather 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.

This study assumes that the NOAA computer model's calculations for wind speed and direction, temperatures, dewpoints and geopotential heights locations where no upper air data exists, are most likely to be reasonably accurate at the higher tropospheric levels, above 400hPa. At lower tropospheric levels, the NOAA calculations may be less accurate, owing to lack of input data and extremely complex terrain.

2.5 Data Management

Whenever possible the thunderstorm analyses in this study concentrated on archived primary data sources, such as the DHM surface data, WMO or ESRL upper air weather data and satellite images. However, in the case of absence of such data, a very frequent occurrence, these analyses relied on the NOAA READY archived computer generated models, which had to manage with missing data as well.

Gorakhpur 00UTC and 12UTC May 18, 2001 ESRL upper air data was missing. In order to calculate Stability Indices for the Pokhara hailstorm, this study turned to the upper air profile created with the NOAA point and click internet site. This technique was not successful, because the NOAA computers had not incorporated original DHM Pokhara surface data into their calculations. Substituting the original DHM Pokhara surface data into the NOAA upper air profile also did not reveal the atmospheric instability that must have been present.

Instead, this study interpolated from the available, original ESRL 00UTC Gorakhpur May 17 and May 19 upper air data, to create a complete vertical profile for 00UTC (0545NST) May 18, 2001. The Pokhara DHM surface data was then substituted into the 00UTC May 18 Gorakhpur sounding, beginning at 800m asl, the elevation of Pokhara and so that Stability Indices such as CAPE, could be calculated.

ESRL data for the Thori hailstorm was uniquely available for both 00UTC and 11UTC enabling this study to calculate two sets of Stability Indices. The half hourly IR images indicate the precise time of the storm. The IR images for Thori also indicate an earlier thunderstorm on May 3 that occurred about six hours before the hailstorm that devastated the village.

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 as well as providing additional information such as the Convective Condensation Level (CCL), the Lifted Condensation Level (LCL), freezing level and estimated hail size before and after melting.

CHAPTER 3

3.1 Pre-Monsoon Thunderstorms in Nepal

3.1.1 Climate characteristics, Heat Lows and the Monsoon Trough

The climate of the Indian sub-continent falls under the southwest summer monsoon regime. During the pre-monsoon months of April and May, a series of slow building thermally induced surface or heat lows begin establishing in the northwest corner of India. The sub-tropical surface heat lows can manifest themselves up to the 850hPa level, but do not generate convective activity unless the appropriate synoptic conditions are present. The surface heat lows do, however, set up a counterclockwise circulation close to the surface. The primary surface heat low is located in the semi-arid regions of northwest India; a secondary heat low develops south of Nepal, over the North Indian plains. During April and May, the secondary heat low is not a stationary phenomenon and tends to change its location. Most frequently, however, this heat low settles over Bihar, where by early May it becomes very active and instrumental in transporting moisture-laden air from the Bay of Bengal in a counterclockwise direction to Bangladesh, to the northeast section of the Indian sub-continent and in particular to the foothills of the Himalayan Range in Nepal.

With increased heating from the sub-tropical sun, the heat lows gradually move eastwards until they form a low pressure zone, parallel to the Himalayan Range in a west to east direction. The surface heat lows eventually develop into the monsoon trough that triggers the southwest monsoon. Official monsoon onset in Nepal is June 10, although onset has been occurring later in recent years.

3.1.2 Bihar Surface Heat Low and Humid Air Transport

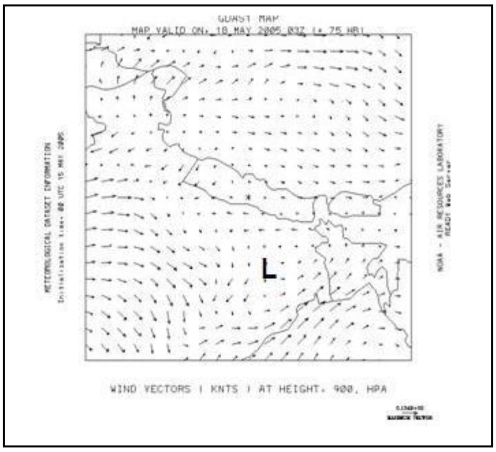


Figure 3.1. The 900hPa wind vectors for 03UTC, 0845NST May 18 and the surface heat low just south of Patna. Source NOAA ARL Archives.

Figure 3.1 illustrates the 900hPa wind vectors over Northern India, Nepal, Bangladesh and the northern tip of the Bay of Bengal for May 18 0845NST. In this analysis, the heat low (marked with **L**) is centered over southern Bihar. The nearly circular area encompassed by the cyclonic circulation is about 900km in diameter, reaches to the Nepal-India border and includes a large section of the Bay of Bengal. In the above image the center of the surface low is about 200km south of the city of Patna.

Table 3. 1. Original Patna upper air data for 12UTC May 18 2005. Source: NOAA/ESRL Radiosonde Database

254	12	18	MAY	2005		
1	99999	42492	25.60N	85.10E	60	1100
2	500	2330	973	69	99999	3
3		VEPT		99999	kt	
9	9970	60	312	232	90	6
4	10000	33	99999	99999	99999	99999
6	9710	290	99999	99999	60	8
4	9250	715	270	200	55	3
6	9190	772	99999	99999	25	1
6	9060	897	99999	99999	300	4

Table 3.1 illustrates the surface, 60m, to 897m asl section of the 12UTC(1745NST) May 18 Patna sounding; a layer of warm, humid air of at least 700m deep with an average dewpoint temperature of 21.6^{o}C is indicated.

Table 3.2. 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

Original wind data only for 05UTC (1045NST), May 18 Gorakhpur (Table 3.2) indicates easterly winds from the surface, 77m asl, to 2133m asl. The layer is at least 850m deep and possibly as much as 2000m. Depths of the surface heat low is likely to vary. Wind speeds are from 3 to 11 knots.

3.1.3 Convective Activity

During the establishing of the monsoon trough when all southwest monsoon pre-requisites are falling into place, the northeast corner of the Indian subcontinent is characterized by vigorous thunderstorm activity. Several areas are particularly susceptible to violent weather. These include NE India, Bhutan, Bangladesh, and the foothills of the Himalayan Range in Nepal. Colder than normal temperatures from a continuous succession of mid-tropospheric waves, “Western Disturbances”, sweep across the northern Indian subcontinent with the still very active sub-tropical jet stream.

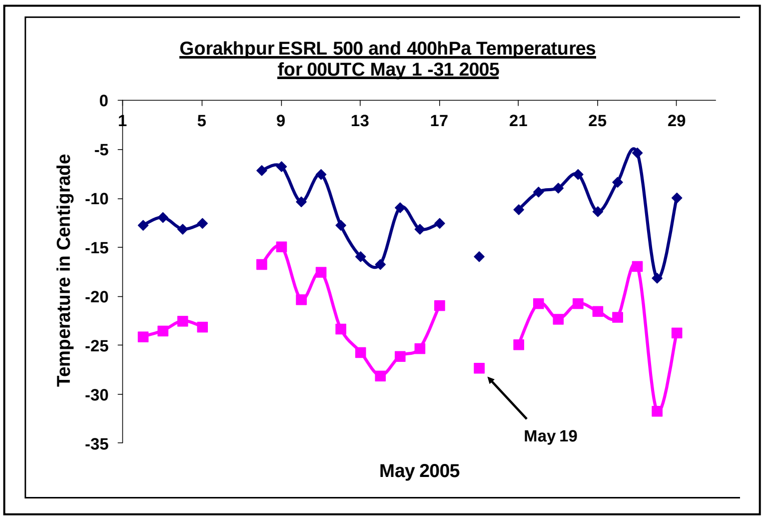


Figure 3.2. Gorakhpur 00UTC 400hPa (bottom line) and 500hPa (top line) temperatures in Centigrade for May 2005. Data for May 5, 6, 7 and 18 are missing. Source: ESRL

The May 1 to May 31, 2005, 00UTC 400hPa and 500hPa temperatures in Centigrade for the Indian upper air station at Gorakhpur, are indicated in Figure 3.2. Gorakhpur upper air data was used most frequently in this study. The temperature ranges are erratic with the 400hPa temperatures for May 2005 varying from -16.7^{o}C on May 8, to -27.3^{o}C on May 19 and -31.7^{o}C on May 28. The 500hPa temperatures varied similarly, from -7.1^{o}C on May 8, to -15.9^{o}C on May 19 and -18.1^{o}C on May 28.
Such cold upper tropospheric conditions, combined with intense surface daytime solar radiation at these sub-tropical latitudes and high dewpoint temperatures result in almost daily thunderstorms often accompanied by large hail.

Frequently, the extreme lapse rates and highly unstable conditions resulting from the superimposed dry and cold air from Central Asia upon the layer of warm, moist Bay of Bengal air are further enhanced by synoptic sources of lift such as low pressure troughs and divergence from the subtropical jetstream. In addition, even very small, travelling embedded low pressure waves at 500hpa and other levels that move eastwards from induced low pressure fields in NW India and Afghanistan can turn a daily mid-afternoon thunderstorm into a violent and destructive event. The subtropical jetstream begins to weaken towards the end of May after which it moves far to the north of the Himalayan Range.

By the middle of May a semi-permanent 500hP low pressure trough is in place over Bangladesh and NE India. Tornadoes result frequently in Bangladesh during the pre-monsoon months. One such destructive storm occurred on May 13, 1996, when 524 people were killed and more than 30, 000 were injured by tornadoes. Bangladesh also holds the record for the world's largest hailstone.

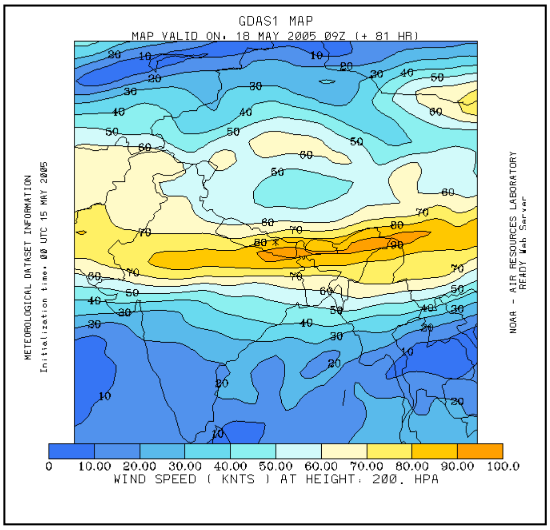


Figure 3.3. 200hPa wind speed for 09UTC May 18, 2005. Source: NOAA ARL Archives.

Figure 3.3 depicts a typical pre-monsoon location of the subtropical jetstream, running west to east across north India and Nepal at 200hPa, approximately 12000m asl. This image is for 09UTC May 18, 2005. The subtropical jetstream, with wind speeds up to 90 knots (jet max) was positioned over the entire eastern section of Nepal with strong divergence indicated over the Pokhara area.

3.1.4 Transport of Bay of Bengal Humid Air to the Himalayas

The most significant source of humid air transported to the mountains and valleys of Nepal is the Bihar surface low. Its counter clockwise circulation sends warm, moist, Bay of Bengal flows to the north Indian plains, including Gorakhpur and the Terai. From there, the well-documented diurnal Mountain-Valley Circulation sends the humid air into the foothills and deep into the valleys of the Himalayan Range. In the Khumbu, surface wind speeds of up to 16m/sec during mid-afternoon at Pheriche, 4300m asl, have been recorded (personal observations). Here both wind speeds and surface dewpoint temperatures reach maximum daytime values at the same time, mid-afternoon. In addition, orographic lifting from mid-tropospheric flows delivers moisture to the mountains and contributes to cloud formation. Synoptic westerly winds transport moist air from the Arabian Sea as well. The latter have been known to cause large unexpected snowfalls in the Annapurna region.

3.1.5 Thunderstorm Activity in Mountainous Terrain

For thunderstorms to occur, the basic ingredients, moisture, cold air aloft and warm surface temperatures need a “trigger”, a source of lift to start the atmosphere destabilization process and begin deep, moist convection. Thunderstorms in the mountains require the same initial conditions as over flat terrain. Complex terrain provides additional mechanisms of forced lifting such as elevated, heated surfaces, orographic lifting and convergence, channeling and lee-side convergence that induce convective activity. “In complex, elevated terrain, all necessary conditions for thunderstorm initiation are almost always present”. This quote from Bob Banta is especially applicable to the Himalayan foothills of Nepal during the pre-monsoon months. In April and May, mid to late afternoon single and multi-cell thunderstorms occur daily. An unstable atmosphere is almost guaranteed at the high, elevated surfaces here where the basic requirements for thunderstorm initiation are present every day: humid air at the surface, a layer of cold, dry air very likely quite close to the surface and very warm surface temperatures from the hot sub-tropical sun high enough to initiate convective activity. At very high elevations, such as 5000m asl, the last two conditions are easily met, but the first, the presence of warm most air is not. Thunderstorms at very high elevations are rare.

It is thought that all thunderstorms produce hail which, at sea level usually melts on the way down. In high, elevated terrain, where the layer of cold air is close to the surface, hail stones are less likely to melt and more likely to land in tact. In Lukla, gateway to Mt. Everest, situated at 2800m asl in the Khumbu in eastern Nepal, the almost daily localized afternoon thunderstorms in May routinely produce hail of 1.5cm and almost never rain (personal observation). Lukla is located in the very steep valley of the Dudh Kosi. High surface temperatures plus the daily up-valley moisture laden winds at speeds of up to 7m/sec destabilize the atmosphere sufficiently to produce brief afternoon thunderstorms with hail that does not have a chance to melt (personal experience).

3.1.6 Thunderstorm Enhancing Tropospheric Lifting Mechanisms

The daily late afternoon thunderstorms during April and May tend to occur in preferred moisture convergence locations. The Pokhara area is one such region as is Thori in the Terai. Since the 2001 storm, the village of Thori has suffered several more hailstorms with extremely large hail. When in addition to the pre-monsoon unstable atmospheric conditions along the southern edge of the Himalayan Range resulting in intense convective activity, there are also in place tropospheric lifting mechanisms, thunderstorm “enhancers” enabling dangerous destabilization of the atmosphere, destructive weather is highly likely. Positive vorticity advection generated in a low pressure trough, or in a small embedded short wave trough, divergence provided by the high speed subtropical jet max directly overhead creating strong lift, plus exceptionally cold, dry air aloft as in the case of Pokhara, can elevate an ordinary thunderstorm into an extremely hazardous and destructive event with damaging wind gusts, tornadoes (as in Bangladesh), very heavy rainfall and very large hail.

3.2 Classification of Thunderstorm Types

Daytime or late afternoon thunderstorms occurring in the Nepal Himalayas above 3000m asl are predominantly single cell air mass thunderstorms. Thunderstorms above 4500m asl are extremely rare. In the high foothills (eg. Pokhara 800m asl and Kathmandu 1400m asl) both single cell and organized multicell thunderstorms have been observed. Thunderstorms along the Tarai in Nepal are known to be violent and destructive, frequently occurring at night. Convective activity can be organized and the cells self-propagating, occasionally travelling across the Gangetic Plains in an easterly direction while attaining massive proportions and leaving a trail of wreckage, caused by very large hail and powerful winds. The latter are known as Mesoscale Convective Systems (MCS).

Infrared (IR) satellite images are an essential tool in thunderstorm forecasting, identifying and thunderstorm studies. In the images, the small bright white circles representing the tall, cold cloud tops of severe convective cells are easily recognized and distinguishable from surrounding clouds that are not so clearly white. Mesoscale Convective Systems can be identified in this manner. The massive anvils of organized thunderstorms are immediately evident on an IR image.

The 00UTC and 12UTC IR satellite images of Figures 3.4 and 3.5 indicate the daily sequences of convective activity during the pre-monsoon months in Nepal. Mornings are clear, with perhaps a few clouds lingering in the high valleys (Figure 3.4). By late morning there is evidence of convective activity and by late afternoon, 1745NST, a line of thunderstorms has formed parallel to the Himalayan Range (Figure 3.5).

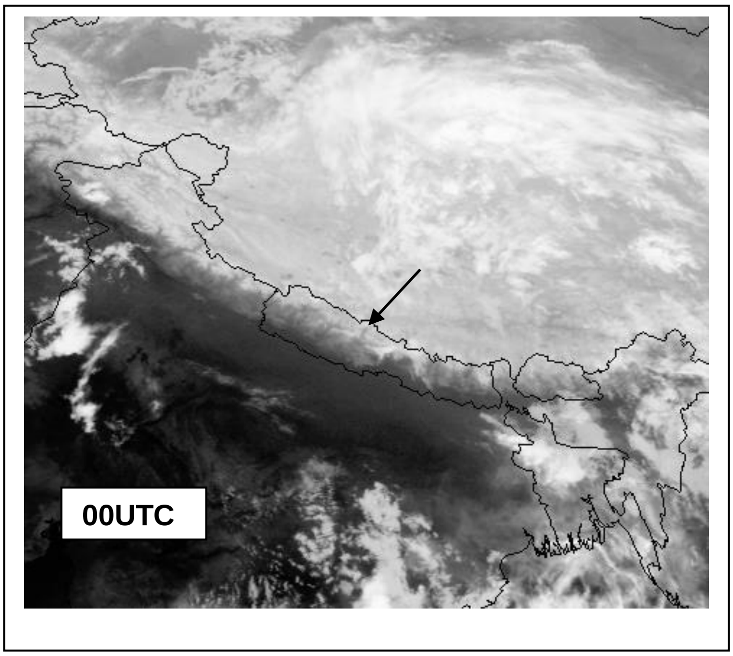


Figure 3. 4. Archived Infrared image of 00UTC (0545NST) May 3, 2001.Source: U of Dundee Receiving Station.

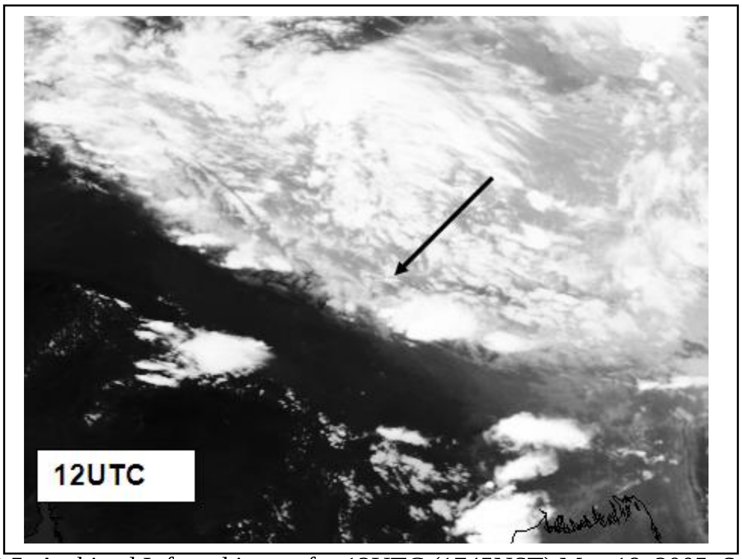


Figure 3.5. Archived Infrared image for 12UTC (1745NST) May 18, 2005. Source: U of Dundee receiving station.

The thunderstorms that form along the Himalayan Range in Nepal can, at times, be severe with very high Stability Indices. The late afternoon cells, 1745NST, illustrated in Figure 3.5 are estimated to be about 15000m asl high and form a cloud shield (cells plus anvils) of at least 400km from west to east. The cells produced large hail as well as destructive downbursts. By 00UTC, 0545NST the next morning, skies have cleared (Figure 3.4). The arrow indicates the northern tip of the Kali Gandaki Valley.

Except for a possible tornado incident on May 10, 1996 in the far southeastern corner of Nepal, supercell thunderstorms similar to the tornadic parent storms found in Bangladesh during April and May have not been documented in Nepal. It has been suggested that the May 10 1996 multi-cluster thunderstorms in Nepal developed into a Mesoscale Convective System as they moved eastwards towards the flat lands of Bangladesh where supercells spawned several destructive tornadoes. Supercell is a term coined by Browning in 1962. It is likely that the highly complex terrain of the Himalayan Range cannot support the formation of supercells by interfering with the initial organization and structure of the cell, thereby inhibiting the cyclonic turning of the convective cell necessary to raise it to supercell level.

3.3 Hail Growth

Hailstorms are a frequent occurrence during the pre-monsoon months of April and May when the mountainous region of Nepal, including the lower foothills becomes a vast area of moisture convergence. In locations of elevated terrain, such as in Kathmandu, 1400m asl, the colder temperatures near the surface prevent the hail from melting before it hits the ground. Severe hail storms with occasional giant hail are common in the east and particularly the southeast of Nepal, closest to Bangladesh, which now holds the world record for the largest hailstone.

Condensation of water vapor into very small cloud droplets occurs early during the forming of the updrafts. Most droplets remain supercooled inside the cloud between the freezing level and the homogeneous ice nucleation temperature, about -40^{o}C. Large hail is formed in the strong updrafts and regions of supercooled water in severe convective storms between levels of -10^{o}C and -30^{o}C. Minute particles of ice, hail-embryos, following impact with super cooled water droplets that are being carried upward by the updraft, grow in size and continue to increase in size as long as they remain suspended inside the cloud by the updraft. Hail growth varies. A single hail stone can grow when layers of super-cooled water droplets are deposited on the original nucleus, like the layered onion effect and in this manner the hail stone retains its round shape. If the stone remains within the area of maximum updraft, it will continue to increase in size as long as the updraft can keep it suspended.

Very large hail, such as those that weigh up to 1kg, is the result of several processes inside the storm, the complexities of which are not precisely known and understood. In the presence of a very high super-cooled liquid water content above the freezing level high in the cloud, conglomerates or irregular clumps of ice collect smaller hailstones and additional water droplets on their way down. In such a case **1.** Sufficiently super cooled water vapor inside the cloud behaves like a glue when the hailstones collide and causes them to fuse or **2.** Hailstones are solid ice and very high inside the cloud will bounce away from each other during collisions. Those that are in the process of falling and melting have a very thin layer of super cooled water on the surface and collisions with other hailstones can cause the hailstones to fuse together. If the air movements inside the cloud throw the fused hailstones back into the updraft and the updraft is sufficiently fast, then the fusion process can continue until the updraft can no longer keep the stone suspended. Or **3.** And this is one of the unknowns, there are still sufficient super cooled water droplets left over high in the cloud which have not yet attached themselves to hail stones and which can, if there is a sufficiently strong updraft, cause the hail stones to further increase in size.

3.4 Strong Updrafts and Windshear

Extreme buoyancy from high CAPE values determine updraft strength. Large hail growth requires the updraft to be wide as well as strong. It is thought that large hail growth occurs not only as the hail stone passes through the storm vertically, but horizontally as well. On spacious flat terrain, such as in Bangladesh and the US, 5 to 10km wide updraft diameters have been documented.

Strong updrafts are the result of well- developed and long lasting storms where the updraft and downdraft are separate from one another. Wind shear, the change of wind speed and/or direction with height causes the updraft to tilt and guarantees that precipitation does not fall back into the updraft, thereby ensuring an unimpeded, continuous supply of warm, moist air to strengthen the storm. Large hail is therefore frequently found in multi and supercell storms with strong vertical wind shear.

Supercells or storms capable of generating tornadoes, have not been documented in Nepal. Nevertheless, during the pre-monsoon season there are many reports of very large hail, which in spite of the highly irregular and complex terrain, comprising of deep narrow valleys, steep and very high mountains, could only have formed in long lasting cells with strongly developed downdrafts and updrafts, cells that under spacious flat terrain conditions could also have spawned tornadoes.

Large hail stones fall faster than small ones and can fall as fast as 50m/sec. Hail falling in elevated terrain spends less time in warmer temperatures near the surface and is less likely to evaporate or melt.

3.5 Hail Time Line

The time duration for significant hail growth is largely dependent on the liquid water content in the cloud and on the length of time it can continue to remain suspended in the updraft. Large hail requires a long storm lifetime .Under extreme values of a liquid water content of 5 g/ m^{-3}, a hail embryo starting from a diameter of 0.5cm must take at least 15 minutes to grow to 10cm and probably twice that long at half that liquid water content . The ice process required for the hail embryo to form is about 20 to 30 minutes. First, a cloud droplet forms, freezes and grows into a snow crystal. The ice crystal starts collecting super cooled water droplets and becomes a graupel or the hail stone embryo. Coalescence to form a large raindrop also takes about 20 to 30 minutes. Therefore under optimum conditions, giant hailstones, such as those observed at Pokhara and at Thori, must take at least and probably more than 90 minutes.

CHAPTER 4

THORI HAILSTORM

4.1 General Information

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. 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. (Appendix 3).

Thori is a small village on the Nepal- India border, just south of the Chitwan National Tiger Park. It is situated at 27.3^{o}N and 84.7^{o}E, 70 km to the southwest of Kathmandu in the Churia Range, south of the High Himalayas at an elevation of 215m asl. 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.

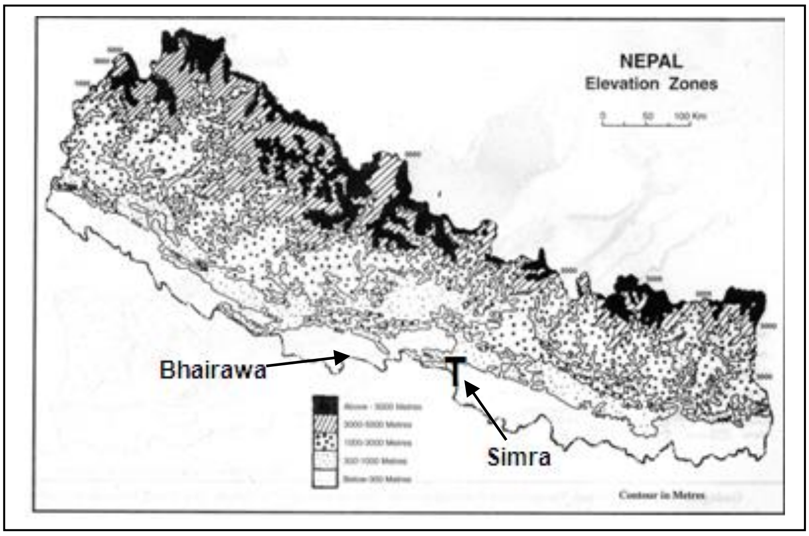


Figure 4.1. Elevation map of Nepal. Locations of Thori (T), Simra and Bhairahawa are indicated.

4.2 Data

Unlike Pokhara, where surface synoptic weather data is collected at the airport by the DHM, there is no local weather data for Thori. The DHM surface synoptic weather stations in Nepal closest to Thori are Kathmandu, 70km to the NE, 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 uses 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.

4.2.1 Simra Observations

Table 4.1. Simra surface data. Temperature, dewpoint temperature, wind speed and direction, pressure and maximum temperature for 03UTC May 2, 2001 to 03UTC May 4, 2001. Source: DHM

	Temperature	Dewpoint Temperature	Windspeed knots	Wind Direction	Pressure hPa	Maximum Temperature
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
May 4 03UTC	23.4C	20.3C	4	270	990.1	

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°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°C (Table 4.1). The maximum surface temperature for Simra on May 2 was 33.2°C. The May 3 the maximum surface temperature was 35.2°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^{o}C. The surface pressure increased 0.8mb. The wind direction became westerly, from 270 degrees at 4 knots.

4.2.2 Bhairahawa Observations

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^{o}C, a two degrees increase from the previous day; the dewpoint temperature was 22.3^{o}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^{o}C, with a dewpoint temperature increasing to 27.4^{o}C by 12UTC, 1745NST. The maximum surface temperature reached 35.5^{o}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 dropped 5.2^{o}C degrees during the previous 24 hours; the dewpoint temperature decreased 2.7^{o}C. Unlike at Simra, the winds remained easterly, from a 110 degree direction at 8 knots.

4.3 University of Dundee Archived Infrared Satellite Images

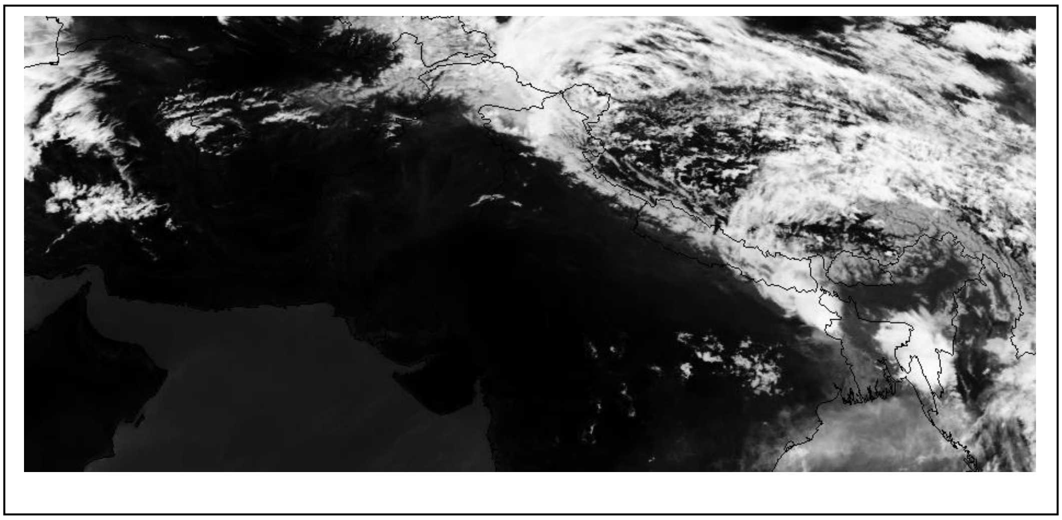


Figure 4.2. 630UTC (1215NST) May 2, 2001 infrared satellite (IR) image of North India and Nepal. Source; U of Dundee Receiving Station.

Figure 4.2 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 colour, 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. 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.

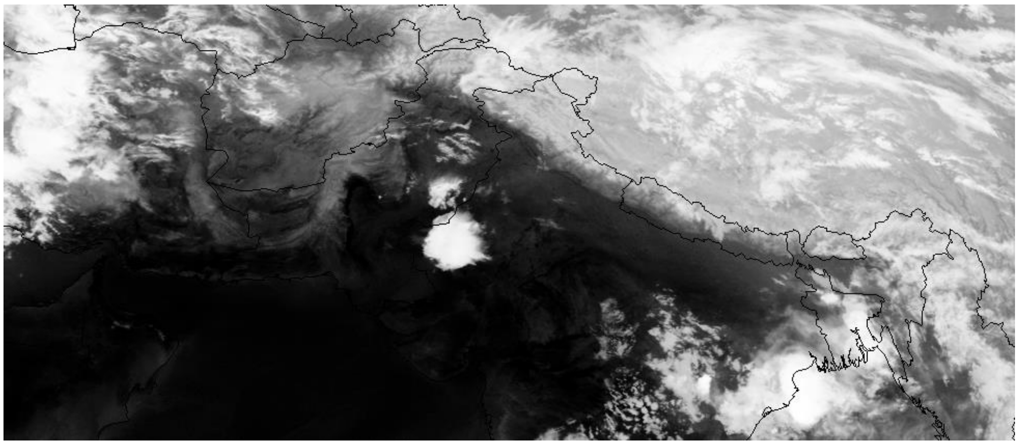


Figure 4.3. 19UTC May 2 (045NST) May 3, 2001 IR image of the study site. Source: U of Dundee Receiving Station

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 4.3). 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 4.3, 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 16.5ºC. The solitary nature of the cloud cluster of figure 4.3, 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 4.3) indicates convective activity along the northern region of the Bay of Bengal as well.

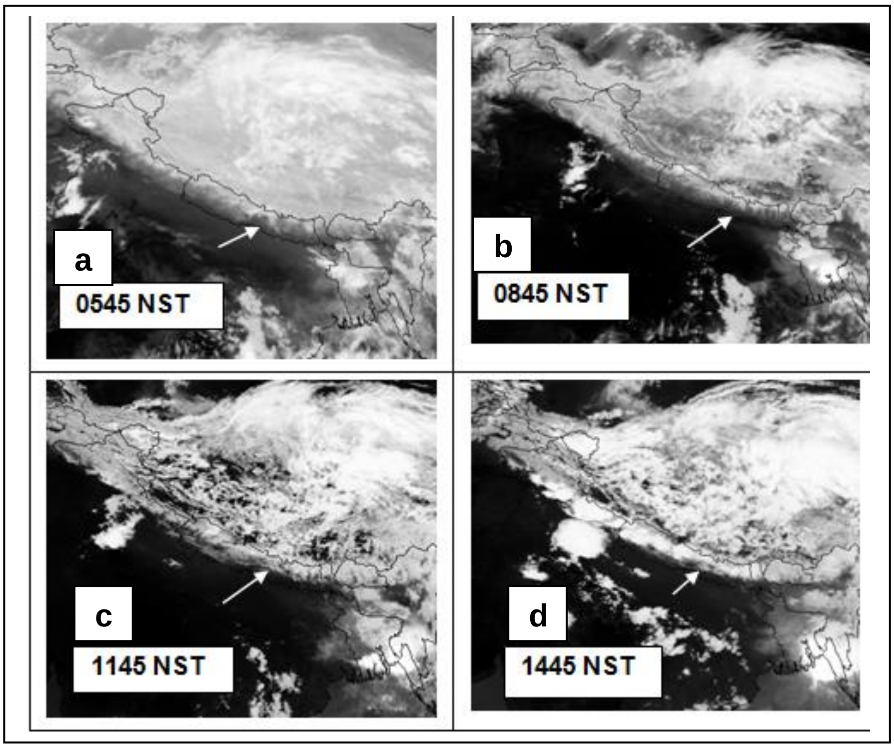


Figure4.4.a, b, c, and d. IR images for 00UTC (0545NST) to 09UTC (1445NST) , May 3, 2001. Source: U of Dundee Receiving Station.

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 4.4.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 colour), including the Thori area (Figure 4.4.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 4.4.d), the bright, white colour 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. 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.

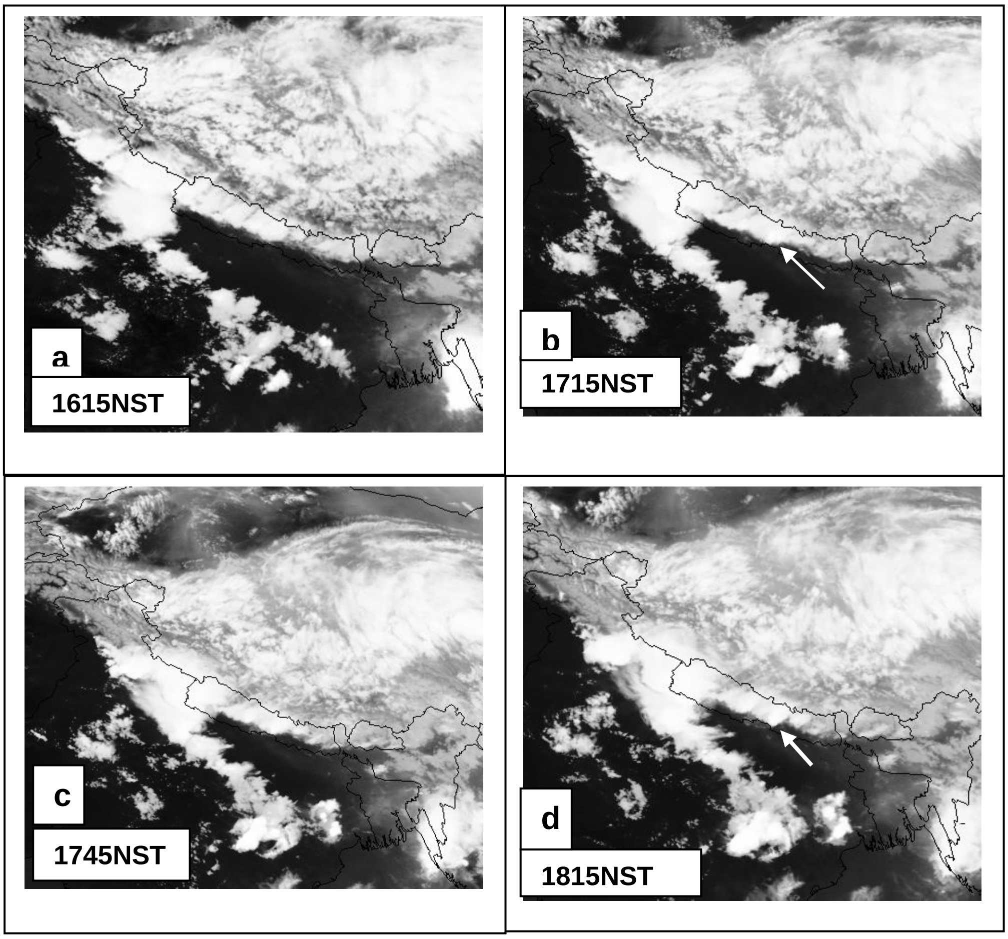


Figure 4. 5 a, b, c, and d. IR images for 1615, 1715, 1745 and 1815NST respectively. Source: U of Dundee Receiving Station

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 4.5 a) 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 (Figure4.5b). 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 colour, 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, reports low, cumulonimbus over $1/8^{th}$ of the sky. Two anvils, originating near the Nepal/India border, possibly the Thori/Bhairahawa area, are visible on the IR image (Figure4.5c). The1815NST (1230UTC) IR image indicates a thunderstorm, a bright, white circle (white arrow), occurring very close to Thori (Figure 4.5d). 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 is has remained stationary. The IR images indicate no convective activity at Gorakhpur and Patna.

Figure 4.6. Thori as seen from 150km up. Source: Google earth

Thori, on the border with India, is a known area of convergence and since this writing has experienced many more destructive hailstorms. The Google Earth image, taken 150km above the surface (Figure 4.6) illustrates several possible reasons for this. Thori (short white arrow) is situated at 215m asl, directly at the tip of a triangle shaped section of the low level Gangetic plains in India, behind which the foothills of the High Himalayas begin. Southerly, southeasterly and southwesterly surface flows are forced towards Thori, like fluids towards the tip of a funnel. In addition, the range directly behind Thori (long white arrow) at 650m is sufficiently high to contribute to the convergence Thori is known for.

Thori is surrounded by wildlife preservation parks, the Valmiki Wildlife Sanctuary to the west, the Chitwan National Park to the North and the Parsa Wildlife Reserve to the east.

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 squared) extremely cold cloud shield of less than -52^{o}C. 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 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.

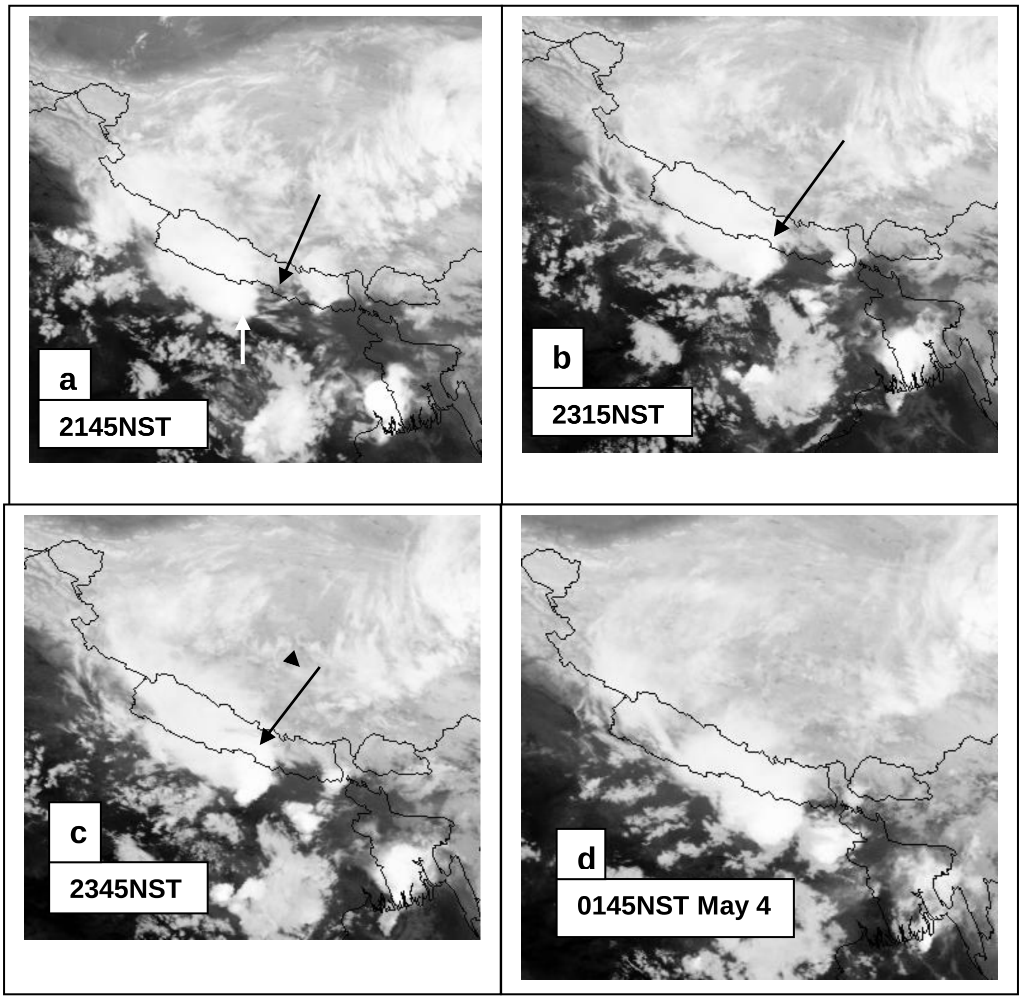


Figure 4.7. a, b, c and d. IR images for 2145, 2315, 2345, NST, May 3 and 0145NST May 4 respectively. Source: U of Dundee Receiving Station

The 2145NST (16UTC) IR images of Figure 4.7a, 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 colour, indicating the high, cold tops of severe thunderstorms (Figure 4.7b). The cold Thori cloud tops (Figure 4.7c) 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 4.7d). The system begins dissipating two hours later.

4.4 Feeder Cells and Hailstone Growth

Very large hail stones require at least 90 minutes from embryo (minute frozen droplets) to final size. Studies have shown that the very large hail stones that fall from a thunderstorm may have reached their final size in the updraft of that thunderstorm, but were not necessarily initiated in the same cell. Instead, the hail stones, beginning with the hail embryo, were generated in several other cells, feeder cells, nearby. Small, still developing hailstones, cannot survive in intense, strong updrafts and are immediately thrown out of the storm. It is likely that the 1kg stones were a conglomerate, products of violent collisions of smaller hailstones inside the updraft of the parent cell and that the storm also produced hail stones of varied sizes, so that total hailstone growth required less than 90 minutes. The hailstorm destroyed 800 dwellings and 200 hectare of crops; most of the hailstones must have been large enough, golf or tennis ball size in order to be that destructive. This study assumes that the 1kg hailstones that were found and weighed by the villagers must have fallen close to the dwellings where they had been sleeping. Whether the crops were crushed by 1kg hailstones as well remains an unknown, because it is unlikely that after such a devastating event with many injuries, villagers would have ventured out into the dark to find and measure hailstones. The hailstones would in all likelihood have melted by sunrise the next day.

The exact time of the storm is not known. The IR images indicate that the storm occurred at some point between 2315NST and 2345NST. The hail embryo stage would therefore have been between 2145NST and 2215NST, indicated by feeder cells nearby.

4.5 Time Line of Feeder Cells

2145NST (1600UTC) - MCS is 70km west of Thori. Convex convective line is east of Gorakhpur. The whitest section of the MCS is south of Nepal. No indications of feeder cells nearby Thori.
2215NST (1630UTC) – Whitest section of the MCS still south of Nepal and over Gorakhpur. The IR image shows some convective activity approximately 10km west of Thori, possibly indications of outflow boundaries initiating new feeder cells.
2245NST (1700UTC) – The cloud tops over Thori appear whiter and are therefore taller than in the previous IR image. The IR images indicate multi cell thunderstorms to the west, north and south of Thori, all likely candidates for feeder cells, with updrafts sufficiently intense to support the first stages of hailstone growth.
2315NST (1730UTC) – Thori and its immediate surroundings, especially to the south is engulfed by the tall, white IR signatures of severe thunderstorms. Large hail growth is occurring.
2345NST (1800UTC) – The IR image is still indicating bright, white cloud tops in the immediate Thori area and its surroundings. The convective line, representing the line of eastward propagating cells has moved 50km to the east of Thori.
0015NST (1830UTC) – The convective line is still well defined, but is now 100km east of Thori. The IR image indicates severe thunderstorm activity well south of Nepal, over Patna.

The first indications on the IR image of possible feeder cells was by about 2245NST, which allowed approximately one hour for large hail growth to occur by 2345NST, when the storm struck Thori. A time line of one hour is not sufficient for the growth of single giant hailstones. However given ample moisture at low tropospheric levels and large numbers of supercooled droplets above the freezing level in the updraft and down draft, accretion by collision can continue almost indefinitely, until the updraft can no longer support the hailstone and it falls to the ground.

4.6 Synoptic and Mesoscale Environments

The Infrared Satellite (IR) images in the previous section provide visual evidence of the late night May 3, 2001Thori thunderstorm, in addition to indicating an earlier storm at approximately 1800NST. The IR images also illustrate the sequence of events occurring over the northern Indian sub-continent beginning May 2. The IR images indicate significant convection over the Thar Desert in Pakistan beginning after 1545NST on May 2, which intensified into a large, single cloud shield by 045NST May 3 (19UTC May 2). During the following hours the cloud shield dissipated and by 0545NST (00UTC) only a small cloud cluster had remained. The IR images also reveal the evolving and intensifying of a possible Mesoscale Convective System (MCS) over Northern India and Nepal by early evening of May 3. Favorable synoptic and mesoscale conditions resulted in widespread instability and severe convective activity along the Himalayan Range, attested to by the many large thunderstorm anvils in the 1030UTC (1615NST May 3) IR image. The small white circle over the Thori area in the 1230UTC IR image indicates an earlier thunderstorm as well.

The IR images testify to the presence of a synoptic and mesoscale environment highly conducive to widespread atmospheric instability. Attempts to identify within the synoptic environment the dynamic upper air lifting mechanisms and areas of enhanced lift that were likely to release the potential atmospheric instability are presented next. The following analyses use both the NOAA Reanalysis Archives and the ESRL original data.

4.6.1 Upper Tropospheric Levels

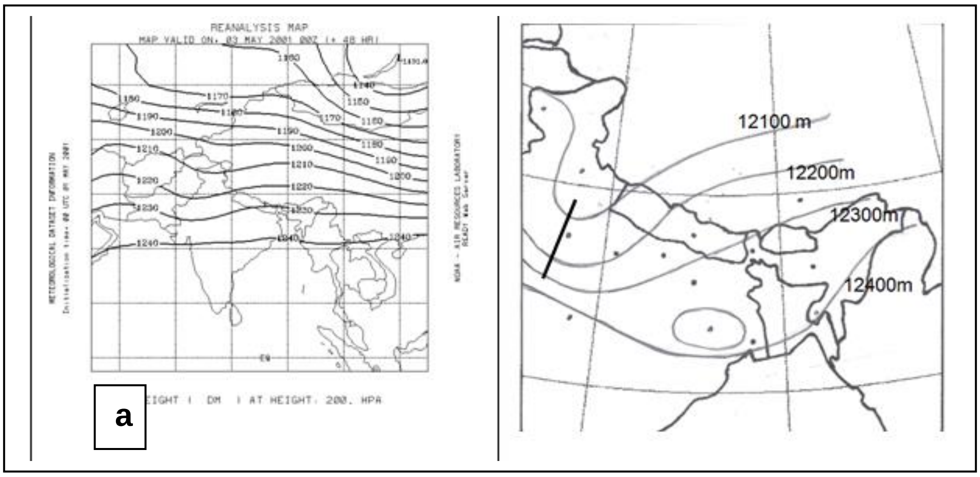


Figure 4.8.a and b. May 3 2001, 00UTC (0545NST) 200hPa geopotential heights (a). Source: NOAA 6-hourly Reanalyses. And (b), hand analyzed 200hPa contours. Source: ESRL. Contour interval is 100m.

The NOAA Reanalysis (NR) 200hPa contours (Figure 4.8a) for May 3 00UTC follow a slight downward curve at 12100 m to 12300m asl over the NW India and the Pakistan border, indicating the disturbance visible in the IR images of the previous section. This area is enclosed by the extremely complex terrain of the Himalayas and by the Karakorams of Pakistan and is the location of the pre-monsoon primary surface heat low over the deserts. Surface heat lows are below 850hPa and manifest themselves at the surface and 925hPa levels, causing the winds to move in a counterclockwise direction. Typically the 200hPa levels and the near to surface circulations remain independent of each other. A high pressure ridge is situated directly to the west over north Pakistan and Afghanistan. Flow over the rest of India and Bangladesh is zonal.

Figure 4.8b was constructed from original ESRL upper air data. On this hand drawn analysis, the 12100m asl contour also starts near Shrinagar, but instead of briefly crossing the NW tip of India as in the NR chart, begins a downward curve, continuing in a straight southward direction before curving back up to the NE west of Delhi. The 12200m and 12300m asl contours follow the 12100m asl curvature, passing through Lucknow, 12180m and south of Gorakhpur, 12320m respectively. The direction of the contours of Figure.4.8b mimic the direction of the thunderstorm anvils in the IR images later in the day of May 3. A SW to NE low pressure trough axis (black line) extends from the India-Pakistan border to west of Delhi. The area east of the low pressure trough axis is a likely location of upper air divergence, a strong upper tropospheric level lifting mechanism generated by vorticity. It is also the location of the cloud cluster in the 00UTC IR image to the west of Delhi. The 12400m asl contour is not zonal as in Figure 4.8a, but instead follows a southeast direction from Gwalior, 12440m asl, curves northeastwards south of Calcutta 12410m, and forms a deep trough over Bangladesh and NE India. An enclosed low of 12310m at Ranchi was drawn in, because of its close proximity to the 12400m geopotential heights contour near Calcutta. The upper air enclosed Ranchi low is located just south of the secondary surface heat low (Bihar Low) of the Indian subcontinent.

There is much temperature data missing from the original ESRL database at higher tropospheric levels. Available data from Delhi and Lucknow indicate a 200hPa temperature decrease of 3.8°C by 12UTC May 3 during the preceding 24 hours. At Gorakhpur, the station closest to Thori, between 00UTC and 12 UTC May, 3 the 200hPa temperature dropped 2.6°C to -52.3°C, the 150hPa temperature dropped 3°C to -65.3°C and the 100hPa temperature fell from -71.9°Cto – 77.9°C. `

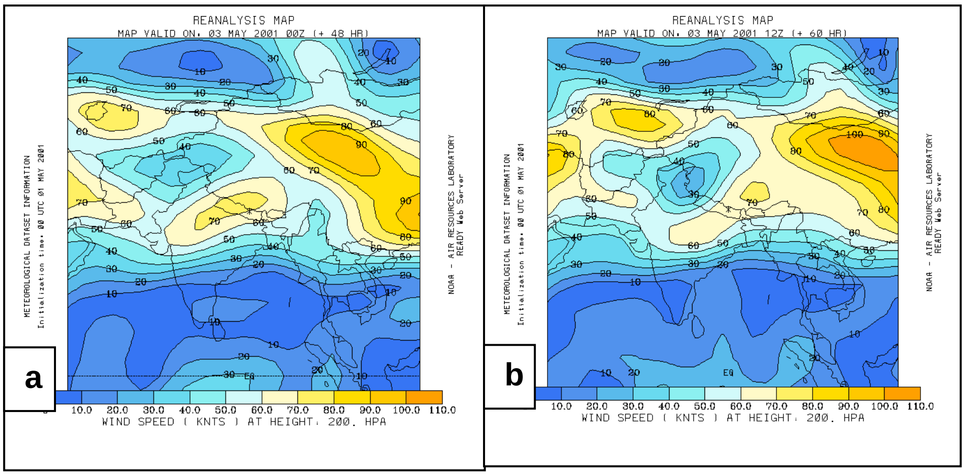


Figure 4.9 a and b. 00UTC(a) and 12UTC(b) May 3, 2001 200hPa wind speeds. Source: NR

With most of the original ESRL upper air wind data missing from the fourteen stations that this study has used, hand drawn wind analyses were not possible although a few individual data points were available, which enabled this study to draw the contours for Figure 4.8b. The NOAA Reanalysis computer calculations incorporate wind information from aircrafts. The resulting upper air charts can frequently be significant forecasting and analysis tools. The NR chart for 00UTC May 3 shows the maximum of the 200hPa subtropical jetstream located far to the northeast of Nepal (Figure 4.9.a). Windspeed over western Nepal and the Delhi-Lucknow-Gorakhpur area was 70 knots, decreasing to 60 knots by 12UTC (Figure 4.9.b).

Original ESRL 200hPa wind data for 00UTC May 3 2001, was missing at Delhi, Lucknow, and Patna. The 200hPa Gorakhpur winds decreased from 50 knots at 00UTC to 34 knots at 12UTC; at 00UTC Gorakhpur wind directions turned southwesterly above 400hPa, from 260 to 235 degrees. By 12UTC May 3, Gorakhpur upper air winds were westerly again, except at 100hPa where winds remained southwesterly, from 245 degrees, as indicated by the anvils in the IR image for 1230UTC. 200hPa wind data for 11UTC May 3 was missing for Lucknow and Patna. 11UTC 200hPa winds at both Delhi and Gorakhpur were westerly at 34 knots.

However, the Delhi 11UTC May 3 wind data include a significant level at 172hPa (13114m) with a wind speed of 83 knots (direction missing), indicating an increase of 49 knots over 1000m and the possible remnant of the subtropical jetstream maximum over the North Indian subcontinent, an unrecorded event because of missing data. The massive anvils in the 11UTC (1645NST) May 3 IR image that reach in 235 degree direction from the India-Nepal border into Tibet, a distance of at least 200km, were more likely the result of 83 knot winds than of 34 knot winds. On the previous day at 00UTC (0545NST) May 2, significant levels from the Delhi, ESRL data indicate 120 knots (direction missing) at 13890m asl (158hPa), 1500m above the 53 knot westerly 200hPa winds. And at 11UTC May 2, 134hPa (14929m) wind speed had increased from 89 knots at 150hPa, to 106 knots.

By comparison at Gorakhpur, wind speed at all upper tropospheric levels, from 400 to 100hPa was less than 39 knots on May 2. Upper air divergence from a significant wind speed discontinuity in the Delhi area, not indicated in the NR data, may have played an important role in the sudden convective activity here that set the scene for further intensifying the next day. The very large and solitary thunderstorm cloud cluster to the west of Delhi on the IR image for 19UTC May 2, 045NST May 3 (Figure 4.3) indicates the presence of a strong, localized, dynamic lifting mechanism, which very likely may have been in place already the previous day.

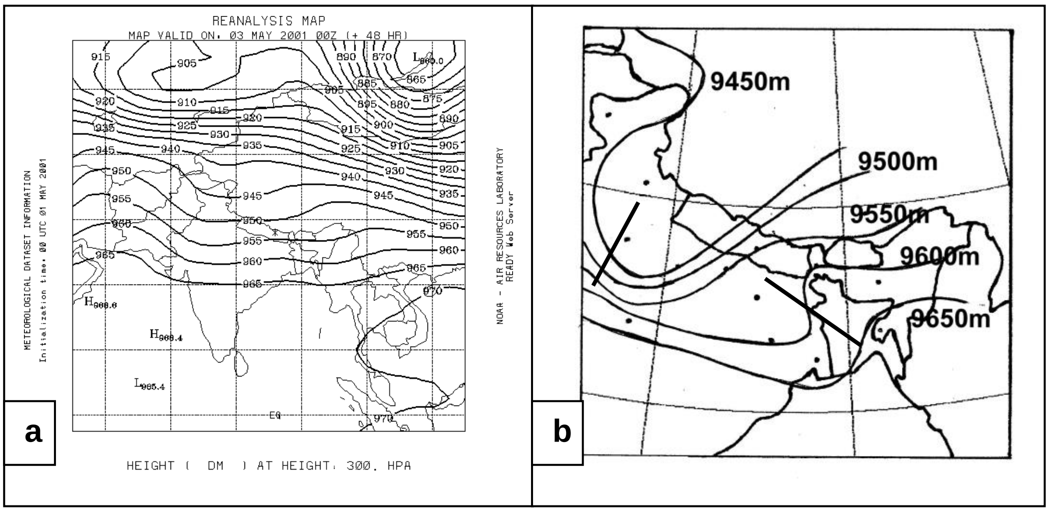


Figure 4.10 a and b. May 3, 2001, 00UTC (0545NST) 300hPa geopotential heights (a). Source: NOAA 6-hourly Reanalyses (NR). And (b), hand analyzed 300hPa contours. Source: ESRL. Contour interval is 50m.

The NR 300hPa geopotential heights for 00UTC May 3, 2001 (Figure 4.10.a) indicates a high pressure ridge over Afghanistan and Kazakhstan which extends from 9450 to 9350m asl. Following the ridge, the 9450m to 9650m asl heights contours descend into a shallow curve into NW India. Except for very slight downward curving at 9600m and 9650m asl over Myanmar, flow over North India and Bangladesh is zonal.

The hand analyzed 300hPa geopotential heights chart (Figure 4.10.b) shows the 9450m heights contour descending from Hotan in China, through Shrinagar, along the Pakistan border, to south of Delhi, 9440m and through Lucknow, 9450m before curving northeastwards through Nepal to China. In view of the explosive thunderstorms (IR image, 1445NST) that were generated several hours later in the Delhi area this analysis drew a positively tilted trough axis (black line). The 9500m contour follows the 9450m curvature as does the 9550m contour; the latter becomes zonal south of Lhasa, 9530m. Unlike NR Figure 4.10a, the 9600m isobar contour in Figure 4.10b curves around Ranchi and passes through Siliguri before continuing in a zonal direction. The 9650m contour curves around Calcutta and continues northeastwards into Myanmar (Guwahati data missing) indicating a low pressure area. A trough axis (black line) runs from east of Calcutta towards Patna.

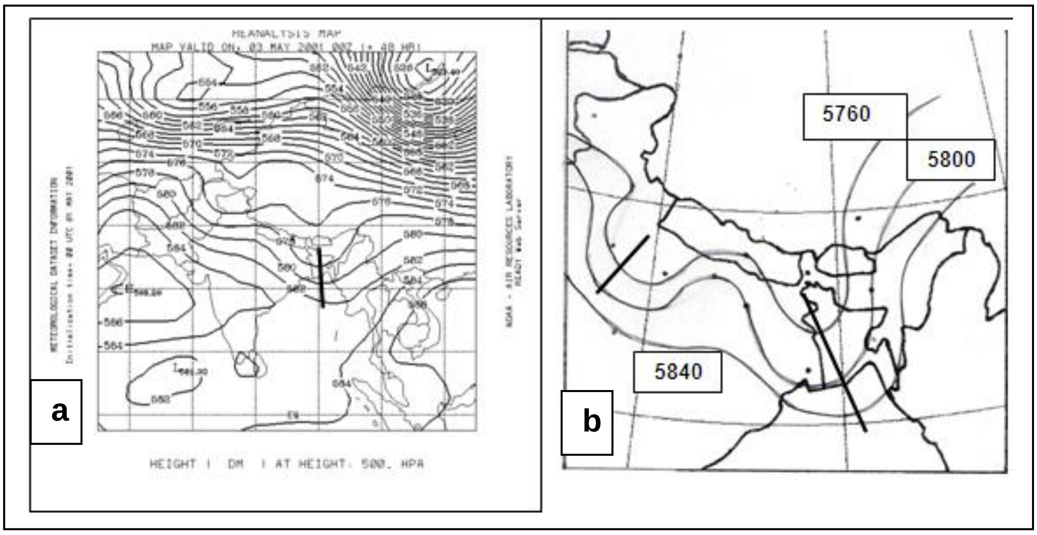


Figure 4.11 a and b. 00UTC (0545NST) May 3 2001, 500hPa geopotential heights (a). Contour interval is 20m. Source: NOAA 6-hourly Reanalyses (NR). And (b), hand analyzed 500hPa geopotential heights. Contour interval is 40m.Source: ESRL.

Figure 4.11a represents the NR computer calculated 500hPa geopotential heights for 00UTC, May 3, 2001. The downward curved 5760 to 5820m asl isobars over the northwest India-Pakistan border area indicate an embedded low pressure short wave aligned with the NR curved contour at 200hPa and 300hPa. This low pressure field is located in the immediate vicinity of the location of the solitary cloud shield of the 045NST May 3 IR image. A strong high pressure ridge over Southern Pakistan, Afghanistan and Iran precedes the trough. The figure indicates a mid-level trough further east over Bangladesh and the Bay of Bengal from 5760 to 5820m asl; a black line shows the location of the trough axis.

The hand analyzed 500hPa geopotential heights for May 3 00UTC (Figure 4.11b), reveal considerable and seasonably appropriate potential atmospheric instability over the north Indian plains. Contour intervals were kept at 40m because original upper air data indicated such varied heights that a string of enclosed low pressure areas would have resulted, a common feature of pre-monsoon characteristics. The 5760m contour was drawn from the Pakistan border south of Shrinagar southeastwards to Patiala, south through Delhi, around Lucknow, 5740m, before curving sharply northeastwards above Gorakhpur, 5800m. The 5760m isobar then curved steeply south into mid-Bangladesh before continuing north towards Lhasa, 5770m. 500hPa wind direction at Lhasa was from 220 degrees, determining the direction of the isobar and confirming the presence of the deep pre-monsoon trough. A low pressure trough axis (black line) was drawn through the embedded short wave between Delhi and Lucknow. East of such a low pressure trough axis, an area of vorticity and the resulting dynamic enhanced lift mechanisms are likely. In the IR images this is also the region where the initial convective organization occurred before eastward propagation began by about 1915NST. The analysis indicates a negatively tilted low pressure trough axis (black line) from the Bay of Bengal to NW Bangladesh, directly east of the high pressure ridge at Gorakhpur. The Bangladesh low pressure trough is a semi-permanent pre-monsoon feature.

The northwesterly, 300 degree, 500hPa winds at Delhi increased from 20 knots at 00UTC to 37 knots by 12UTC. Westerly 500hPa 290 degree winds at Lucknow remained at 31 knots during the day. Wind data above 400hPa was missing at Lucknow for both 00UTC and 11UTC. At Gorakhpur the 500hPa 00UTC winds were northwesterly at 42 knots; by 11UTC, the wind direction remained unchanged at 40 knots. Wind direction at Patna was also northwesterly at 25 knots. All 12UTC May 3 Patna data was missing.

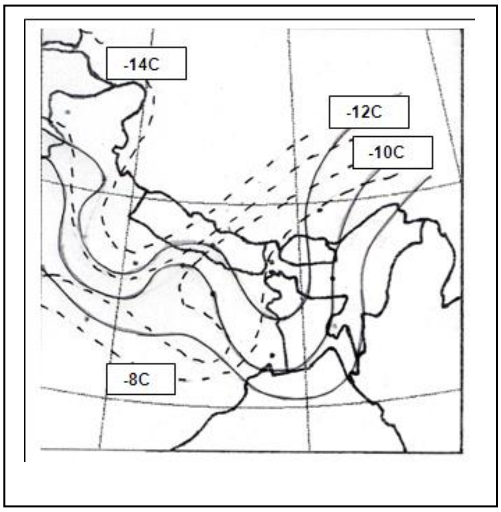


Figure 4.12. 00UTC May 3 2001, 500hPa geopotential heights and isotherms. Isotherm interval, 2 degrees centigrade. Source: ESRL

The 00UTC May 3, 2001 500hPa temperatures ranged from -14°C at Patiala to -7.1°C at Calcutta (Figure 4.12). Temperatures at Delhi, Lucknow and Gorakhpur were -13.7°C, -13.3°C and -10.1°C respectively. Upper air data for the Thori area was not available. In the above 00UTC analysis, cold air advection from northwesterly

500hPa winds places Thori between the -10ºC and -12ºC isotherms, contributing to the severe atmospheric instability in the region.

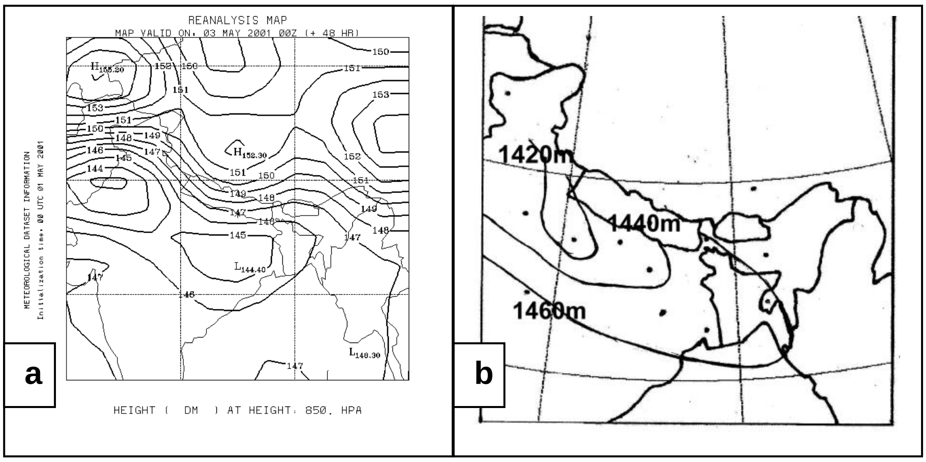


Figure 4.13 a and b. 00UTC (0545NST) May 3 2001, 850hPa geopotential heights (a). Contour interval is 10m. Source: NOAA 6-hourly Reanalyses (NR) and (b), hand drawn 850hPa geopotential heights. Contour interval is 10m. Source: ESRL.

Figure 4.13a is the computer calculated NR 850hPa geopotential heights for 00UTC May 3. Unfortunately, the on average 1450m asl high contours found their way into the image where the terrain is considerably higher, such as the Himalayan Range and the Tibetan Plateau. However, the locations of the surface heat lows over northwest India (Thar Desert) and over Bihar are identified correctly.

Figure 4.13b takes into account the very high topography of northwest India and the Himalayan Range. Therefore the 850hPa geopotential heights are not continuous as in the hand drawn 500hPa chart of Figure 4.10b. The 850hPa hand drawn contours stop at the Himalayan Range. Gauhati upper air data was missing for May 3, 2001.The 850hPa 1420m contour begins at Patiala, (Shrinagar to the northwest in Kashmir is at 1587m asl) heads straight south and slightly east towards Lucknow, curves around Lucknow and exits into the western tip of Nepal. The 1430m heights contour begins just west of Delhi and heads east as it parallels the 1420m contour around Lucknow. The 1440m heights contour parallels the 1430m contour, except that it extends sharply close to Patna, (850hPa height 1339m asl) before it becomes northwesterly and also ends in the foot hills of western Nepal. The preceding three 850hPa heights contours suggest a negatively tilted low pressure trough, a condition amplified by the 850hPa geopotential height difference between Lucknow1415m asl and Gorakhpur, 1448m asl.

The 1440m, 850hPa heights contour begins northwest of Gwalior, follows a southeasterly direction, curves around Calcutta and ends in the foothills of eastern Nepal. The 1460m contour begins west of Gwalior, parallels the previous contour, curves around Calcutta and ends at Siliguri. The 850hPa low pressure field, located in a west to east direction across the Gangetic Plains, at this time resembles the establishing of the southeast monsoon trough.

Straight, 100 degree, easterly 22 knot winds at Gorakhpur were faster and opposite to both Lucknow, 7 knots from the northwest, and Patna, 4 knots from the west. The 850hPa winds at Delhi were 8 knots from a 280 degree direction; at 11UTC wind speed at Delhi increased to 21 knots from 290 degrees.

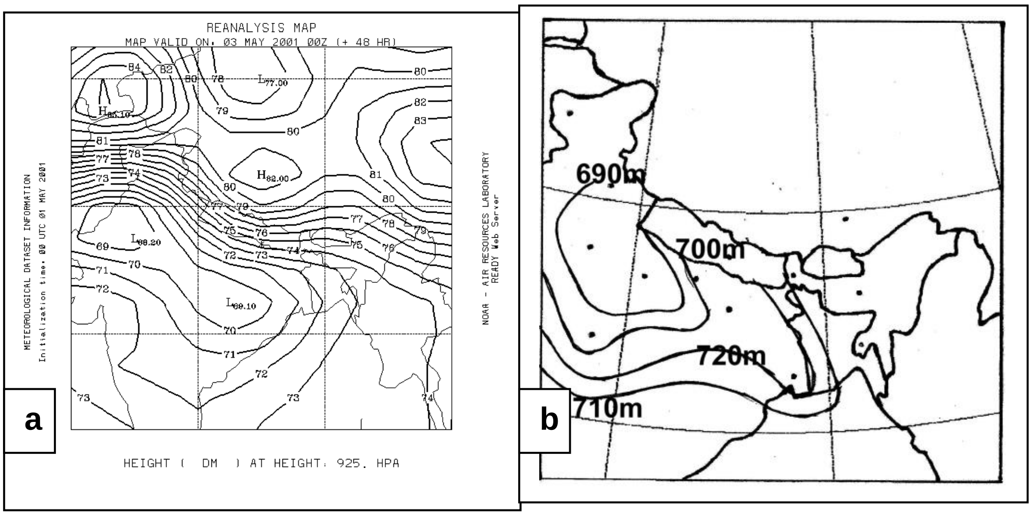


Figure 4.14 a and b. 00UTC May 3. 2001, 00UTC 925hPa geopotential heights (a). Contour interval is10m. Source: NOAA 6-hourly Reanalyses and (b), hand drawn 925hPa chart for wind speed and direction. Contour interval is 10m. Source: ESRL.

Despite the chaotic nature of the NOAA Re-analysis for 925hPa 00UTC May 3 due to the computers calculating heights differences in areas with elevations far above the 925hPa heights such as the Tibetan Plateau, the analysis results over the north Indian plains appear logical (Figure 4.14a). The NOAA computers calculated an enclosed, elongated low pressure area at 700m asl directly to the south of and parallel to Nepal, reaching across north India from the NW to the SE and approximately 2000km long. This region represents the low pressure field that becomes the monsoon trough in June (Figure 4.14b). The 682m asl center of this 925hPa low in the Lucknow and Delhi area is in alignment with the mid and upper tropospheric levels previously described. The latter 925hPa low pressure field together with the 925hPa low pressure field to the south of Patna are also the locations of the pre-monsoon surface heat lows.

In Figure 4.14b, the hand analyzed 925hPa geopotential heights are also deliberately not continuous and end at the barrier topography of the Himalayan Range. The 925hPa analysis confirms the extended northwest to southeast low pressure field over north India, The 925hPa, 690m high contour was drawn around Patiala, Delhi and Lucknow, the area of lowest pressure on the chart. Elevations of Delhi and Patiala are 216m and 251m asl respectively. The 700m contour begins northwest of Gwalior, passes south of Gwalior before continuing north and then east towards Patna. West of Patna, the contour follows a northwest direction before ending in the foothills of western Nepal. The 710m heights isobar parallels the 700hPa path, beginning west of Gwalior and continuing towards Ranchi, before curving around Calcutta and ending in the eastern foothills of Nepal, west of Siliguri. The 720m isobar parallels the 710m contour, and ends at Siliguri. Notable is the geopotential height difference between Lucknow, 684m asl and Gorakhpur, 705m asl, of 21 meters. Winds at Delhi were 4 knots from 235 degrees and increased to 10 knots from a 310 degree direction by 11UTC.

At Lucknow winds were 9 knots from a northeast, 55 degree direction; winds became easterly by 11UTC and decreased to 4 knots. The 925hPa winds at Gorakhpur were 17 knots from a 100 degree direction, suggesting an area of possible convergence east of Lucknow. By 11UTC, the Gorakhpur winds had decreased to 8 knots from the northeast, 30 degrees. The 00UTC winds at Patna were from 115 degrees at 7 knots. Winds at Ranchi were 6 knots from a 310 degree direction. The cyclonic direction of the 925hPa winds confirm the establishing of a very active surface heat low over Bihar. The Bihar surface heat low is not a stationary phenomenon. On May 3, 00UTC, the center of the low was located in the far southwestern corner of Bihar, much further west, approximately 250km, from its more usual location, southeast of Patna.

4.6.2 Negative Surface Pressure Tendencies

Table 4.2. 24 hour negative surface pressure tendencies in mb for 00UTC May 2 to 00UTC May 3, 2001. Source: ESRL and DHM

24 hr Negative Surface Pressure Tendencies in mb.
00UTC May 2 to 00UTC May 3

Delhi	Lucknow	Gorakhpur	Bhairawa	Simra	Patna	Calcutta
3	4	4	3	2.9	3	5

The 24 hour negative surface pressure tendencies for 00UTCMay 3 are shown in Table 4.2 and are further indications of an approaching low pressure field and of the widespread surface pressure decrease occurring across North India, with surface pressure values at Lucknow and Gorakhpur both dropping by 4 mb, Patna and Delhi by 3mb and Calcutta 5mb. The DHM data indicated a 2.9mb surface pressure decrease at Simra and 3mb at Bhairahawa.

4.6.3 Geopotential Heights Behavior

Identifying the eastward travelling path of an embedded low pressure short wave trough, also known as a “kink” in the isobars, can be challenging in the presence of missing, and/or vital upper air data. Geopotential heights charts indicate that at 00UTC May 3, such a low pressure trough existed just east of Delhi, which the IR images confirm. Most original North India upper air data for 11UTC May 3 was missing. Although the May 3 06UTC and 09UTC IR images show evidence of the embedded low pressure trough’s intensifying while progressing in an eastwards direction, because of the aforementioned shortcomings, the geopotential heights charts may not be completely accurate and cannot pinpoint precisely where the “kink” was located by May 3 11UTC or whether it had been travelling at all.

Geopotential heights tend to fall ahead of an advancing low pressure field. The following section investigates the geopotential heights’ decreases and increases (Guwahati data was missing) at low, mid and upper tropospheric levels, determining thereby the synoptic and mesoscale environments responsible for generating the severe potential atmospheric instability on May 3 not only at Thori, and along the foothills of the Himalayan Range, but along the entire length of the Gangetic Plains as well.

Table 4.3. Indicates the 00UTC May 2 to 00UTC May 3 changes in Geopotential heights in m asl. for Delhi, Lucknow, Gorakhpur and Patna. Source: ESRL

00UTC May 2 to 00UTC May 3 Geopotential Heights Changes in m asl

	Delhi	Lucknow	Gorakhpur	Patna
925hPa	-28	-42	-35	-24
850hPa	-31	-61	-44	-23
500hPa	-60	-130	-30	-30
300hPa	-130	-210	-40	-50
200hPa	m	-250	-10	m

Table 4.3 compares the pressure level changes for the North Indian stations for which data is available. Dramatic geopotential heights decreases occurred along the entire length of North India already between 00UTC May 2 and 00UTC May 3. Decreases in geopotential heights between 925hPa and 500hPa were most severe at Lucknow where the 925hPa decrease was 42m, the 850hPa decrease was 44m and the 500hPa loss in height was a dramatic 130m from 5870m at 00UTC, May 2. The 300hPa and 200hPa geopotential heights at Lucknow fell 210m and 250m respectively. Not all geopotential heights changes could be calculated at Delhi because of missing data, but the 60m drop at 500hpa and the 130m decrease at 300hPa at Delhi indicate dynamic change in the synoptic environment with the likelihood of severe potential atmospheric instability. The overall geopotential heights decreases at Gorakhpur, down 115m and Patna, down 104m, up to 300hPa, during this 24 hour period were less dramatic but no less significant in demonstrating significant changes in the synoptic environment, leading to severe atmospheric destabilization.

Table 4.4 Geopotential heights changes in m from 00UTC May 3 to 12UTC May 3, 2001 for Delhi, Lucknow and Gorakhpur. Source: ESRL

00UTC May 3 to 12UTC May 3 Geopotential Heights Changes in m asl

	Delhi, 12UTC		Lucknow, 12UTC		Gorakhpur, 12UTC	
925hPa	-13,	669m	-13	671m	-5,	700m
850hPa	-6,	1423m	+18	1433m	-7,	1441m
500hPa	+10,	5770m	+110	5850m	-10,	5790m
300hPa	+30,	9470m	+170	9620m	+10,	9570m
200hPa	m	12160m	+200	12380m	-10,	12310m

From 00UTC to 12UTC May3, Delhi, Lucknow and Gorakhpur data indicate continuing geopotential heights decreases at 925hPa of 13m, 13m and 5m respectively. At Gorakhpur the 500hPa geopotential height had decreased a further 10m by 12UTC to 5790m asl, suggesting that at 500hPa, the isobaric irregularity, the "kink" was still positioned west of the city. But at Lucknow, between 00UTC to 12UTC May 3, the geopotential heights appeared to have recovered at mid and upper tropospheric levels (Table 4.4). The Lucknow 500hPa geopotential height had gained an impressive 110m, to 5850m, indicating the strong likelihood for a new position of the embedded travelling low pressure trough in between Lucknow and Gorakhpur. Patna data was missing.

4.6.4 Interpolating 500hPa Geopotential Heights Chart for 11UTC May 3

This study makes an additional attempt to locate the eastward travelling 500hPa low pressure trough on May 3 at 11UTC, by interpolating from the 00UTC May 3 and 00UTC May 4 ESRL upper air data.

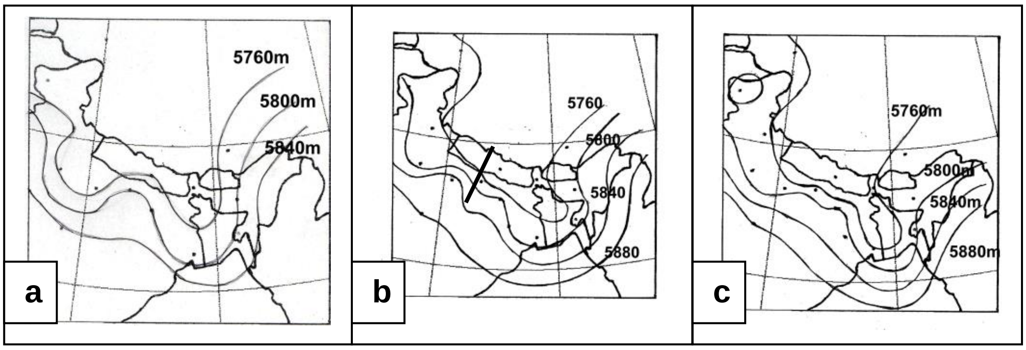


Figure 4.15.a, b and c. Hand analyzed 500hPa geopotential heights for 00UTC May 3, 2001 (a), 12UTC May 3, 2001(b) and for 00UTC May 4, 2001 (c). Contour interval 40m. Source: ESRL

The sequential hand analyzed 500hPa geopotential heights charts for 00UTC and 12UTC, May 3 and 00UTC May 4 are presented next. Of the fourteen upper air stations this study has used, 12UTC May 3, 2001 data from only five India stations, Shrinagar, Patiala, Delhi, Lucknow and Gorakhpur was available; Hotan (China) data was available, but not Lhasa, on the Tibetan Plateau. This study interpolated from 500hPa 00UTC May 3 and 00UTC May 4 Patna, Siliguri, Guwahati, Ranchi, Gwalior and Calcutta data to construct a geopotential heights analysis for 500hPa 12 UTC May 3 (Figure 4.15b)

The 00UTC May 3, 5760m geopotential heights contour which marks the low pressure trough in the Delhi area (Figure 4.15a) has moved north of Delhi and is replaced at 12UTC by the 5800m contour (Figure 4.15b). By 12UTC May 3, the 5760m contour enters India east of Patiala and descends southeastwards north of Gorakhpur, 5790m before curving in central Bangladesh towards the northwest towards Siliguri and then towards Lhasa. The previously indicated high pressure ridge at Gorakhpur, 00UTC, formed by both 5760m and 5800m geopotential heights contours has disappeared by 12UTC. After marking an area of high pressure slightly north of Lucknow (Figure 4.14b), both 5800m and 5840m, 500hPa contours display a southward shaped curve southeast of Gorakhpur, a “kink” before continuing in a south easterly direction towards the Bay of Bengal.

On 00UTC May 4, the 5760m heights contour enters India northeast of Patiala and continues south towards Lucknow. The contour then heads east towards Gorakhpur, now at 5770m, where it curves slightly northwards before descending into the now smaller “kink” in between Gorakhpur and Patna. At Calcutta, at 00UTC May 4, the 500hPa geopotential heights have fallen 50m to 5750m. The analysis shows a massive curved pre-monsoon low pressure trough over the Bay of Bengal, Bangladesh, Eastern Nepal and a section of India, typical of the season.

On 00UTC and 11UTC May 3, winds at Gorakhpur at both 500hPa and 400hPa were northwesterly at 40 knots. At 00UTC, the winds at Gorakhpur above 400hPa became southwesterly at slightly decreased speeds, except at 200hPa where the wind reached 50knots. Above Gorakhpur at 400hPa, by 11UTC May 3, winds remained westerly and wind speed decreased steadily.

Accurate knowledge of the potential vorticity values generated to the east of the trough axis drawn through the 5800m and 5840m geopotential heights contours in between Gorakhpur and Patna would have been very helpful for future forecasting purposes. 1kg hailstones at Thori close to midnight on May 3 imply that most, if not all, known severe thunderstorm enhancing mechanisms were in place.

4.6.5 Upper Air Temperatures at Gorakhpur/Thori

Table 4.5. 925 to 100hPa temperatures in Centigrade at Gorakhpur from 00UTC April 30 to 00UTC May 4, 2001. Source: ESRL

	Apr 30 00UTC	**May 2 00UTC**	**May 3 00UTC**	**May 3 11UTC**	**May 4 00UTC**
925	26.0	27.6	**27.2**	**26.2**	**25.2**
850	22.8	25.6	**22.0**	**21.0**	**20.0**
700	9.8	**9.6**	11.8	**11.6**	**8.9**
500	-10.5	**-10.7**	-10.1	-8.9	**-12.0**
400	-23.9	-18.9	**-19.3**	-19.1	**- 21.8**
300	-38.5	-33.3	-33.3	**-33.5**	**- 35.1**
250	-44.1	-42.3	-39.9	**-41.1**	-40.0
200	-49.7	**-53.3**	-49.7	**-52.3**	-49.3
150	-60.9	**-62.1**	**-62.3**	**-65.3**	-62.2

The vertical temperature profiles at Gorakhpur for 00UTC April 30 to 00UTC May 4, 2001 are indicated in Table 4.5 The available 11UTC May 3 temperature data was also included in the chart. Values in bold face signify a temperature decrease from the previous measurement period at the same level. Subtle temperature decreases of about 2^{o}C at low tropospheric levels, 925hPa and 850hPa had occurred by 00UTC May 4. The 700hPa temperature dropped 2.9^{o}C during the 24 hour period before 00UTC May 4, while the 500hPa temperature dropped 3.1^{o}C between 11UTC May 3 and 00UTC May 4. At 400hPa and 300hPa, temperatures decreased 2.7^{o}C and 1.6^{o}C respectively between 11UTC May 3 and 00UTC May 4. Table 4.5 illustrates significant warming between 11UTC May 3 and 00UTC May 4, at upper tropospheric levels, 250hPa to 100hPa. During the latter 13 hour period, warming at 100hPa was most dramatic with the temperature increasing from -77.9^{o}C to -64^{o}C.

4.7 Moisture Advection for Thori

Table 4.6 a. 925hPa 00UTC April 30 to May 4 2001 Temperatures and Dewpoint Temperatures in centigrade for Delhi, Lucknow, Gorakhpur, Patna and Calcutta. Source: ESRL archives.
Table 4.6 b. 925hPa, 00UTC April30 to May 4, 2001 wind speed and direction for Delhi, Lucknow, Gorakhpur, Patna and Calcutta.

925hPa 720m asl 00UTC Temperatures and Dewpoint Temperatures in Degrees Centigrade

	Delhi	Lucknow	Gorakhpur	Patna	Calcutta
	T TD	T TD	T TD	T TD	T TD
April 30	30.2, 10.2	29.2, 1.2	26.0, 25.9	29.4, 28.1	24.2, 23.9
May 1	33.6, 20.6	26.0, 21.0	m	25.4, m	26.6, 24.3
May 2	30.2, 7.2	30.0, 16.0	27.6, 27.5	22.8, 22.7	25.4, 20.6
May 3	28.8, 10.8	21.6, 15.6	27.2, 19.2	24.2, 17.2	25.6, 23.7
May 4	29.6, 4.6	26.8, 16.8	25.2, 22.2	23.2, 16.2	22.6, 13.6

(a)

925hPa 720m asl 00UTC Wind Speed and Direction

	Delhi	Lucknow	Gorakhpur	Patna	Calcutta
	kts, degr.	kts, degr.	kts, degr.	kts degr.	kts degr.
April 30	9, 275	13, 55	20, 110	13, 120	30, 190
May 1	15, 300	12,145	m	17, 130	10, 160
May 2	6, 335	14,150	20, 80	18, 145	19, 220
May 3	4, 235	9, 55	17, 100	7, 115	10, 155
May 4	16, 200	9,140	14, 120	16, 300	7, 265

(b)

The cyclonic circulation of the Bihar surface heat low provides the mechanism for the transport of humid air from the Bay of Bengal to the North Indian Gangetic Plains in the west and to the foothills of the High Himalayas. The humid air is then further advected in a westerly direction into Nepal's mountainous terrain by the diurnal mountain – valley circulation. For optimum warm air and moisture advection into the foothills of the High Himalayas, the combination of daytime up- valley winds plus warm, moist southeasterly lower tropospheric flows from the south of Nepal, e.g from Patna and Gorakhpur is ideal.

High 925hPa dewpoint temperature values averaging 21°C at Calcutta, 21.3°C at Patna, 23.7°C at Gorakhpur are indicated in Table 4.6a for the period 00UTC April 30 to 00UTC May 4. At Delhi and Lucknow the dewpoint temperatures averaged 10.7^oC and 14^oC respectively for the same period.

With minor variations, 925hPa wind directions at Gorakhpur were consistently easterly in a counterclockwise direction from the Bihar heat low, at speeds from 14 to 20 knots (Table 4.6b). At Gorakhpur on May 2 winds were straight easterly at 20 knots with a dewpoint of 27.5^oC, while at 00UTC May 3 winds were 17 knots from 100 degrees, with the dewpoint temperature dropping almost 10 degrees centigrade to 19.2^oC. Not included in the above charts because of missing data from other stations was the 11UTC Gorakhpur 925hPa dewpoint temperature of 18.2^oC. The latter, in addition to the severe potential instability already present, was likely a significant factor contributing to thunderstorm initiation at Thori in the late afternoon.

At Patna (Table 4.6b) 00UTC on May 2, the 925hPa winds were southeasterly, from 145 degrees at 18 knots and the dewpoint temperature was 22.7^oC. At 00UTC May 3, the Patna wind direction changed to easterly, 115 degrees and the wind speed had dropped dramatically to 7 knots. On May 4, 00UTC, the Patna winds indicate a notable change from the usual easterly direction to westerly, 300 degrees at a speed of 16 knots.

The 925hPa dewpoint temperatures at Calcutta were, in spite of the consistent southerly and easterly wind direction components and high wind speeds from 10 to 30 knots between April 30 and May 3, considerably lower than those at Gorakhpur.

Winds at Lucknow were northeasterly, 55 degrees, on April 30 and May 3 at 13 and 9 knots respectively. On May 1, 2 and 4 the Lucknow wind speeds were 12, 14 and 9 knots respectively, from the southeast accompanied by dewpoint temperatures of 21^oC and 16^oC on May 1 and 2. Lucknow and Delhi 925hPa winds were directly opposite on May 1, 2 and 3 (Table 4.6b). ; e.g., on May 3, at 00UTC the Delhi wind direction was from 235 degrees, with a dewpoint temperature of 10.8^oC and the Lucknow direction was from 55 degrees with a dewpoint temperature of 15.6^oC. The resulting convergence, slightly southwest of Delhi, visible in the IR images beginning at 06UTC (1145NST) May 3, evolved into the MCS that began travelling eastwards by 1915NST and produced Thori’s violent weather.

4.7.1 Mesoscale Convective Systems and the Low Level Jet

Studies have shown that MCCs and MCSs are most prolific on the east side of south to north mountain ranges, such as the Rocky Mountains in the US where the fast, westerly flows are lifted orographically and converge several hundred kilometers east of the Rockies. Such lee-side convergence has been found to be closely connected to the initiation of Mesoscale Convective Systems. The initial convective activity that preceded the formation of the MCS on May 2, 2001 over the Thar Desert may well have been the result of lee-side convergence from mid and upper tropospheric northwesterly winds passing over the Hindu Kush in Afghanistan and Pakistan. The distance, 500km, between the likely location of the lee-side convergence, beginning 008UTC May 2, in this study and the 5000m asl plus mountain ranges to the northwest in Afghanistan is remarkably similar to that in the US. The MCSs that generate tornadoes over Oklahoma, all had their origins about 450km east of the Rockies.

Briefly described in Section 2, most MCSs have the following characteristics:

- They are very large complexes, with a combination of both convective and stratiform clouds. Supercells can be embedded in the system.
- The convective clouds lead the system as it travels and propagates, creating a “convective line”, which can be convex or concave.
- They begin as individual cells at midday, merge and propagate into larger clusters and reach maximum size around midnight, often producing large hail.
- They also require a constant source of low-level, warm, humid air in the form of a low-level jet, so that convection can be initiated above the surface and above the nighttime stable planetary boundary layer.
- They tend to propagate parallel to 1000-500hPa thickness contours and high Theta-E levels.

The existence of a nocturnal low- level jet, a thin, moving ribbon of air that may or may not be within the stable planetary boundary layer and that can accelerate at speeds of up to 30 knots was confirmed in the 1950’s in North America when studies were being conducted concerning the elevated convection occurring in multi- cell thunderstorms east of the Rocky Mountains late at night (the Great Plains nocturnal jet). The low-level jet can be a daytime phenomenon as well. Both are associated with several causes, the most significant for this study being the synoptic-scale horizontal temperature gradients over sloping terrain. Low-level jets have been reported at heights of up to 900m asl. The nocturnal low-level jets fuel the initiation of nighttime elevated convection, multi-cell thunderstorms, or Mesoscale Convective Systems when daytime thermodynamic surface heating cannot occur.

One of the criteria that is used to distinguish the jet is that it has a speed maximum of more than 2m/sec (4 knots) faster than the wind speeds directly above it and that the latter is below a height of 1500m asl.

Isolating wind speed differences between 925hPa and 850hPa, and using the above criteria, this study found the following:

Delhi – 925hPa wind speeds higher than 850hPa on 00UTC April 30, May 1, May 4 and at 11UTC on May 2. Wind directions northwest.

Lucknow – 925hPa wind speeds higher than 850hPa on 00UTC May 1 and May 2, (twice as fast) and May 4. Wind direction, southeast. May 3, wind direction northeast.

Gorakhpur – 925hPa wind speeds higher than 850hPa on 00UTC on April 30, 20 knots (almost three times faster), May 2 twice as fast at 20 knots. May 1 and 4 wind data missing. Wind directions from the east.

Patna – 925hPa wind speeds higher than 850hPa on 00UTC April 30, four times faster. May 1 twice as fast, May 2 twice as fast, May 3 twice as fast. Wind directions, southeast.

The above description suggests that nocturnal low-level jets are generated over the Gangetic Plains. With the exception of Delhi, the direction of the low-levels jets described in the above section parallel the direction of the cyclonic circulation of the Bihar surface heat low at 925hPa. This study assumes that the fast 925hPa wind speeds at e.g. Gorakhpur are perhaps a combination of both mesoscale features, with the nocturnal low-level jet augmenting the circulation from the Bihar surface heat low. The above description also indicates that at Gorakhpur, the station nearest to Thori, on 00UTC May 3 the 925hPa wind speeds did not exceed those at 850hPa. The 925hPa wind speed was 17 knot from the east with a dewpoint temperature of 19.2^{o}C. However, the 850hPa wind speed on 00UTC May 3 was 22 knots, from the same direction with a dewpoint temperature of 16^{o}C. Temperatures at 925hPa and 850hPa were 27.2^{o}C and 22^{o}C respectively, providing a reliable supply of warm, humid air.

At 11UTC (1645NST) May 3, the leading edge of the MCS was directly over Lucknow, where the ESRL data indicate a plentiful supply of warm, humid air at both 925hPa and 850hPa. The 925hPa winds were 4 knots from 115 degrees with a dewpoint temperature of 22.2^{o}C and temperature of 34.2^{o}C. The 850hPa winds were 11 knots from 200 degrees with a dewpoint temperature of 18.4^{o}C and a temperature of 29.4^{o}C. Surface winds were 0, the surface temperature was 35^{o}C and the dewpoint temperature was 21^{o}C, 1.2^{o}C lower than at 925hPa. At Gorakhpur, 11UTC, low level wind directions had changed to northerly at 7 knots, although temperatures and dewpoint temperatures at 925hPa and 850hPa had changed very little. The Gorakhpur low-tropospheric change of wind directions from easterly to northerly may be reflecting the arrival of the embedded short-wave trough or "kink" that was indicated in the 500hPa 11UTC geopotential heights analysis. By 00UTC May 4, the 925hPa Gorakhpur winds had resumed their southeasterly direction, from 120 degrees, at 14 knots, with a temperature of 25.2^{o}C and a dewpoint temperature of 22.2^{o}C. Patna data for 11UTC May 3 was missing, but on May 4, 00UTC the data indicate warm, humid air from a 300 degree direction at 16 knots.

When at 1915NST(1330UTC), the MCS begins intensifying and moving eastwards at speeds of up 70km/hour , the upper tropospheric westerly winds steer the system south of and parallel to the barrier created by the High Himalayas, in a 310 – 130 degree direction. The low-level tropospheric environment of the Gangetic Plains in which the MCS is travelling and intensifying and which is continuously supplying the system with warm, humid air may not have done so at first via the mechanism of a single consistent nocturnal low-level jet. Warm, humid air was plentiful and may have been drawn into the updrafts of the propagating cells from different directions, including north and south as well as east, until the nocturnal easterly low-level jet, as indicated in the Gorakhpur data, had become well established. S.F. Corfidi in "Weather and Forecasting", suggests that, "The speed of MCS motion was found to be modulated by the location of maximum low-level moisture convergence relative to existing convection." Studies have shown that nocturnal low-level jets reach their maximum speeds about midnight, which coincides with the time of the Thori hail storm. .

4.8 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 4.7. 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. Source: ESRL and DHM

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

Table 4.7 shows 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 dewpoint temperatures for Thori (Simara/Bhairahawa) were 29°C and 22.6°C respectively; surface winds were 5 m/sec from a 120 degree direction. Dewpoint values of -273.1°C at 400hPa and higher indicate levels of extremely dry air that the radiosonde does not record.

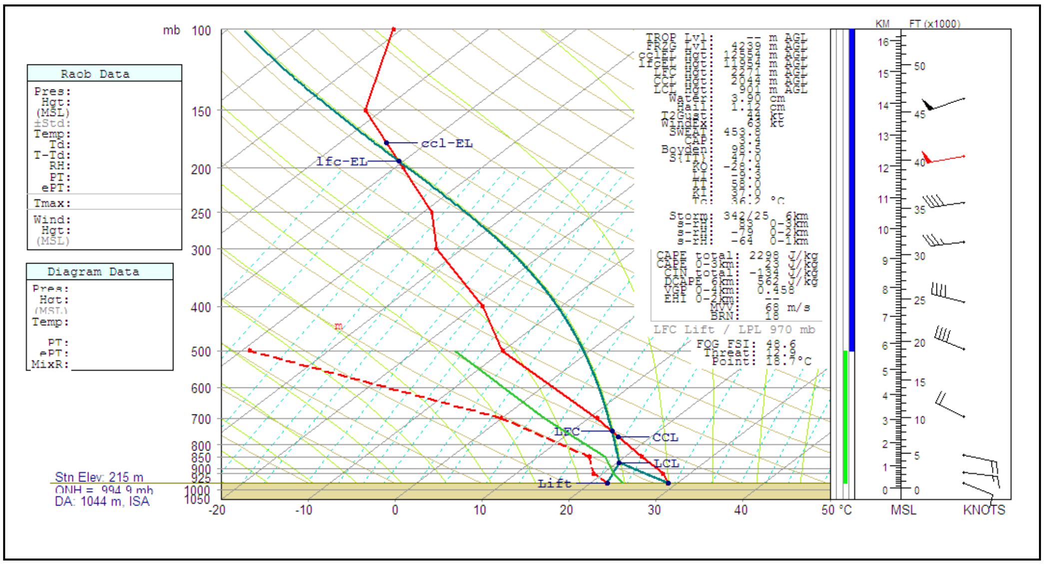


Figure 4.16. Skew-T log P chart for Thori, 00UTC May 3, 2001 including Stability Index calculations. Source: ESRL and DHM

The Skew-T log P chart for Thori calculated with the RAOB.ERS computer program for 00UTC May 3 using the data in Table 4.7 is shown in Figure 4.16. 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 SkewT 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^{o}C. Negative CAPE (CIN) is -134J/kg and the convective temperature (Tc) is 36.2^{o}C. The maximum surface temperature for Simra on May 2 was 33.2^{o}C (maximum surface temperature data missing for May 3) and for Bhairahawa the maximum temperatures for May 2 and May 3 were 34.2^{o}C and 35.5^{o}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^{o}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^{o}C and -30^{o}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 many reports of the storm's devastation leads 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.

Table 4.8. Original 11UTC May 3 Gorakhpur ESRL upper air and 12UTC Bhairahawa DHM surface data. Source: ESRL and DHM

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

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 4.8) 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. The Lifted Index, however was -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 4.8). 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.

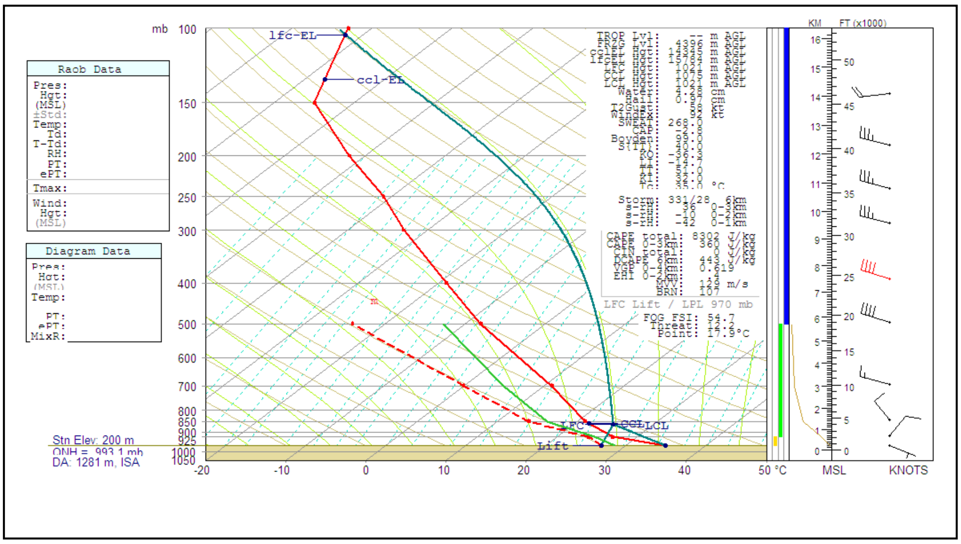


Figure 4.17. Stability Index calculations for Thori, 11UTC May 3, 2001. Source: ESRL and DHM

Figure 4.17 shows the Skew-T log P chart and stability index calculations for Thori, 11 UTC May 3, using the data of Chart 4, except for the 100hPa temperature, which this study was forced to increase by 4^{o}C from -77.9^{o}C to -73.9^{o}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^{o}C, predicted hail size was .97cm, 8cm before melting and precipitable water was 4.28cm. 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 SkewT diagram with the area where the most intense CAPE and therefore the strongest updraft are located.

Table 4.9 00UTC and 11UTC May 3temperature and dewpoint temperature comparisons in Centigrade for Thori. Source: ESRL and DHM

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

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 4.9). 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. The data show a gradual temperature decrease at the upper tropospheric levels, beginning at 250hPa with a small temperature decrease, 1.2^{o}C, from -39.9^{o}C to -41.1^{o}C. The 200hPa temperature fell 2.6^{o}C from -49.7^{o}C to -52.3^{o}C and the 150hPa temperature dropped 3^{o}C to -65.3^{o}C. At 100hPa the temperature decrease was 6^{o}C, to -77.9^{o}C.

At 00UTC, the 500hPa dewpoint temperature was low, -39.1^{o}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^{o}C to -24.9^{o}C. Again, the data indicate the higher tropospheric levels to be extremely dry and therefore not recorded.

Table 4.10 00UTC and 11UTC May 3, 2001 wind speed and wind direction comparisons for Thori / Gorakhpur. Source: ESRL and DHM

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

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 4.10). 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^{o}C, undoubtedly enhancing existing moisture convergence at Thori.

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 and 18UTC (1115NST and 1145NST).

CAPE values of both 00UTC and 11UTC soundings were more than adequate to sustain large hail growth. The 11 UTC 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.

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.

Table 4.11 a and b. Thori/Gorakhpur 11UTC May 3 and 00UTC May 4 2001 surface and upper air data. Source: ESRL

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)

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)

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 SkewT logP chart and the profiles drawn, the mandatory level values were easily located (Table 4.11b).

Significantly colder air had arrived by 00UTC May 4 at mid- and upper tropospheric levels, between 700hPa and 300hPa (Table 4.11a and b). Temperatures at 500hPa had decreased 3.1°C from -8.9°C to -12°C and at 300hPa the temperatures dropped 1.6°C to -35.1°C. A warming trend, however, was indicated at the higher tropospheric levels, beginning at 250hPa, where the temperature increased 1.1°C. At 200hPa the temperature increased by 3°C to -49.3°C from – 52.3°C, at 150hPa by 3.1°C to -62.2°C and at 100hPa, the 11UTC May 3 temperature of -77.9°C increased a surprising 13.9°C to -64°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°C to -15°C and -0.4°C to 2.1°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.

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 SkewT-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 4.12 Upper air data for Thori averaged from 11UTC May 3 and 00UTC May 4 Gorakhpur. Source: ESRL

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

Table 4.12 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.

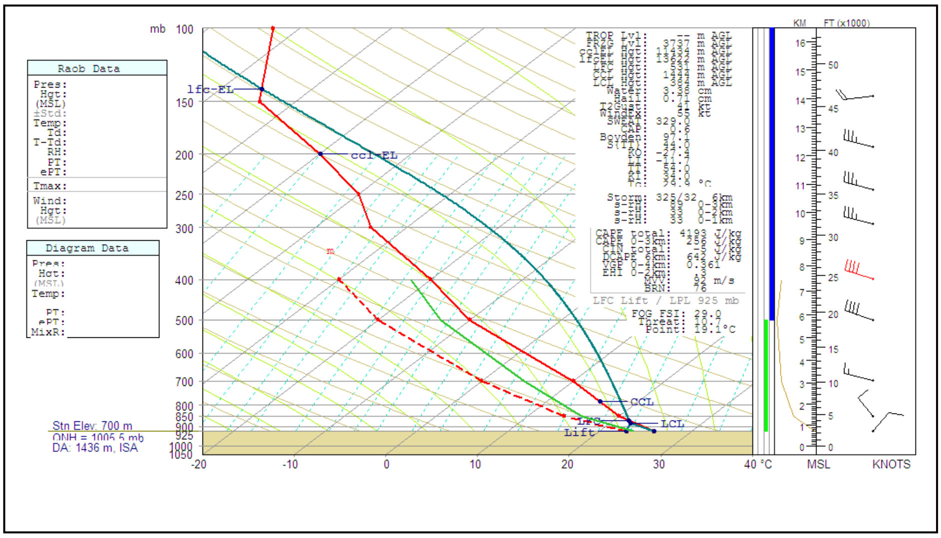


Figure 4.18. SkewT logP chart and Stability Index calculations for Thori elevated convection from 925hPa at 1730UTC May 3, 2001. Source: ESRL and RAOB ERS. File 3A

The Stability Indices calculated by the RAOB program for Thori for 1730UTC May 3 from the SkewT logP chart in Figure 4.18 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 71cm after melting. The steepest lapse rates were between 700hPa and 500hPa, 7.7^{o}C and 400hPa to 300hPa, 7^{o}C respectively, somewhat steeper than the lapse rates calculated for 11UTC. The wet bulb zero level lowered the freezing level, 0^{o}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 very likely that the first storm 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, 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.

4.9 Thori Overview, Discussion and Summary

4.9.1 Infrared Satellite Images

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.

4.9.2 Synoptic and Mesoscale Observations

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.

Decreasing geopotential heights at all tropospheric levels on May 3, in addition to a small "kink" at 12UTC in the interpolated 500hPa geopotential heights chart with a trough axis positioned between Gorakhpur and Thori, are indicative of a small, eastward travelling, embedded short-wave low pressure trough.

Wind speeds on May 3 at 500hPa and 400hPa at Gorakhpur were more than 40 knots leading to high vorticity values in the foothills of the Himalayas and at Thori. Two data points in the May 2 Delhi soundings, at 00UTC and 11UTC note wind speeds of 120 knots at 158hPa (13890m asl) and 106 knots at 134hPa (14929m asl). On May 3 at 11UTC, at 172hPa (13114m asl) the wind speed was 83 knots. Although the wind direction was missing for all three, thunderstorm enhancement resulting from the divergence caused by these high speed upper tropospheric winds was likely. The data also indicate the arrival of very cold air aloft e.g., at Gorakhpur where the 100hPa temperature fell 6°C to -77.9°C by 11UTC May 3. The 500hPa isotherm chart for 00UTC May 3 indicates further significant cold air advection. The data have shown ample moisture availability at the surface and low tropospheric levels, advected from the Bay of Bengal by the Bihar surface heat low. Geopotential heights charts constructed for 850hPa and 925hPa, further emphasize the atmospheric instability across the Gangetic Plains and foothills in Nepal. The data indicate negative 24 hour surface pressure tendencies of up to 5 mb across northern India and at Thori (Simra). At both Simara and Bhairahawa, surface data indicate a large increase of dewpoint temperatures, to 27.4°C by 12UTC, winds from the east and southeast, and high daytime maximum temperatures. The Thori area was well within the Bihar surface heat low circulation. In the Himalayan foothills, the daytime up-valley flows occur at Thori as well, with the thermally driven diurnal flows beginning between 800NST and 900NST at very low wind speeds of not more than 2 knots and maximum wind speeds reached by mid-afternoon. 10 knot, southeast, humid winds at 845NST suggest an ample moisture source for Thori at the surface and at low tropospheric levels supplied by cyclonic circulation of the Bihar surface heat low. The latter, plus lifting enhancement provided by the "kink" at 500hPa, in addition to the likely explosive nature of the breaking of the capping inversion by convective cell propagation over the foothills to the west, resulted in Thori's first thunderstorm just before sunset.

4.9.3 MCS and the Low level Jet

Thori's second and considerably more severe thunderstorm occurred within a MCS that reached the Thori area close to midnight on May 3 after crossing the Gangetic Plains and the western half of Nepal at speeds of up to 70km per hour. The synoptic and mesoscale environment of the Indian sub-continent of May 2 to early May 4, 2001, favored all essential conditions for organized thunderstorm formation and eventual MCS genesis, beginning with the initially topographically induced lee-side convergence on May 2 over the desert that Pakistan shares with India. To the west, the India side of the desert, the Thar Desert is the location of the pre-monsoon primary surface heat low, where a heat-driven surface and low-tropospheric counterclockwise circulation is initiated in early April. The quickly evolving and intensifying convective cells illustrated in the IR images beginning at 08UTC, mid-afternoon on May 2, testify to the presence of all required thunderstorm ingredients, a source of moisture, at or near the surface, cold air aloft and a “trigger” mechanism that initiates the convective activity. When the organized cluster of convective cells had reached MCS size by 14UTC, it was still located over the desert in Pakistan.

This study assumes that during the day over desert-type terrain in Pakistan, a highly stable boundary layer settles above the hot surface, creating a strong capping inversion in the process. Maximum surface temperatures in the Thar Desert have been known to reach 50^{o}C in May, resulting in high temperatures at 925hPa and 850hPa. Therefore, considering a strong capping inversion, the likely lack of moisture, surface heating initiated convection for the initial convective activity is unrealistic. This study suggests that the initial topographically induced lee-side convergence received strong, dynamic upper air support from an embedded short wave trough that was identified in the synoptic section of this paper for 00URC May 3. Also, this study identified in the Delhi ESRL data for 11UTC May 2, a daytime 925hPa jet at 16 knots from a northeast 20 degree direction, with a temperature of 35.6^{o}C and a dewpoint temperature of 15.6^{o}C. At 850hPa, the wind direction was from the northwest, 315 degrees, at 13 knots, with a temperature of 27.6^{o}C and a dewpoint temperature of 12.6^{o}C. The 925hPa and 850hPa Delhi data suggest that daytime elevated convection may have occurred, with moisture advection from a strong daytime low level jet. ESRL data from Jodhpur, located in southeast Rajasthan indicate several instances between April 30 and May 4 where the 00UTC 925hPa winds were faster than both the 850hPa and 700hPa winds. Therefore, the likely establishing later in the evening of a nocturnal low level jet, allowed the intense, organized convective cells to be maintained until midnight May 2, by which time the thunderstorm cluster had attained MCS dimensions, crossed into India and was positioned directly above the pre-monsoon primary surface heat low, an event that occurs very infrequently.

The May 2 storm cluster (MCS) had dissipated significantly by 00UTC May 3. By early afternoon, May 3, the 00UTC storm cluster had intensified into a very large cloud shield with MCS dimensions and was located over Delhi. The MCS had been propagating eastwards towards Delhi as a result of (1), more abundant moisture availability, (2), dynamic mid and upper level tropospheric lifting mechanism provided by and eastward travelling embedded short wave trough, (3) steering by the upper tropospheric winds and (4), divergence from subtropical jetstream level winds indicated in the Delhi wind data. The increased convective activity over the Gangetic Plains and the foothills of the High Himalayas by 11UTC May 3 testifies to the increase of moisture availability during the day, the enhanced lifting mechanism caused by vorticity from the eastward travelling “kink” in the isobars and the cold temperatures aloft, resulting in the pervasive atmospheric instability in the entire region and also resulting in Thori’s first thunderstorm by 1815NST.

When the May 3 MCS began propagating and travelling eastwards by 1915NST (40 minutes after sunset), a nocturnal low level jet, supplying warm, humid air at low tropospheric levels for elevated convection, would not likely have been established. However, low level winds from within the sphere of the counterclockwise circulation determined by the Bihar surface heat low, could easily fulfill the same function and provide a constant moisture source for the propagating convective cells and for convection from outflow boundaries until the establishing of the nocturnal low level jet. 00UTC wind data from Gorakhpur described in a previous section indicates the existence of a strong nocturnal low level jet at 925hPa that likely reached maximum speeds at midnight, the time of Thori’s devastating hailstorm.

4.9.4 Stability Indices

Stability Indices (SI) calculated for Thori, using Gorakhpur ESRL upper air data and DHM Simra and/or Bhairahawa surface data for 00UTC and 11UTC May 3 confirmed the atmospheric instability described earlier. At 00UTC, CAPE and potential updraft velocity were 2298J/kg and 68m/sec respectively. The negative CAPE of -134J/kg and the capping inversion that it implied would likely no longer be valid later in the day when both surface temperatures and dewpoint temperatures are expected to rise.

SI calculated for Thori with the 11UTC upper air Gorakhpur data took into account the complex terrain surrounding Thori and its likely effect on daytime temperature and dewpoint temperature increases at low tropospheric levels. Surface temperature and dewpoint temperature at Thori/Bhairahawa were 35.5°C and 27.4°C respectively. The resulting SI were, CAPE 8320J/kg, no negative CAPE, Lifted Index -14.9 and a potential maximum velocity of 129m/sec, capable of sustaining large hail growth. The freezing level and the Wet Bulb Zero levels went up, because the 500hPh temperature at Gorakhpur had increased by 1.2°C.

To calculate SI indices for 2330NST May 3, this study averaged the 11UTC May 3 upper air data with that of 00UTC May. Assuming elevated convection, the calculations began at 925hPa, 500m above the Thori elevation of 215m asl. Very high CAPE, 4193J/kg was indicated, a Lifted Index of -11.7, and a maximum vertical velocity of 92m/sec. Lapse rates above 500hPa were slightly steeper than at 11UTC; the hail growth zone -10°C to -30°C was located in the area of thickest CAPE on the SkewT Log P chart.

In spite of the fact that the 11UTC SI calculations indicated potentially more severe weather than the calculations for midnight on May 3, the first thunderstorm, also clearly visible in the IR images, was not as violent as the second. When the first storm occurred, about 1815NST, the villagers would have been able to inspect their fields for hail damage, because it was still light. Also, two severe storms in one day would have been mentioned in the local newspaper article (Appendix 2). It is likely that the short duration of the first thunderstorm, the result of a propagating parent storm to the west, inhibited large hail growth.

The second and very destructive Thori storm, had its origins along the convective line of an eastwards travelling MCS, propagating towards the constant moisture supply of the Bihar heat low, combined with a nocturnal low level jet from the southeast. Consequently, it is possible that low tropospheric level dewpoint temperatures were higher than indicated in the SkewT logP chart, raising potential SI severity values, but actual data for this is not available. With the advantage of feeder cells nearby, and enough time to establish an intense, wide, tilted updraft where large hail growth proceeded without interruption, the midnight Thori hailstorm, unfortunately for the villagers, had turned into a historically destructive event.

Gorakhpur data at 00UTC May 3 for 925hPa (700m asl) indicate 17 knot winds from a 100 degree direction with temperature and dewpoint temperatures of 27.2°C and 19.2°C respectively. At 12UTC, 1745NST May 3, Thori (Bhairahawa data, Simra missing) surface winds continued from the southeast at 5 knots and the dewpoint temperature had increased to 27.4°C. Maximum surface temperature for May 3 was 35.5°C indicating adequate surface conditions for destabilizing the atmosphere and thunderstorm initiation. The thunderstorm in the Thori area indicated by large, bright, white dots in the IR images between 1715NST and 1815NST attests to the existence of sufficiently cold air aloft.

The sequence of IR images, beginning at 630UTC, 1215NST on May 2, illustrates the evolving of a cluster of organized thunderstorm cells into a MCS of at least 200km in diameter by 045NST May 3 over the Thar Desert in Rajasthan, India. The location of the MCS is also the location of the pre-monsoon primary surface heat low on the sub-continent. The solitary nature of the MCS testifies not only to the lack of low level moisture in the desert, but also to the likely existence of localized dynamic lifting mechanisms at upper tropospheric levels, such as positive vorticity advection (PVA) generated by an embedded low pressure trough. The MCS has dissipated into a small cloud cluster by 00UTC, 0545NST May 3, when it begins intensifying, and moving.

There are 2 travelling situations travelling eastward. The kink and the MCS. The MCS needs a potentially unstable atmosphere, with sufficient moisture several hundred meters above the surface, so the elevation convection can occur together with cell propagation from gust fronts

In the east, a low pressure trough, centered over Bangladesh and Calcutta and stretching from the northwest to the southeast, a usual pre-monsoon feature, was settled at all tropospheric levels.

Furthermore, the data show that the location of the initial May 2 multi storm cluster over the Thar Desert was positioned very close to or possibly directly above the pre-monsoon primary surface heat low. In the very few cases where the surface heat low receives upper air support, a highly active storm system is likely to develop.

In a country such as Nepal, where the Himalayan Range has created some of the most complex terrain found on this globe and where the meteorological infrastructure is still in its infancy, attempts to analyze fully and describe the conditions preceding the Thori storm can be frustrating at best. The Thori village and its very near surroundings are known locations for destructive hail, but 1 kg hailstones were a rarity. The question arises therefore: "What made this storm different and apparently worse than anything the villagers had experienced before?

All severe thunderstorms enhancers must have been in place for some time. Very large hail, from embryo stage in possibly a neighboring cell, to the cell directly above Thori, is not likely to be generated within a time frame that is less than 60 to 90 minutes.

The solitary cloud cluster to the west of Delhi on the IR image for 045NST May 3 (Figure 4.3) indicates that a strong lifting mechanism must have been in place already the previous day. The IR images for May 2 show convection not beginning until mid-afternoon the presence of a strong dynamic lifting mechanism. In the ESRL 00UTC (0545NST) May 2, 2001 Delhi upper air wind profile, two data points stand out: 53 knots from a 280 degree direction at 200hPa (12310m asl), followed by 120 knots (direction missing), 1500m higher, at 158hPa (13809m asl). In the 11UTC May 2 Delhi upper air profile, winds at 300hPa were 55 knots from 275D, at 250hPa winds increased to were 76 knots from275D, at 200hPa winds were 83 knots from 275D, at 150hPa (14240m asl) winds were 89 knots from 270D and at 134hPa (14929m asl) wind speed increased to 106 knots (direction missing). By comparison, at Gorakhpur wind speed at all upper air levels, was less than 39 knots on May 2.

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 this time the characteristic Mesoscale Convective System (MCS) behavior of the cloud cluster is becoming evident. This includes not only the size of the system, but also its cell propagation and intensifying long after sunset, at night when surface based convection is no longer possible.

A constant supply of warm, humid air at low tropospheric levels so that elevated convection can be initiated. The source of humid air is usually a low level jet, at approximately 925hPa (700m asl), that can attain speeds of 20 knots. MCSs that propagate and cause severe storms late at night, are usually fuelled by a nocturnal low level jet. The MCS in the above IR images may have started propagating before a nocturnal low level had been fully established. The IR images jet system. The jet can be nocturnal forms in the low level warm, humid air and the necessary establishing of a low level jet as a constant source of low level warm, humid air so that elevated convection can be initiated.

CHAPTER 5

POKHARA HAILSTORM

5.1 General Information

On May 18, 2005 at approximately 330pm a severe thunderstorm struck Pokhara. Hailstones, estimated at 1kg caused considerable destruction, including damaging 1000 cars, within a period of about 15 to 20 minutes. One person was killed. 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. As the storm moved south eastwards, the hail stones became more varied and irregular in shape and size, 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.

Pokhara is situated in the Himalayan foothills at about 800m asl. The city is a popular holiday and tourist destination located at 28^{o}N and 84^{o}E. Pokhara is about 140km to the west of Kathmandu and is directly 25 km south of the Annapurna massif. Pokhara is the gateway to several major tourist destinations in western Nepal.

Thunderstorms without hail had occurred in the late afternoons of May 16 and 17. The Pokhara valley is surrounded in the east, north and northwest by high mountains. These act as barriers and induce precipitation from orographically lifted humid air. Precipitation results also 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. Inhabitants of Nepal’s rural areas have become accustomed to almost daily thunderstorms during the month of May, with accompanying lightening and often hail. Still, the destruction of the May 18 afternoon storm was completely unexpected.

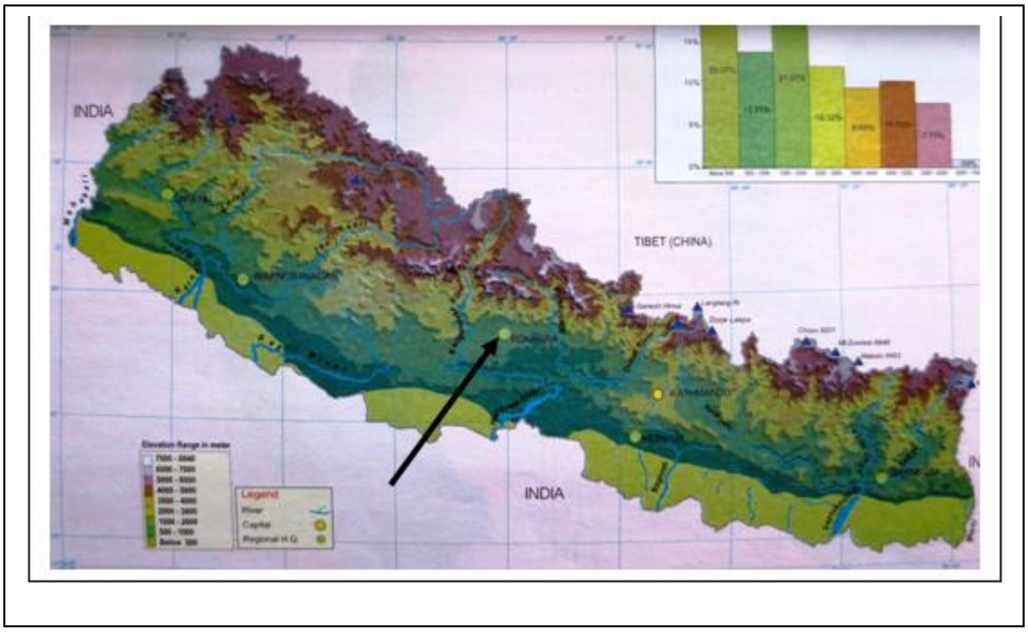


Figure 5. 1 Map of Nepal. Elevations are noted at left bottom. Pokhara is indicated with an arrow.

5.2 Pokhara Airport DHM Synoptic Surface Data for May 18 2005

5.2.1 Surface Temperature and Dewpoint Temperature

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°C 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°Cand 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

5.2.2 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.

5.2.3 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.

5.2.4 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 $2/8^{th}$ with cloud types consisting of mostly cumulus (Cl) but also some thin stratocumulus (Cm) 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 $1/8^{th}$ consisting only of fair-weather cumulus with an observed cloud base at 600 – 1000 m agl (Code 5); visibility was 10km.

From 0845NST to 1145 NST the total cloud amount remained at $1/8^{th}$ 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). Visibility decreased only slightly to 12km.

5.2.5 Present and past weather

At 0545NST both present and past weather were noted as Code 0, defined in the FMH handbook as “cloud covering ½ or less of the sky throughout the preceding three hours”. At 0845NST present weather was FMH handbook 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.

Past weather remained at Code 0, “Cloud covering ½ or less of the sky throughout the preceding three hours”, for all five observation times. The DHM staff did not observe a thunderstorm at 1530NST, May 18. In contrast, on both the 16th and 17th of May, the preceding two days, at 1745NST a thunderstorm had occurred during the preceding three hours, and precipitation, but no hail, had been observed at observation time.

5.3 University of Dundee Archived Infrared Satellite Images for May 18 2005

This study was unable to obtain half hourly Infrared Satellite Images for the Pokhara hailstorm analyses. Three hourly images have been used instead. Several Water Vapor Images were available, in addition to one Visible Satellite Image for May 18 09UTC.

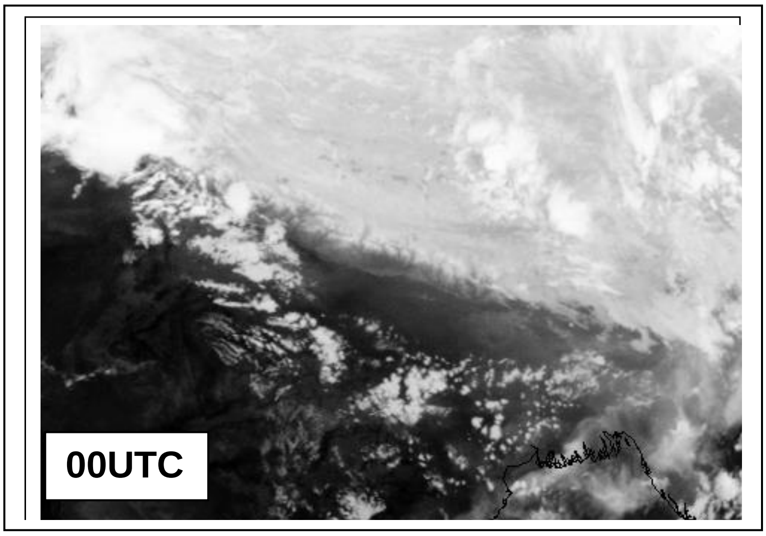


Figure 5.2. 00UTC (0545NST), May 18, 2005, Infrared Satellite (IR) image of the North Indian subcontinent. Source: University of Dundee Receiving Station

The above infrared image (Figure 5.2) 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 Gandaki 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 an easy reference point for the location of Pokhara (white arrow), which in the IR image above is located slightly to the lower right of the Kali Gandaki Valley, below the grayish white colored (cold in IR images) high mountainous areas. Pokhara is approximately 25km directly south of the Annapurna Massif.

In this IR image (0545NST), the North Indian plains are dark in colour, indicating a warm surface and mostly clear skies. There are some clouds scattered across North India which the IR image translates into a dull white. The presence of humid air and convective activity is appropriate for this time of the year with the onset of the SW monsoon approximately three weeks away.

The High Himalaya mountain range with its snow-capped peaks appears in the IR image as a dull grayish white, the small, slightly brighter white areas indicating some cloud cover over the higher mountain valleys and perhaps attached to the mountains. Intensely developed thunderstorm storm cells will have very clear, well defined, white cloud tops with crisp edges. As to be expected, the high Tibetan Plateau is cold (very light grey) on this IR image and at this time, 0545NST, there is no evidence of extensive convective activity at or near Pokhara.

Synoptic DHM Pokhara Airport observations indicate a total cloud cover of 2 oktas ($2/8^{th}$) of cumulus clouds with a cloud base height of 300 – 600 m agl (FM Handbook code 4) and visibility of 8km.

West of Nepal the IR images indicate a large cloud cluster, an area of rising air indicated with **L.** Low pressure here over NW India, Kashmir (Shrinagar) and the Karakorams resulting in convection and cloud formation is likely induced by a synoptic embedded short wave. In this high mountainous terrain topographically induced embedded short waves occur frequently. These small low pressure waves can travel eastward and cause widespread instability, as illustrated by the very bright, white dots in the vicinity of Delhi on the IR image. At 00UTC (0545NST) the 500hPa height at Delhi was 5740m asl, having dropped 100m since 12UTC May 16.

Sunrise in Nepal on May 18, occurs at approximately 0510NST.

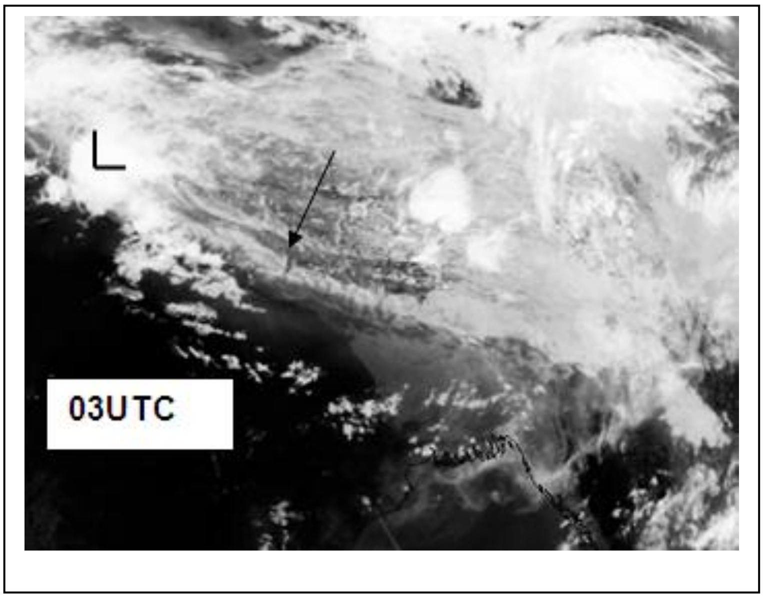


Figure 5.3. 03UTC (0845NST) May 18, 2005. Archived Infrared Satellite Image. Source: U of Dundee

In this IR image for 0845NST, the Kali Gandaki Valley is again clearly visible. Comparing shades of grey and almost-white in the High Himalaya area, other valleys are also clear at this time. The Indian continent and Tibetan Plateau are warming up, but there is no evidence yet of the convective activity resulting from daytime up-valley flows into the High Himalayas. Up-valley flows into the mountains from the lower regions will have started already by this time, however with low wind speeds at onset and sufficient moisture for cloud formation not yet available.

Synoptic DHM Pokhara Airport observations indicate some clearing at this time with the total cloud cover reduced to 1 okta (1/8th sky covered) of cumulus clouds, now with a higher cloud base height of 600 – 1000 m agl (FM Handbook, code 5) and visibility of 10km.

To the northwest of Lhasa on the Tibetan Plateau and northeast of the Kali Gandaki, convective activity has already resulted in a cluster of convective cells, resembling a Mesoscale Convective System.

At this time the above IR image is indicating slight eastward movement of the cloud cluster and low pressure field (L) over NW India and Pakistan.

Some fair-weather clouds are seen over the North Indian plains. The IR image indicates low cloud cover over the Ganges River Delta and Bangladesh; the latter area is prone to devastating tornadoes during the pre-monsoon months.

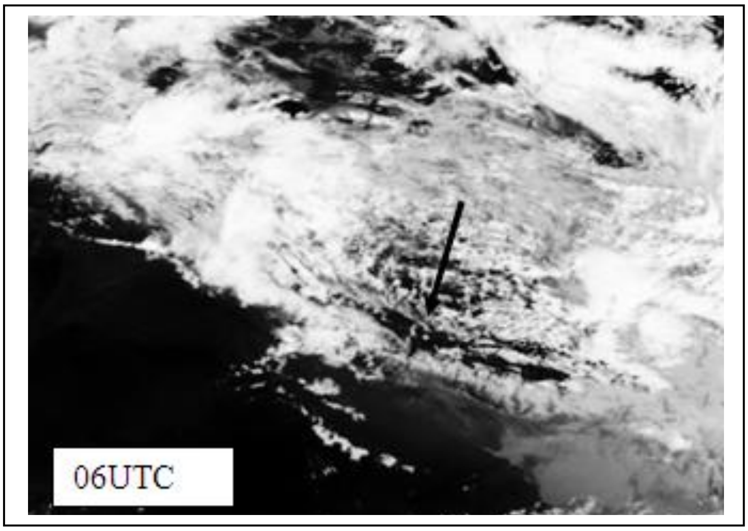


Figure 5.4. 06UTC (1145NST), May 18, 2005. Archived Infrared Satellite Image. Source: U of Dundee

The IR image of Figure 5.4 shows the subcontinent getting warmer (darker in color). Areas in Tibet directly to the north of the High Himalayas are also very dark (surface is warm) and there are scattered clouds. Except for the southern tip of the Kali Gandhki Valley, several Himalayan valleys to the east in Nepal are still visible. The distinctly white areas over the Himalayan Range to the west of Nepal indicate considerable convective activity. At this time the cloud cover in the Pokhara area is similar to the high Himalayas further to the east. Moisture transport by up-valley and low level southeasterly flows has not yet produced visible tall cumulus cloud formation.

The cluster of clouds to the WNW of Nepal which had exhibited beginnings of cyclonic circulation in the 03UTC IR image has lost its circular appearance and has shifted slightly to the north. Along its southern edge, there now appears a line of distinct convective cells along the Himalayan Range; the bright white colour and sharp outlines suggest a strong potential for thunderstorms.

The outline of the cloud cluster over eastern Tibet has become less defined.

Synoptic DHM Pokhara Airport observations indicate the total cloud cover still 1 okta ($1/8^{th}$ sky covered) of cumulus clouds, with the same cloud base height of 600 – 1000 m agl (Handbook, code 5) and visibility of 15km.

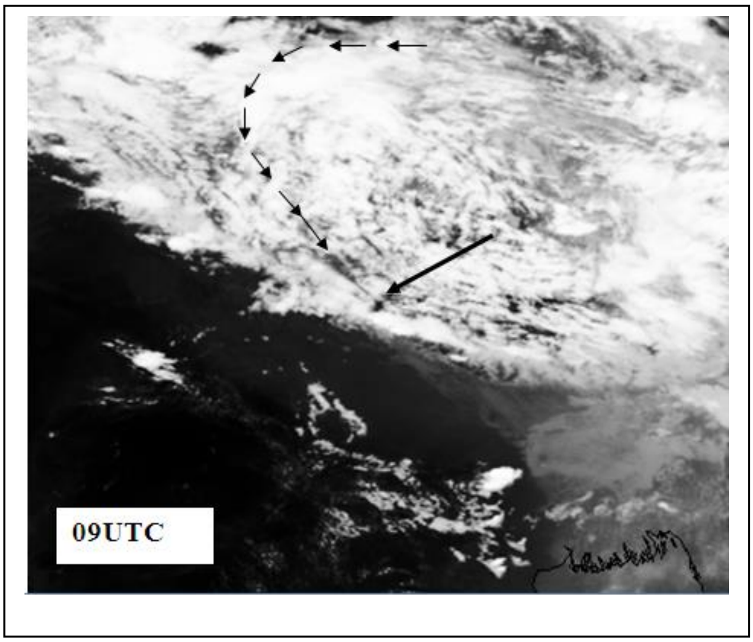


Figure 5.5. 09UTC (1445NST), May 18, 2005. Archived Infrared Satellite Image. Source: U of Dundee

In the Figure 5.5 IR image of 09UTC (1445NST), marked changes have occurred since the last image of three hours earlier at 1145NST. The tip of the Kali Gandaki

Valley (arrow) bordering on Tibet (China) is still visible. While the entire subcontinent to the south of the high mountains was heating, 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 now 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. Hail growth accompanied by a strong updraft inside the developing cell has been occurring for at least 30 minutes already.

The earlier, 0545NST cloud cluster over NW India and Pakistan can no longer be distinguished and several well defined, likely thunderstorm cells have appeared in its place along the flanks of the Himalayan Range. Cyclonic circulation is clearly visible over the Tibetan Plateau (arrows) at this time, suggesting that the low pressure field, initially visible over NW India and Pakistan, crossed the high Karakorams, reformed and strengthened over Tibet (China). The small arrows on Figure 5.5 indicating the large low pressure area over Tibet (China) also indicate counterclockwise winds that approach the Himalayan Range from an approximately 320 degrees direction. There are no upper air stations in southern Tibet, directly to the north of the Himalayan Range, but Lhasa upper air data for 00UTC May 18 confirms humid air at 500hPa and heavy cloud cover over the Plateau between 400hPa and 250hPa as seen in the IR image. It is not improbable that humid air was advected into the Himalayan Mountains, including Pokhara, from the direction of the Tibetan Plateau, as well as from the Gangetic Plains to the south. In addition, upper air data from Hotan (China) located at the northwest edge of the Plateau, indicated at 500hPa northwesterly winds at 42 knots, and an extremely low temperature of -18.9^{o}C on 12UTC May 17.

Synoptic DHM Pokhara Airport observations now 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 (FM Handbook, Code 4) and visibility still at 15km.

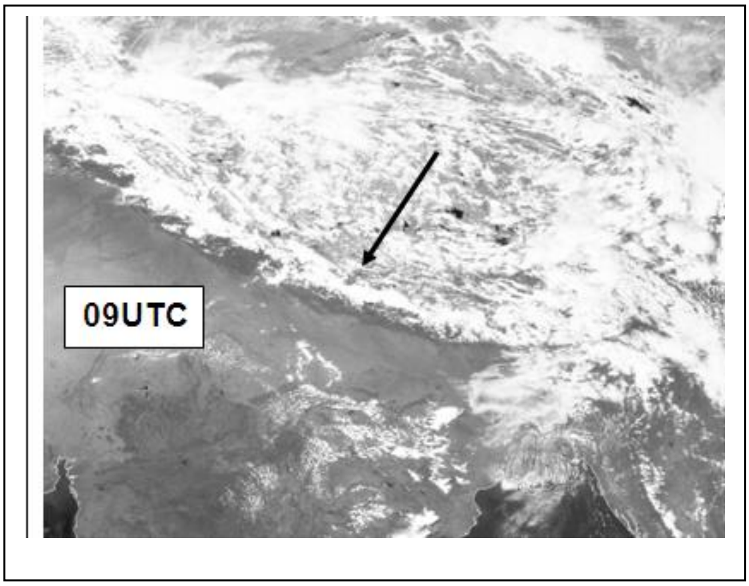


Figure 5.6. 09UTC (1445NST), May 18, 2005. Archived Visible Satellite Image. Source: U of Dundee

The 09UTC (1445NST) May 18 image (Figure 5.6) is a Visible Channel image and confirms the 1445NST IR image information. The northern tip of the Kali Gandhaki Valley is also clearly visible here. There is a line of potential thunderstorm cells all along the foothills of the Himalayas, drawing a perfect arc and dividing line between the lowlands to the south and the Himalaya mountain chain. The cyclonic circulation over the Tibetan Plateau is visible on this image as well.

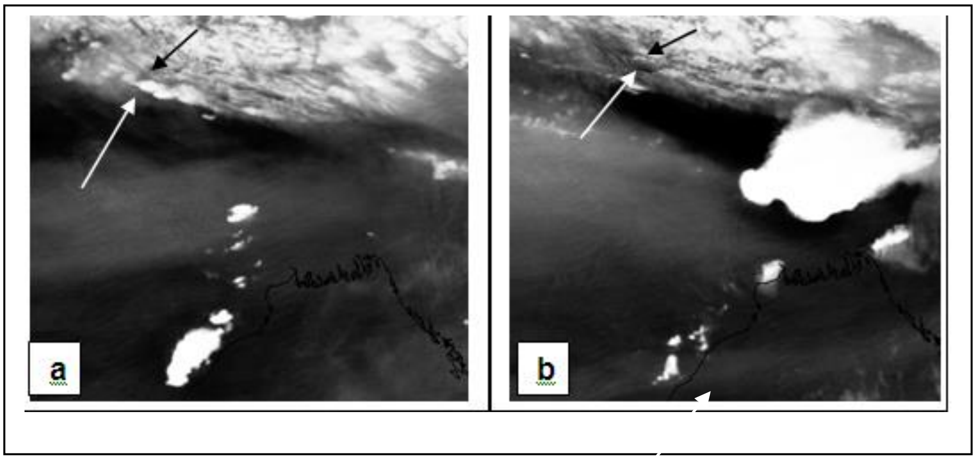


Figure 5.7 a and b. 09UTC (1445NST), May 18, 2005 (a) and 09UTC (1445NST), May 17, 2005 (b), archived Water Vapor Satellite Images. Source: U of Dundee.

Figures 5.7a and b for 09UTC (1445NST) May 18 and May 17, respectively, compare the indications of severe convective activity at Pokhara and in the Himalayan foothills during the afternoon. The bright, white IR in Figure 5.7a for May 18, 1445NST, indicates the Pokhara's growing, very tall hailstorm (white arrow) 45 minutes before the storm occurred. The single, developing Pokhara convective cell is directly to the southeast of the still clear Kali Gandaki Valley (black arrow). Unlike the abnormally early convection at Pokhara on May 18, in comparison the May 17 IR for the same time, also 1445NST, represents the more usual, early stages for convective activity in the foothills during this period (white arrow). Figure 5.7a also indicates two, single convective cells to the east of Pokhara. All the anvils 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 May 18, 1445NST Water Vapor image also indicates that at this time, convective activity to the west of the Kali Gandaki as seen in the previous 09UTC (1445NST) IR image, had not yet progressed to the anvil stage.

In the above Water Vapor images the muted grey color over the Gangetic Plains, south of the substantially whiter shades of the Himalayan Range, illustrates the abundant amount of humid air that has settled over the plains. The humid air advected by the Bihar surface heat low from the Bay of Bengal resulted on May 17 (Figure 5.7b) in a massive Mesoscale Convective Complex (MCC) later in the day, covering all of Bangladesh.

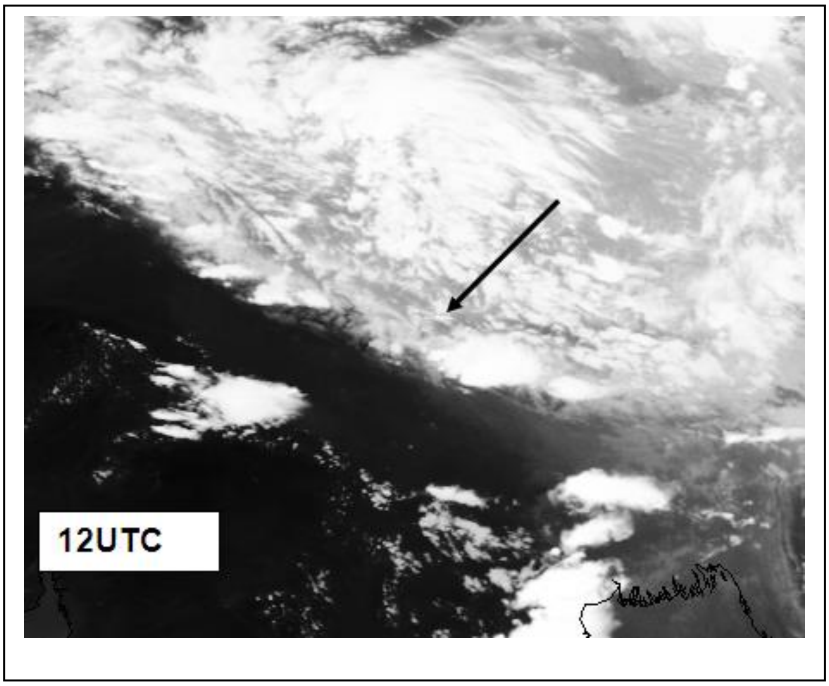


Figure 5.8. 12UTC (1745NST), May 18, 2005. Archived Infrared Satellite Image. Source: U of Dundee

The 12UTC, 1745NST IR image indicates a large cluster of cells southeast of the Kali Gandaki where at least 4 individual thunderstorms have clearly defined edges along their southern flanks (Figure 5.8). Anvils are pointing eastward and appear have joined. The combined length of the cloud shield from west to east is at least 400km. Propagation of the thunderstorm cells towards the southeast is indicated. In far eastern Nepal, a large single cell thunderstorm is seen dissipating, its anvil extending approximately 260km. Gorakhpur ESRL upper air data indicate 80 to 90 knot westerly winds at 150hPa, approximately 14000m asl, that determine the direction of the anvil.

Two hours after Pokhara's historic hailstorm, propagating new storm cell clusters have formed southeast of Pokhara, over the low foothills. Traces in the IR image of the earlier, by now dissipating Pokhara hail storm are no longer visible.

Synoptic DHM Pokhara Airport observations 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 (FM Handbook, code 3) and some stratocumulus clouds at a different height (code 8); cloud base of the latter was not noted. Visibility is 12 km.

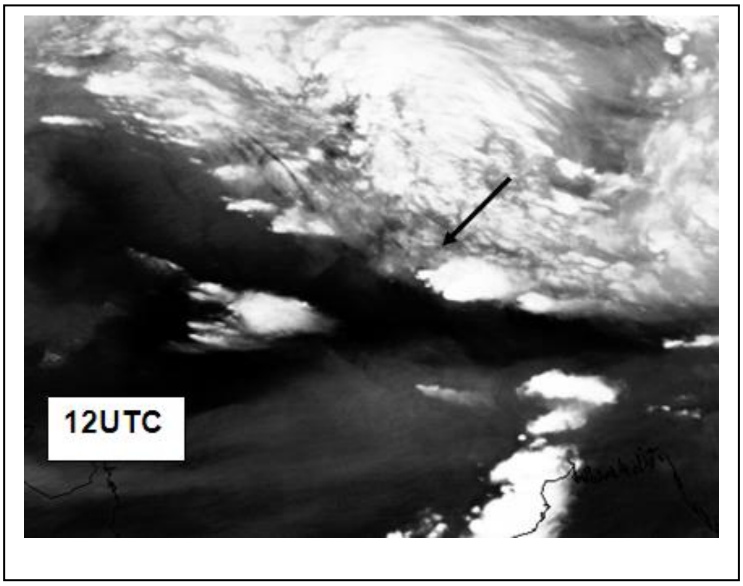


Figure 5.9. 12UTC (1745NST) May 18, 2005. Archived Water Vapour Satellite Image. Source: University of Dundee

There are at least fourteen thunderstorms plus anvils in this Water Vapour satellite image for 1745NST in this section of the Indian subcontinent (Fig 5.9). Thunderstorm cells east of the Kali Gandaki (arrow) are propagating in an east southeast direction along the Terai.

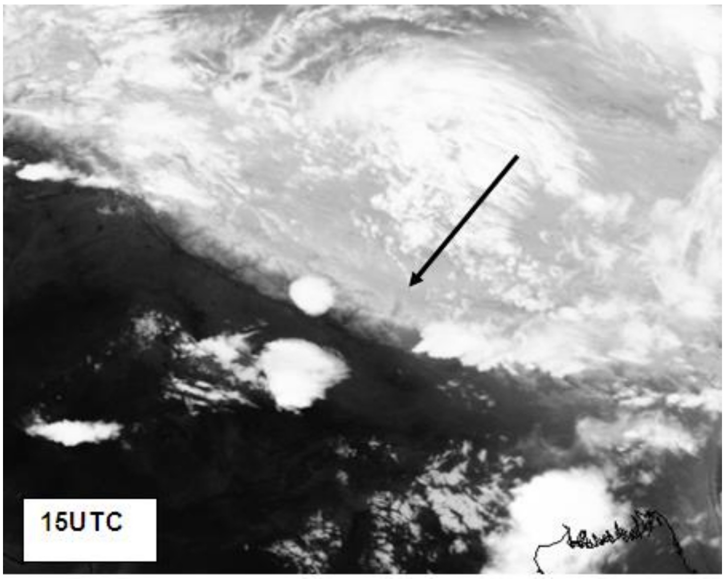


Figure 5.10 15UTC (2045NST) May 18, 2005. Archived Infrared Satellite Image. Source: U of Dundee.

In 15UTC (2045NST) IR image (Figure 5.10), the Kali Gandaki Valley is again visible. Skies over Pokhara are clearing. In the central and eastern section of Nepal several more thunderstorm cells with their anvils have emerged and appear to be propagating and moving in an easterly direction parallel to the Himalayan Range. The anvils in this image are pointing to the northeast, indicating 230 degree, southwest winds aloft. Over the southwest corner of Nepal, a well defined, bright white circle has appeared. This large, cloud cluster has a diameter the width of Nepal. The IR image indicates considerable clearing along the High Himalayas east and west of the newly formed cluster. Another well defined, but much larger cloud cluster has formed directly to the south of the smaller Nepal cluster. The solitary nature of both suggests cell propagating, perhaps elevated convection fuelled by a low level jet, and possibly dynamic upper air lifting mechanisms, such as found east of an upper tropospheric low pressure trough. May 18 is about 3 weeks away from the monsoon onset and upper level synoptic disturbances generating extreme atmospheric instability are still a frequent occurrence. The change in wind direction from 270 to 230 degrees, as illustrated by anvil orientation between 12 and 15UTC, suggests a possible curving or "kink" in the isobars at very high, at least 12000m asl, tropospheric levels. The isobar "kink" may exist at lower and mid-tropospheric levels as well, but this study does not have primary data sources to confirm this.

North India is still very dark in colour indicating very little surface cooling. No synoptic observations were done at this time (2045NST) at the Pokhara Airport.

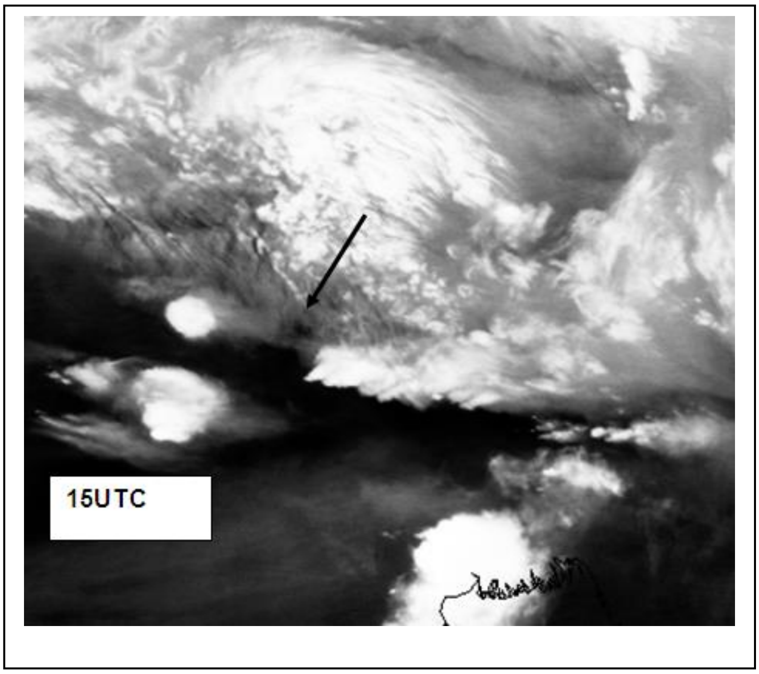


Figure 5.11. 15UTC (2045NST), May 18, 2005. Archived Water Vapor Satellite Image. Source: University of Dundee

The above water vapor image for 2045NST, illustrates again the prevalent thunderstorm initiation typical of pre-monsoon weather behavior over the northern Indian subcontinent (Fig 5.11). Active thunderstorm cell genesis is more clearly visible on the satellite water vapor images. Many (perhaps eight) cells are lined up west to east along the Nepal-India border. These appear to be further south than the convective activity seen in the 09UTC IR image, when the convective cells were observed in the foothills of the High Himalayas. Convection resulting in very white (therefore tall, cold) cloud tops in the above water vapor image is occurring directly over the still very dark colored Gangetic plains. The 12UTC image indicated convective activity in this location as well, indicating active cell propagation. Convection occurring much later is normally associated with elevated convection above a stable boundary layer and the presence of a low level nocturnal jet.

5.4 Synoptic and Mesoscale Scale Environments

By the end of May many of the prerequisite monsoon onset conditions are falling into place. The surface heat lows have expanded and stretched out over the Gangetic Plains and humid air advection from the Bay of Bengal has sent surface and low tropospheric dewpoint temperatures across the plains and the Himalayan foothills into the high double digits, as seen in the IR satellite images of the previous section. The synoptic environment and the possible lifting mechanisms or “triggers” that release the potential atmospheric instability needed for severe convective activity are examined next. The extraordinarily destructive hailstorm was one of its most severe in Pokhara’s eyewitness history. Pokhara is a known area of moisture convergence. 1kg hailstones require exceptional meteorological conditions and thunderstorm severity “enhancers”. Vorticity maxima generated by deep low pressure areas at low and mid-tropospheric levels, can cause the low to deepen and become a strong lifting mechanism for convective initiation at the surface. Atmospheric destabilizing features must have been in place several hours before the storm struck Pokhara.

5.4.1 Upper Tropospheric Levels

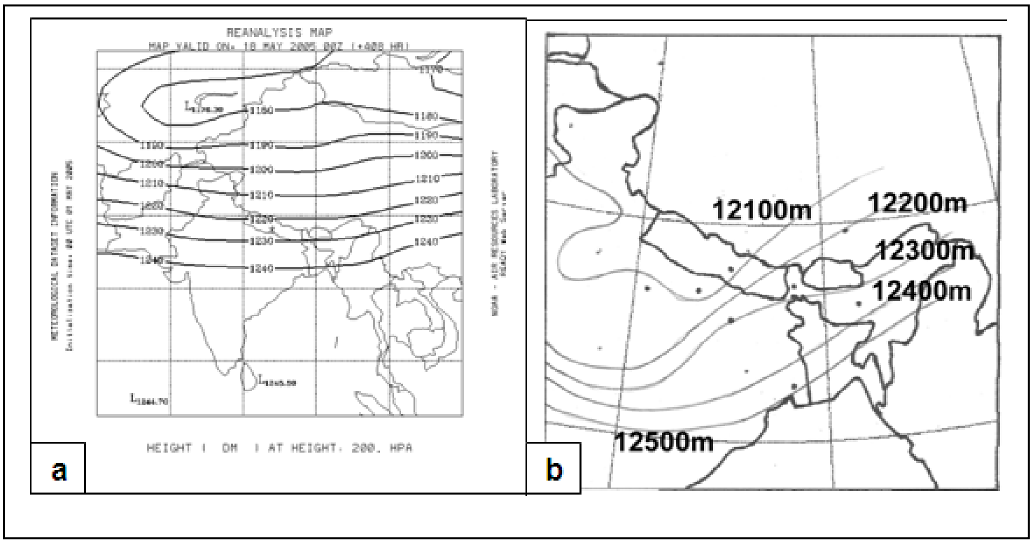


Figure 5.12 a and b. May 18,2005 00UTC (0545NST) 200hPa geopotential heights (a). Source: NOAA 6-hourly Reanalyses. And (b), hand analyzed 200hPa contours. Source: ESRL. Contour interval is 100m.

The NOAA Reanalysis (NR) 200hPa contours (Figure 5.12a) for May 18 are completely zonal. Upper tropospheric disturbances are not indicated on Figure 5.12 a and b.

The differences between Figures 5.12 a and b are striking. Figure 5.12b was constructed with original NOAA ESRL upper air data. On this analysis the 12100m isobar also begins just below Shrinagar in Kashmir, but turns to the south at Patiala, continues in a southerly direction past Delhi, 12060m, then becomes easterly towards Lucknow. The contour continues in an easterly direction, passing to the north of Lucknow, 12150m and to the south of Gorakhpur, 12075m, before passing close to Kathmandu and into Tibet, China. The pattern of the 12100m contour reveals two embedded low pressure areas, at Delhi and at Gorakhpur. The 12200m contour curves around Gwalior and then heads into a northeasterly direction towards Lhasa, China, 12220m. The next three contours, the 12300m, 12400m and the 12500m follow the 12200m contour. The 200hPa Calcutta geopotential height was at 12510m asl, with a wind direction from the southwest. The hand analyzed chart indicates that the 200hPa Lucknow isobar height was about 100m higher than both the Delhi and Gorakhpur heights suggesting embedded short wave low pressure troughs at Delhi and at Gorakhpur and a high pressure ridge at Lucknow. There is convective activity in the Delhi and Lucknow region at this level in the 00UTC Infrared satellite image, but none at Gorakhpur.

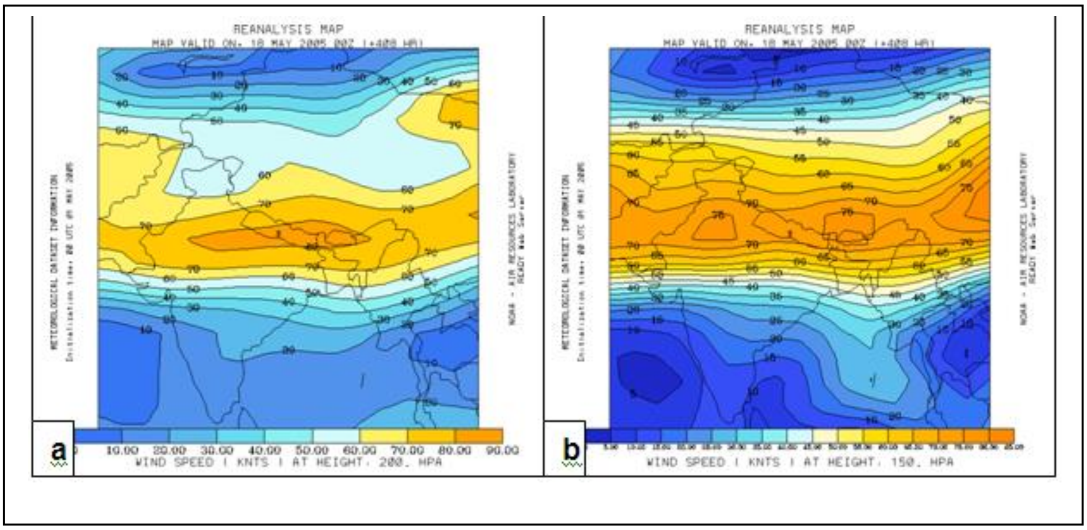


Figure 5.13 a and b. 00UTC 200hPa (a) and 00UTC 150hPa (b) May 18, 2001 wind speeds. Source: NR

With the exception of a few significant levels, wind data at the upper tropospheric levels was usually missing from the India ESRL archived data and complete hand drawn analyses were not possible for this study. The analyses here used the NOAA Reanalysis wind charts. Figure 5.13a shows the 200hPa subtropical jet stream maximum directly over Nepal in a straight west to east direction with a speed of 80 knots. 70 knot winds envelop all of northern India and southern Tibet. The wind analysis in Figure 5.13b is for 150hPa, using a wind speed interval of 5 knots, not 10 knots as in the previous Figure 5.13a. The 150hPa, approximately 14000m asl, wind speed chart reveals a wind speed varying between 70 and 75 knots. Divergence at upper tropospheric levels is frequently a result of varying wind speeds. Original 00UTC May 18 ESRL 200hPa wind data from Lucknow indicates westerly winds at 88 knots. Winds at 250hPa were westerly at 87 knots and at 300hPa westerly at 82 knots, pointing to a 3000m deep layer with wind speeds more than 80 knots. Original Delhi wind data also shows westerly winds at 200hPa of 80 knots, but the winds at 250hPa are 12 knots less and at 150hPa, 40 knots slower.

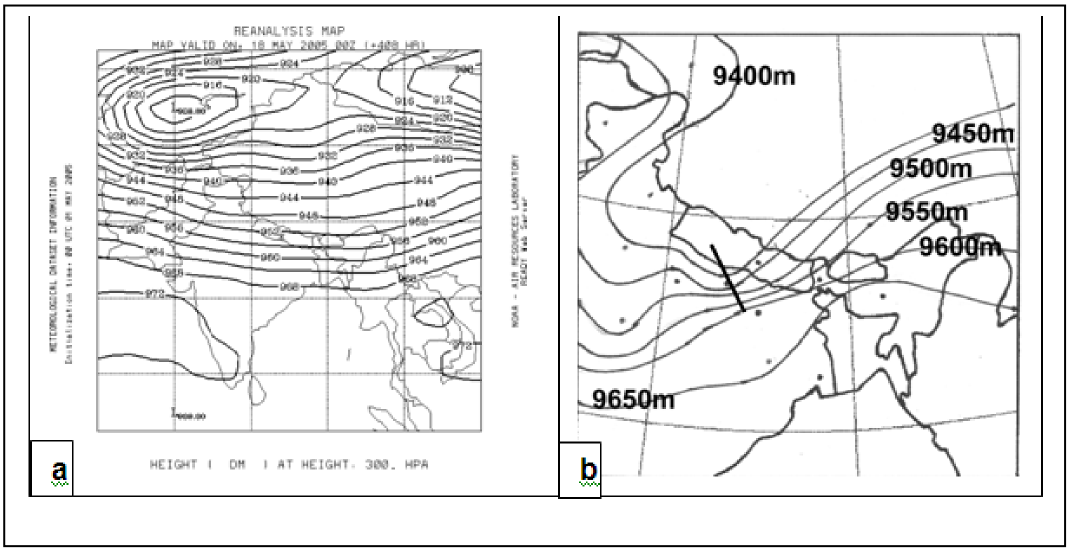


Figure 5.14 a and b. May 18, 2005, 00UTC (0545NST) 300hPa geopotential heights (a). Source: NOAA 6-hourly Reanalyses (NR). And (b), hand analyzed 300hPa contours. Source: ESRL. Contour interval is 50m.

The NOAA Reanalysis (NR) 300hPa geopotential heights (Figure 5.14a) for May 18 are zonal and as with the 200hPa geopotential heights there are no upper tropospheric level disturbances indicated in Figure 5.14 a and b.

The hand analyzed 300hPa geopotential heights Figure 5.14b shows the 9400m geopotential heights contour descending from Hotan in China, passing in between Shrinagar and Patiala, and just north Delhi curving eastwards towards Nepal. The contour continues slightly south of Nepal, before curving steeply north northeast, and passing through central Nepal into China. The 9450m contour begins west of Delhi, immediately begins a southward curve and halfway to Gwalior turns to the northeast and continues towards Lucknow. As in the previous 200hPa chart, the Lucknow 300hPa geopotential height, at 9480m, is higher by 70m, than the Delhi and Gorakhpur heights, resulting in slight ridging above Lucknow and a small low pressure trough south of Delhi. The 9500m contour closely follows the 9450m contour. This low pressure wave appears intensified because the 9500m contour loops around Gwalior before making a northward turn towards Lucknow. The contour curves around Gorakhpur before crossing Nepal into China. The 9550m contour follows the previous contour through India and Nepal and passes through Lhasa, 9550m from a southwesterly direction. The 9600m contour passes north of Patna, very close to the previous four. The geopotential height difference between Patna, 9640m and Gorakhpur, 9410m, is 230m, allowing this study to draw a low pressure trough axis from Patna to Gorakhpur (black line). The axis is negatively tilted. Also, a trough with such a steep incline is likely to generate positive vorticity advection to the right of its axis which in the above chart falls over central Nepal. One of the "trigger" or dynamic lifting mechanism that initiated the 1kg hailstone producing thunderstorm cell at Pokhara may have been the divergence of this low pressure trough. As in the 00UTC 200hPa hand analyzed geopotential heights chart, the 00UTC 300hPa heights analysis also reveals a synoptic disturbance to the west and southwest of Nepal.

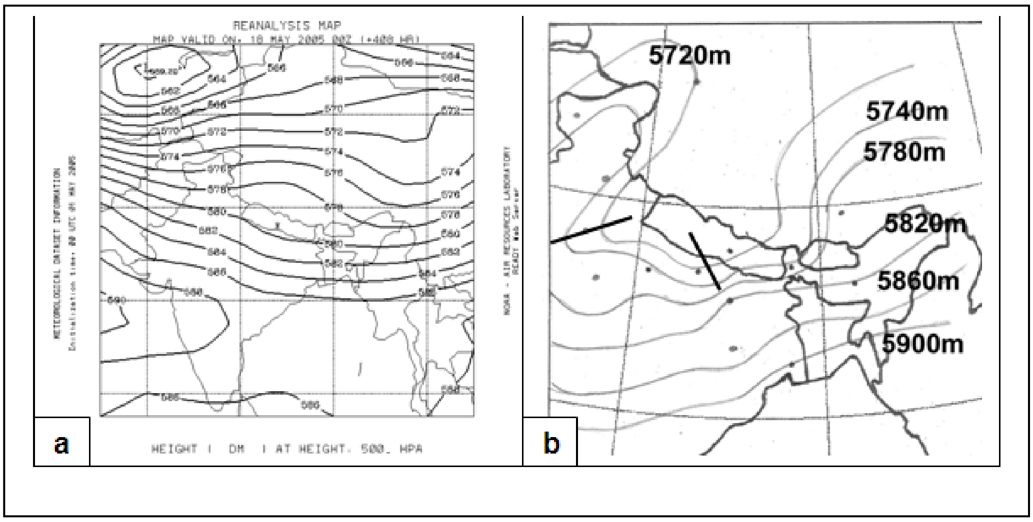


Figure 5.15 a and b. 00UTC (0545NST) May 18, 2005, 500hPa geopotential heights (a). Contour interval is 20m. Source: NOAA 6-hourly Reanalyses (NR). And (b), hand analyzed 500hPa geopotential heights. Contour interval is 40m.Source: ESRL.

The NOAA Reanalysis (NR) 500hPa geopotential heights (Figure 5.15a) across the North Indian subcontinent for May 18 are again mostly zonal. There is a very slight southward curving over Bangladesh and Myanmar, but a synoptic disturbance is not indicated. The 500hPa isobars in the chart curve very slightly around the High Himalayas.

The hand analyzed 500hPa geopotential heights for May 18 00UTC (Figure 5.15 b), reveal considerable potential atmospheric instability over the north Indian plains, southwest, south and west of Nepal. The 500hPa geopotential contour heights ranged from 5720m at Gorakhpur to 5920m at Calcutta, and follow similar directions as in the 300hPa geopotential heights chart . With the onset of the monsoon 3 weeks away, the pattern of the 500hPa isobars starts resembling that of the monsoon trough. Because of ridging at Patna, the isobars are very close together between Patna and Gorakhpur. After the 5740m contour, the remaining isobar contours were drawn at 40m intervals.

1. The 5720m contour runs directly south from Hotan in China, turns eastward at Delhi, continues just south of the Nepal border, passes through Gorakhpur and proceeds in a northeasterly direction into China.

2. The 5740m contour follows the 5720m curve from Shrinagar to slightly west of Delhi, curves east towards Lucknow and then continues southeast below Gorakhpur

before passing through the southeastern tip of Nepal to Siliguri, where it runs directly north to China.

3. The 5780m contour begins west of Gwalior, curves north towards Lucknow and then follows the 5740m contour through Bhutan into China.

4. The 5820m contour follows the curve of the 5780m contour, passes through Patna, heads straight east through Guwahati and continues into China after passing through NE India.

5. The 5860m and 5900m contours run in a similar direction as the 5820m contour, with the former passing just south of Ranchi and the latter just above Calcutta.

A low pressure trough axis (black line) was drawn through the embedded short wave between Delhi and Lucknow.

The height difference between Patna and Gorakhpur on the 500hPa geopotential heights chart was 120m. As on the 300hPa heights chart, a low pressure trough axis has been drawn (black line) through the embedded short wave. To the right of the negatively tilted axis, vorticity maxima, dynamic enhanced lift mechanisms, over central Nepal and possibly the Pokhara area were likely. 37 knot winds at Gorakhpur were northwesterly following the curved contour. At Patna, winds were westerly, also 37 knots. 12UTC ESRL data was available for Lucknow and indicated a 120m geopotential height increase between 00UTC and 12UTC on May 18. At Gorakhpur, however, the 500hPa heights had started falling already at 00UTC May 17. May 18 data for Gorakhpur was missing, but by 00UTC May 19, the 500hPa geopotential height had dropped to 5680m suggesting the likelihood of an even steeper low pressure trough axis on May 18.

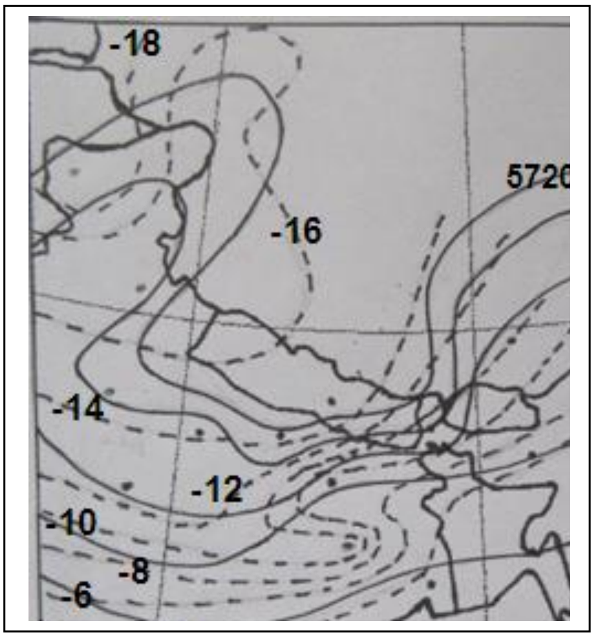


Figure 5.16. Hand drawn 00UTC May 18,2005 500hPa Geopotential Heights and Isotherms. Isotherm interval is 2 degrees centigrade. Source: NOAA/ESRL radiosonde Database.

The 500hPa geopotential heights and isotherms analysis (Figure 5.16) indicates an intrusion of significantly colder air on May 18 at 00UTC (0545NST). Cold air advection from Hotan, China is indicated north of Delhi where the -16°C isotherm crosses the 5720m and 5740m isobars. The cold westerly flows send -16°C temperatures directly eastward towards the Gorakhpur area and towards central Nepal. 500hPa temperature at Lucknow was -14.1°C and at Gorakhpur the 500hPa temperature fell to -15.9°C by 00UTC May 19.

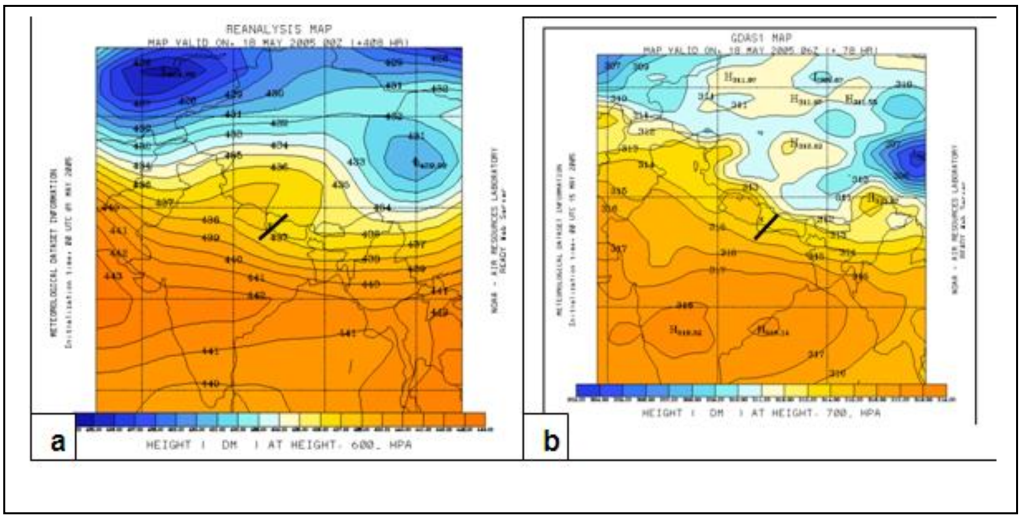


Figure 5.17 a and b. 00UTC (0545NST) May 18, 2005 600hPa Geopotential Heights. Interval 10m (a) and 06UTC (1145NST) May 18 2005.700hPa Geopotential Heights. Interval 10m (b). Source: NOAA Reanalysis

The 00UTC (0545NST) 600hPa NOAA Reanalysis of Figure 5.17a indicates some curving of the 4370m isobar in the vicinity of central Nepal and the Pokhara area (black line). A hand drawn chart was not constructed because of missing data. The 06UTC (1145NST) 700hPa NOAA Reanalysis of Figure 5.17b indicates a small embedded low pressure trough at 3140m over the central Nepal area, preceded by a high pressure ridge over central Nepal. This study drew a positively tilted trough axis (black line) through Central Nepal.

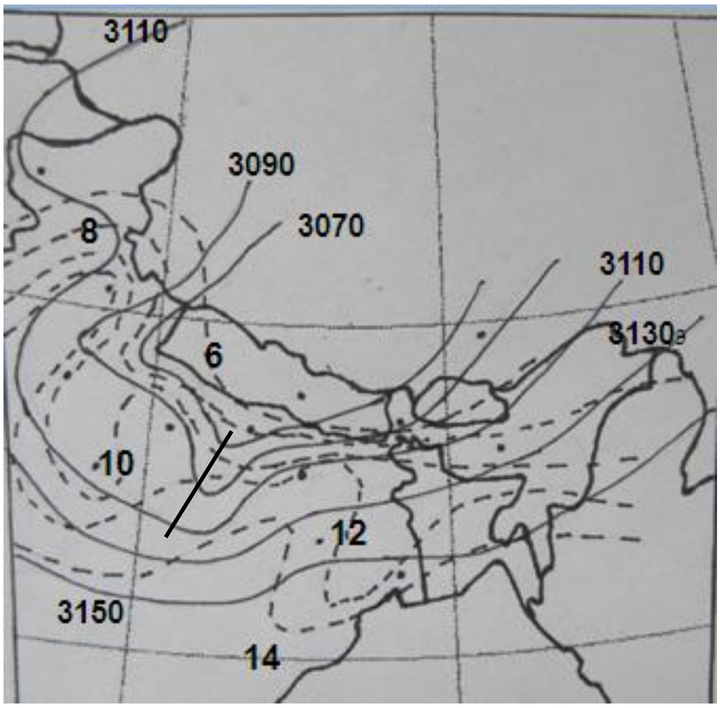


Figure 5.18. 00UTC (0545NST) May 18, 2005. 700hPa Geopotential Heights and Isotherms. Source: NOAA/ESRL Radiosonde database.

The 700 hPa chart (Figure 5.18) can be drawn only for the area south of the Himalayas, because at approximately 3100m asl, the 700hPa geopotential heights fall below the elevation of the Tibetan Plateau and below much of the Himalayan Range. In the hand drawn chart above, the isobars are drawn at 20m intervals. Temperatures are in centigrade at 2 degree intervals. At 00UTC, the 700hPa contours indicate an embedded short wave trough at 3070m at Gorakhpur and east of Lucknow. Wind directions at Gorakhpur and Lucknow were from 290 and 300 degrees respectively, allowing the isobars to be drawn as indicated in the chart.

A positively tilted axis was drawn in an approximate southwest to northeast direction (black line) slightly to the west of Gorakhpur and into central Nepal. Negatively tilted trough axes were drawn in approximately the same location at 300hPa and 500hPa. Original ESRL Radiosonde data for Gorakhpur 00UTC May 17 indicate 42 knot winds from a 285 degree direction. May18 data for Gorakhpur was missing and this study determined wind speed and direction for Gorakhpur from May 17 and May 19 data. The May 18 Gorakhpur 700hPa wind speed and direction was calculated at 36 knots from the northwest.

The 8°C isotherm crosses the heights contours at Patiala, Delhi and at Gorakhpur, indicating cold air advection. The 6°C isotherm on the chart is located just south of Pokhara.

5.4.2 500hPa Geopotential Heights at Gorakhpur.

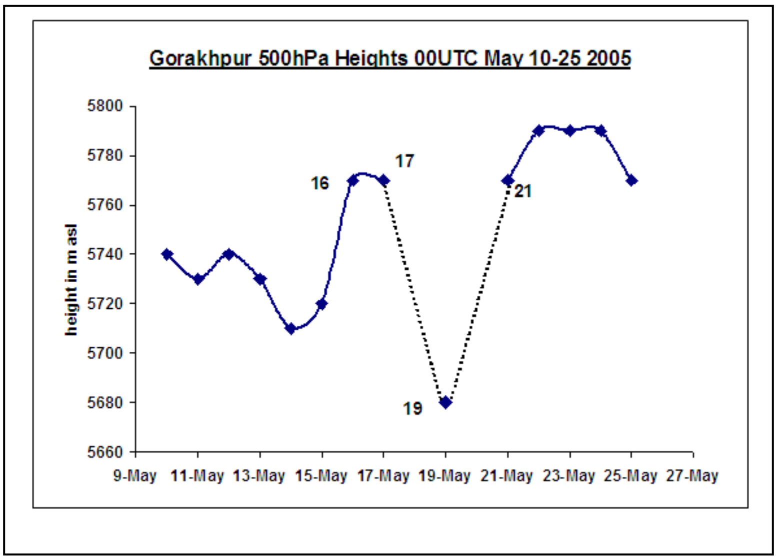


Figure 5.19. Gorakhpur 500hPa Geopotential Heights May 10 to 25, 2005. Source: Original archived NOAA/ESRL Radiosonde data

Figure 5.19 traces the 00UTC 500hPa geopotential heights at Gorakhpur from May 10 to May 25, 2005, using ESRL archived upper air data. The 500hPa Gorakhpur geopotential heights ranged from 5740m on May 10 to 5770m on May 17 and falling to 5710m on May 14. Original data for May 18 and 20 was missing. Gorakhpur 500hPa geopotential heights dropped 90m from May 17, 5770m to May19, 5680m. Such a height decrease is likely to indicate the approach of an east to west travelling embedded low pressure trough. By May 21 the 500hPa geopotential heights at Gorakhpur had returned to 5770m.

Table 5.1. 00UTC May 16- 19, 2005. Geopotential Heights in m asl at Gorakhpur. Source: NOAA/ ESRL Radiosonde database.

Gorakhpur 00UTC Geopotential Heights in M asl

	925	850	700	600	500	400	300	200
May 16	719	1454	3102	4352	5770	7430	9460	m
May 17	707	1439	3073	4326	5770	7450	9500	12190
May 18	m	m	m	m	m	m	m	m
May 19	723	1449	3054	4278	5680	7330	9330	11960

A significant decrease in geopotential heights at Gorakhpur is confirmed in Table 5.1 Between 00UTC May 17 and 00UTC May 19, the 700hPa geopotential heights fell19m, at 600hPa the heights fell 48m, at 500hPa, 90m, at 400hPa, 120m, at 300hPa 170m and at 200hPa 230m (Table 5.1). The decrease in heights was most dramatic between 600 and 200hPa. The 925 and 850hPa geopotential heights at Gorakhpur, on the other hand, increased 16 and 10m respectively from 00UTC May 17 to May 19. Surface pressure did not change. The Gorakhpur geopotential heights decreases appear to have been confined to the mid- and upper tropospheric levels.

5.4.3 Divergence Aloft

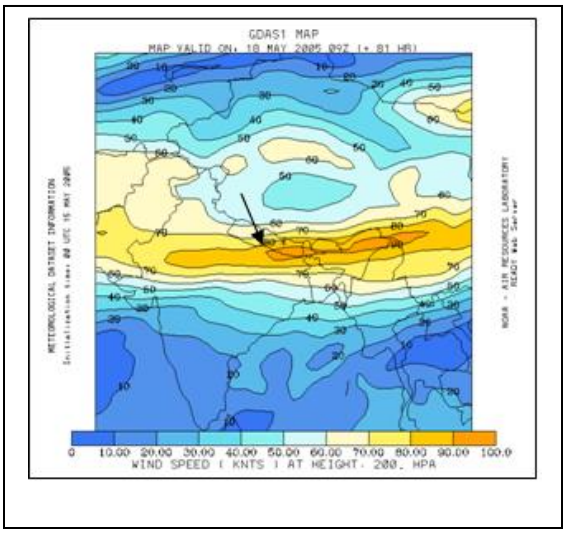


Figure 5.20. 09UTC May 18,2005. 200hPa wind speed in knots. Source: NOAA ARL

A significant lifting mechanism and thunderstorm enhancer is divergence aloft. The archived NOAA 200hPa wind speed charts for 09UTC May 18 indicate the subtropical jetstream in an almost straight west to east position across Nepal, with maximum wind speeds of 90 knots inside the maximum of the jet (Figure 5.20). An increase from 80 to 90 knots over central Nepal occurred between 06 and 09UTC, with the entrance to the maximum 90 knot region very close to the Pokhara area (arrow). The entrance to a jetstream max positioned directly above an area of severe deep, moist convection, can frequently be a significant atmospheric destabilizing agent or “trigger mechanism”. The 90 knot jet maximum returned to 80 knots by12UTC.

5.4.4 Cold Air Intrusion at Pokhara

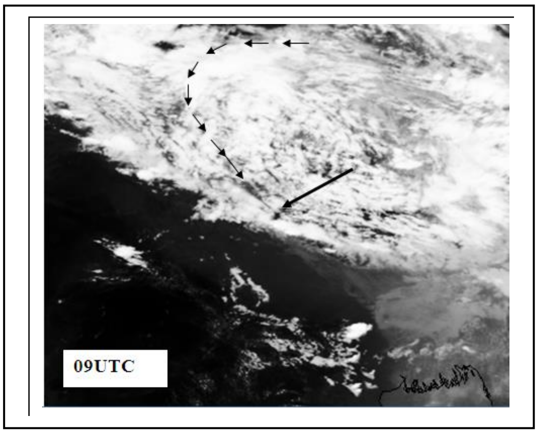


Figure 5.21. Infrared Image of 09UTC May 18, 2005 for North India, Nepal and Tibet (China). Source: University of Dundee

The Pokhara hailstorm analyses in this study were fortunate to have access to Gorakhpur upper air data. However, Pokhara is located in the middle of the Himalayas, just south of the 8000m asl Annapurna Region and not 180km further south in the Gangetic Plains. The large low pressure area over Tibet in the 09UTC IR image in the previous section (Figure 5.21), that is cut off by the barrier created by the Himalaya Range, illustrates that by mid-afternoon the counterclockwise wind circulation of the Tibet low pressure area was approaching the Himalayan mountains at approximately an angle of 320 degrees. The Himalayas are situated at an angle of about 300 degrees in a northwest to southeast position, so that winds having the same direction are likely to continue parallel to the mountains. At an angle greater than 300 degrees, such as in this case, 320 degrees, the winds will be interrupted and orographically lifted into and across the Himalayan mountain range.

Table 5.2. 12UTC May 17, 2005 and 00UTC May 18, 2005 original 500, 400 and 300hPa upper air data for Hotan (China). Source: ESRL

12UTC May 17

	hPa	m asl	T	Td	Dir	kts
4	5000	5730	-189	-349	295	42
4	4000	7350	-311	-349	265	56
4	3000	9320	-477	-557	280	73

The city of Hotan is situated at the edge of the Taklamakan Desert, approximately 400km NNW of the Tibetan Plateau. There are no upper air stations on the western side of the Plateau, the reason why there are no hand drawn geopotential heights analyses over that section of the plateau in this study. The upper air data in Table 5.2 indicates the extremely cold 500, 400 and 300hPa temperatures for 12UTC May 17 and 00UTC May 18, respectively, at Hotan, which by 00UTC May 18 was being advected into Northwest India. Wind speeds at 12UTC May 17 ranged from 42 knots at 500hPa to 73 knots at 300hPa and temperatures ranged from -18.9^{o}C at 500hPa to -47.7^{o}C at 300hPa. In view of the fact that the Pokhara hailstorm was not only very severe, but it occurred at least two hours earlier than the usual late afternoon air mass thunderstorm, it is not an unlikely scenario that the winds indicated by the arrows in Figure 5.21 enhanced convection on the lee-side of the Annapurnas, by advecting extremely cold temperatures into the Pokhara region by midday on May 18.

5.5. Stability Index Calculations

5.5.1. Determining Stability Indices

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 was missing. There is 05UTC May 18 Gorakhpur wind data only from the surface to 2000m.

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 (Convective Available Potential Energy), 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.

The IR satellite images indicate no convective activity for Gorakhpur on the 18th. Unlike locations in the Terai and foothills of the Himalayas, Gorakhpur did not have a thunderstorm.

5.5.2. Archived NOAA ARL Computer Calculations 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 28.13N and 84.0E. The NOAA ARL computers place this location at 1100m asl and not at 800m asl, the elevation of Pokhara. 800m asl is the height for which there is DHM surface data . 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) May 18 and for 09UTC (1445NST) May 18; the storm occurred at 1530NST May 18. 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 reasons unknown, the DHM airport staff did not observe the 1530NST hailstorm and the storm is not in their records. Atmospheric profiles were constructed for all four days to assist this study's analyses.

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

Table 5.3. Stability Indices for Pokhara, 00UTC 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 5.3. 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 May 2012, 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 5.4. 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 5.4. Most striking are the differences in dewpoint temperatures between the DHM data and the values calculated by NOAA; the DHM values are on average 15.1^{o}C higher.

Table 5.5. 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

Table 5.5 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^{o}C and 40.5^{o}C are very high and not realistic for destabilizing the atmosphere and initiating severe convective activity at 800m.

The maximum daytime temperatures recorded by the DHM for May 16 to May 19 do not exceed 30^{o}C. The calculations shown in Table 5.4 indicate no predictions for hail formation.

5.5.3 NOAA/ESRL Radiosonde Data Base 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.

Table 5.5 indicates the original ESRL rawinsonde data for Gorakhpur, 00UTC May 17. Here the only complete upper air data levels, that is, the mandatory levels of geopotential height, pressure, temperature, dewpoint, wind direction and wind speed in knots, were at the surface, 925, 850 and 700 hPa. Geopotential heights were recorded at all mandatory and significant levels. Temperature plus dewpoint temperatures only were recorded at 613, 607, 600 and 599Pa. Temperature data only was recorded at nine additional levels above 500hPa up to 157hPa. Wind speed and direction was recorded at two significant levels, 683 and 509hPa. Most wind data is missing. 99999 indicate missing data.

For May 19th (Table 5.6) most mandatory levels were available: 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, but again much missing wind data.

Table 5.6. Original archived upper air data for Gorakhpur, 00UTC May 17 2005. Source: NOAA ESRL Radiosonde Database

254	0	17	MAY	2005		
1	99999	42379	26.75N	83.37E	77	0
2	2000	2870	99999	30	99999	3
3	VEGK		99999	kt		
9	9930	77	264	194	90	8
4	10000	15	99999	99999	99999	99999
6	9700	285	99999	99999	80	19
5	9460	499	228	158	99999	99999
4	9250	707	222	132	140	12
6	8870	1070	99999	99999	195	3
4	8500	1439	198	17	285	7
5	7940	2020	180	-40	99999	99999
5	7630	2359	180	-40	99999	99999
5	7290	2745	150	-90	99999	99999
4	7000	3073	124	-146	285	42

Table 5.7. Original archived upper air data for Gorakhpur, 00UTC May 19, 2005. Source: NOAA ESRL Radiosonde Database

254	0	19	MAY	2005		
1	99999	42379	26.75N	83.37E	77	0
2	500	384	1150	35	99999	3
3		VEGK		99999	kt	
9	9940	77	272	202	90	6
4	10000	38	99999	99999	99999	99999
5	9270	684	224	197	99999	99999
4	9250	723	222	192	20	7
5	8580	1364	154	44	99999	99999
4	8500	1449	148	38	310	14
5	7270	2741	50	-110	99999	99999
4	7000	3054	34	-126	290	25
5	6600	3526	0	-150	99999	99999
5	6000	4278	-61	-141	99999	99999
5	5840	4488	-71	-131	99999	99999
5	5360	5117	-367	-477	99999	99999
5	5320	5206	-121	-241	99999	99999

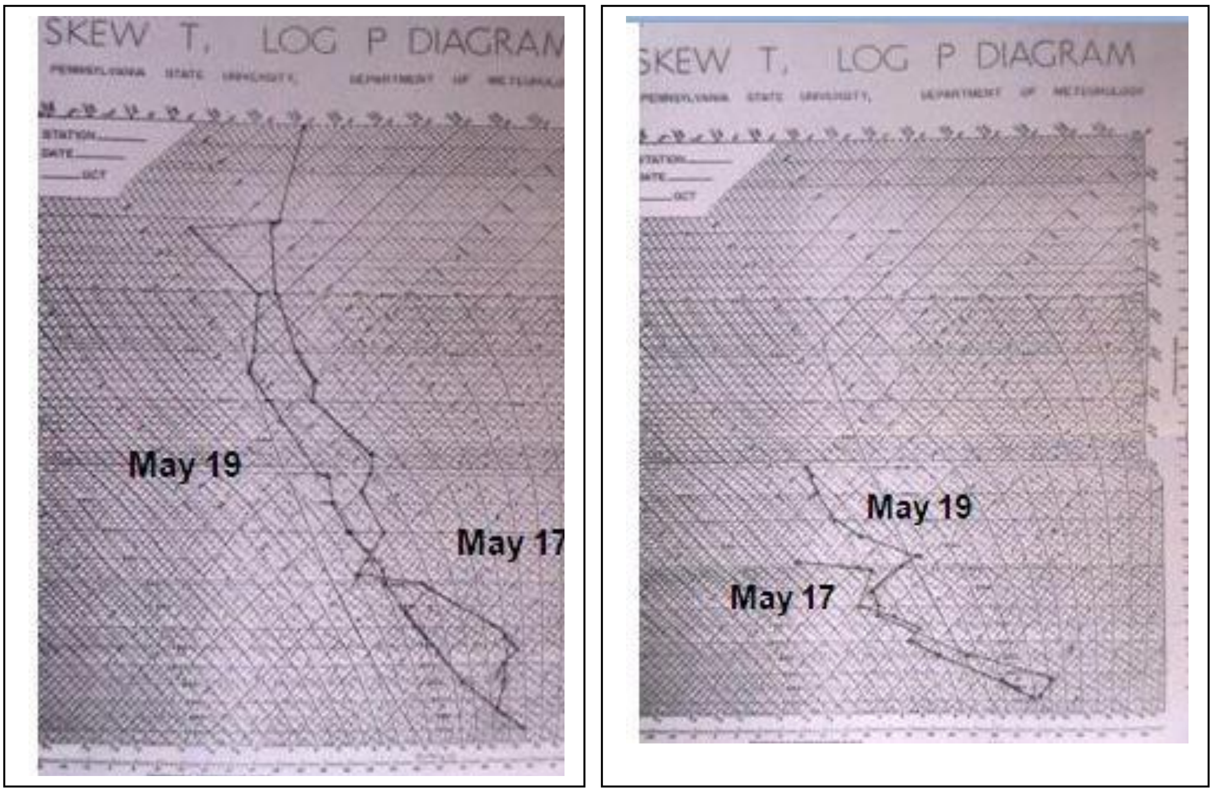
5.5.4 Temperature, Dewpoint Temperatures and Geopotential Heights for Gorakhpur

Averaging temperatures at available mandatory levels involved only simple arithmetic. To average/interpolate between two sets of data points that were frequently at different significant levels, therefore at different geopotential heights, this study used the Pennsylvania State University, Dept. of Meteorology SkewT- log P charts.

First, on one chart (Figure 5.22 a and b) 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 identical geopotential heights became a simple procedure.

The same procedure was followed for the dewpoint temperatures, although there were far fewer data points (Figure 5.22 a, and b). Recording of dewpoint temperature data stops at 599hPa on May 17, at 28.5ºC and at 400hPa at 39.3ºC 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.



Figures 5.22. a and b: SkewT log P Temperature and Dewpoint Temperature diagrams for Gorakhpur 00UTC, May 17 and 19, 2005. Source: NOAA/ESRL Radiosonde Data base

Figure 5.22.a and b 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 super dry adiabatic between the surface and 700hPa. Between 400 and 250hPa, on May 19, temperatures had dropped by an average of 5.8^{o}C, for example at 370hPa temperature decreased from -24.5^{o}C on May 17 to -32^{o}C on May 19.

Table 5.8 gives us the Gorakhpur 500 and 400hPa temperatures in centigrade for 00UTC May 1 to 31 2005, using the original ESRL archived data. There is missing data, but the data still show distinct cold air intrusions on May 13- 14, on May 18-19 and on May 28.

Original ESRL temperature data in Table 5.8 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^{o}C by 00UTC May 18. At Delhi the 500hPa temperature drops 5^{o}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^{o}C; at 400hPa at Lucknow the temperature change was small, decreasing only 1.2^{o}C by 00UTC May 18. The 500 and 400hPa temperatures at Gorakhpur dropped to -15.9^{o}C and -27.3^{o}C respectively by 00UTC May 19, a total drop of 9.8^{o}C, the coldest of these four stations after Shrinagar. At 34.08^{o}N and 74.83^{o}E Shrinagar is considerably further north. 19 May data was missing at Delhi and Shrinagar.

Table 5.8. 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**

5.5.5. 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 at 2133m asl from the Gorakhpur station (Table 5.9). 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 invaluable for normally inaccessible locations like the Himalayan Range.

Table 5.9. 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 5.10. 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

Note, Values followed by (19) are from original May 19 data only. May 17 dewpoints stopped at 600hPa and on May 19 at 400hPa. Dewpoint values above 400hPa are from NOAA ARL data. Values followed by "est" were estimated using both May 19 and NOAA ARL data.

Values followed by N are taken from NOAA ARL when no other data was available.

The completed Gorakhpur upper air profile for 00UTC May 18 from the surface, 77m asl (993hPa) to 26456m asl (20hPa) is shown in Table 5.10.

5.5.6. Gorakhpur Profile adjusted for Pokhara

To calculate the Stability Indices for Pokhara the above profile 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 5.10). 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.

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 previously estimated Gorakhpur 850hPa dewpoint temperature was changed to 18°C from 2.7°C (Table 5.11).

Table 5.11. 09UTC May 18 Pokhara surface, 900hPa and 850hPa data. Source: DHM

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

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 does not. Zero CAPE means 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 *(Doswell et. al.,2001).* It is important to remember that an extremely violent storm producing 1kg hailstones did occur mid-afternoon on May 18, between 1530 and 1550NST. All the necessary conditions for thunderstorm initiation, including a deep layer of humid air must have been in place at least an hour before 1530NST, to allow giant hail to grow.

This study aims to find, therefore, in spite of the lack of original 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.

5.5.7. Observed Cloud Base Heights versus 09UTC May 18 Surface Dewpoint Temperatures and Moisture Convergence Areas near Pokhara

There are valuable cloud observations by the DHM, including three hourly estimations of cloud base heights. A cloud base indicates that rising air has reached saturation level and that the air has condensed. At this level, the CCL, temperature and dewpoint temperatures are the same.

Using a SkewT- log P chart (Pennsylvania State University, Dept. of Meteorology) 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^{o}C and dewpoint temperature of 19.5^{o}C. The SkewT cloud base height (the LCL) is actually closer to 600m than to 1000m agl.

2. At 1145NST, with a surface temperature of 26.4^{o}C and dewpoint temperature of 20^{o}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^{o}C and the dewpoint temperature dropped slightly to 19.9^{o}C. The maximum surface temperature of 30^{o}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 28C and the surface dewpoint temperature of 19.9^{o}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 (*Egger et. al., 2000 , Rosoff et. al.,1998).* 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 *(Banta 1990, Barry 1992).* 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^{o}C and dewpoint temperature of 20^{o}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.

5.6. 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 sent westwards towards the foothills of the Himalayan Range. Table 5.12 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^{o}C at Patna; the average dewpoint here increased to 25.2^{o}C by 12UTC May 17. Surface winds from the east, then southeast and south at 645m asl at speeds of up to 15 knots exhibit the cyclonic circulation of this surface heat low.

Table 5.12. Original Patna upper air data for 00UTC May 17, 2005. Source: NOAA/ESRL Radiosonde Database

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

Table 5.13. 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 993hPa	499m asl 946hPa	719m asl 925hPa
May 16	**19.8C**	**missing**	**14.4C**
May 17	**19.4C**	**15.8C**	**13.2C**
May 18	**19.7C est.**	**19.9C est**	**16.2C est**
May 19	**20.2C**	**missing**	**19.2C**

.

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 5.13), the surface dewpoint temperatures at Gorakhpur averaged 19.8^{o}C; at 925hPa, the average was 15.8^{o}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 (*Ohata et. al.,1981, Rosoff et. al., 1998,* *Egger et. al., 2000*). Areas of significant moisture convergence result in the mountains from both mechanisms, the mountain-valley circulation and orographic lifting,

5.7. 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),if an air parcel is lifted dry adiabatically from the 30°C surface to 850hPa, which is 24°C, then if 850hPa is the cloud base height, 24°C is also the dewpoint temperature at that level. 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.

If this study assumes that the cloud base height (CCL) was at 600m agl, 850hPa, with a temperature of 24°C, then the resulting surface dewpoint temperature was 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 5.22) . Further Stability Indices calculations were made, using surface dewpoint temperatures of 22, 23, and 24ºC. All are extremely high. For each additional degree of surface dewpoint temperature, CAPE increases approximately 800J/Kg.

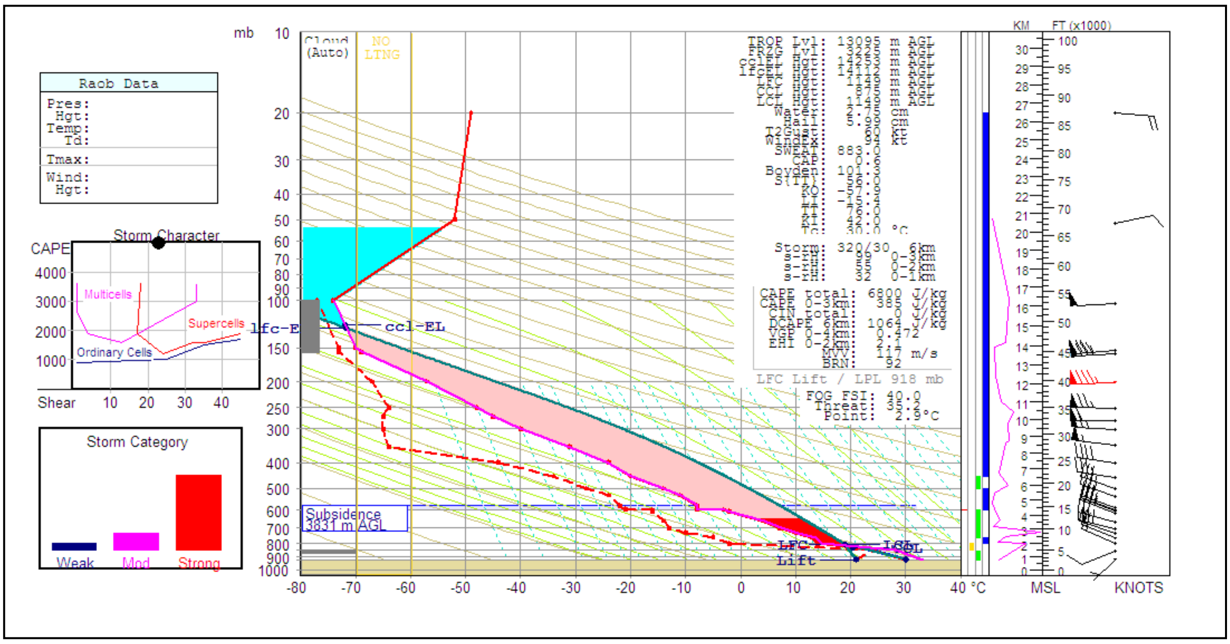


Figure 5.23. RAOB diagram indicating Stability Indices for Pokhara, 00UTC May 18, 2005. Source: NOAA/ESRL Radiosonde Database, DHM and NOAA ARL

The above Figure 5.23 shows the Skew-T log P chart and stability index calculations for Pokhara, 00UTC May 18. Following adjustments in the vertical profile at the surface and lowest tropospheric levels reflecting more realistic meteorological conditions, the RAOB calculations for potential CAPE values and other Stability Indices at Pokhara were surprisingly high. The LCL (Lifted Condensation Level) was at 1149m agl and the CCL (Convective Condensation Level) at 875m agl. Tc is 30ºC. The mid-level lapse rate between 760 and 500hPa is very steep and almost parallel to the dry adiabat, indicating a potentially extremely unstable atmosphere. The sounding is a “tall, skinny” sounding, more than 15000m high, with a freezing level at 3225m agl and a wet bulb zero height of 2231m agl, indicating a strong likelihood of very large hail. Precipitable water was low, 2.75cm, suggesting that the Pokhara giant hail producing storm may have been a LP (Low Precipitation) thunderstorm, similar to the classic supercells, notorious for generating very large hail stones, without rain. A MVV (maximum vertical velocity) of 117m/sec is likely to remain a theoretical value;

however, the updraft at Pokhara must have been sufficiently strong to keep extremely large hail stones aloft. Wind shear in the vertical profile was weak, a consequence of the highly complex terrain.

The hail growth zone, between -10ºC and -30ºC, is located approximately between 550hPa and 350hPa and coincides on the above SkewT diagram with the widest section of the CAPE area where the most intense CAPE and therefore the strongest updraft are located.

In spite of seemingly exaggerated, dangerously high Stability Indices, this study is theorizing 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.

CHAPTER 6

CONCLUSIONS

The preceding meteorological analyses of two severe, pre-monsoon thunderstorms in Nepal confirm much of what is already known about thunderstorm severity. The two thunderstorms were similar in that both generated hailstones estimated to weigh 1 kg, both occurred in May, they were both initiated in complex mountainous terrain and the basic convective initiation mechanisms were in place. Further detailed investigation indicated that the thunderstorms occurred under different circumstances and were the result of different thunderstorm enhancing processes.

The Thori hailstorm occurred close to midnight on May 3, 2001; convection was not thermodynamic. Infrared satellite images indicate that the storm was initially generated by a topographically induced lee- side convergence area in the deserts of Pakistan on May 2. Enhancement of the initial convective cell was provided by an upper level synoptic disturbance. Following propagation eastwards, the thunderstorm cells moved into the primary pre-monsoon surface heat low over the Thar Desert in India, an infrequently documented occurrence. This study also found several instances during this time of a fast daytime low level jet at 925hPa, providing warm, humid air, allowing the cells to propagate above the intensely heated, stable planetary boundary layer of the desert. The active cell propagation resulted in the formation of a Mesoscale Convective System near Delhi from where on May 3 at 1330UTC (1915NST) the system began propagating eastwards towards Thori. Fuelled at first by warm, humid air from the counter clockwise circulation of the active Bihar secondary surface heat low, the MCS attained speeds of up to 70km/hr several hours later when a fast, moisture laden easterly nocturnal low level jet, indicated in the 925hPa wind data from Gorakhpur and Patna, became established. The Thori region is also a known area of moisture convergence and experiences frequent hailstorms during the pre-monsoon months even with the absence of convection enhancers, such as active upper level support or a nocturnal low level jet. In this case, on May 3, ample and continuous moisture from the nocturnal low level jet likely strengthened the MCS and allowed for elevated convection at Thori, resulting in giant hail close to midnight. Pervasive atmospheric instability and dynamic lifting mechanisms aloft caused by a travelling embedded low pressure short wave at mid and upper tropospheric levels completed the scene for a severe weather event. The large CAPE values resulting from the high moisture content at low tropospheric levels ensured the intense maximum updraft where giant hail growth could occur so that the hail stones, after falling and melting on the way down, weighed 1kg when they hit the ground.

Unlike the Thori storm, convection for the Pokhara hailstorm was thermodynamic. Initial surface heating and convection took place north of Pokhara, towards the Annapurnas, probably about midday. Pokhara is at 800m asl and by mid-May surface temperatures can reach a maximum of 30 to 32 degrees centigrade. At this elevation, morning inversions are erased very quickly and lapse rates from the surface become very steep. Pokhara is situated in a valley and warm, humid air from the Gangetic Plains to the south is advected into the Pokhara region by the diurnal mountain-valley flows that reach maximum speeds by mid-afternoon.

Analyses of the synoptic environment indicated low pressure troughs at mid and upper tropospheric levels, typical of the season. Hand drawn synoptic charts for 00UTC May 18 indicate a very deep low pressure trough between 700 and 200hPa in the Gorakhpur area, with a low pressure axis oriented in a southeast northwest direction so that vorticity maxima generated dynamic lifting mechanisms directly above Pokhara were extremely likely. High humidity levels resulting from an active Bihar surface heat low contributed to the potential atmospheric instability in the region. Late afternoon thunderstorms had occurred on May 16 and 17 and there would have been a similar storm on May 18, except for several unusual and infrequent meteorological circumstances that were brought to light in the Infrared Images.

At 00UTC May 18, a low pressure area over northern Pakistan began crossing over the Karakorams and reformed over the Tibetan Plateau, resulting in wind directions approaching the Himalayan Range from a northwesterly direction, 320 degrees by 09UTC. Original ESRL data from Hotan (China), northwest of the Plateau indicate exceptionally cold temperatures at 500hPa, 400hPa and 300hPa at 12UTC May 17 and 00UTC May 18, accompanied by jetstream speed winds at 300hPa on May 17. Upper air temperatures had decreased at all the North Indian cities by 00UTC May

18. The Pokhara hailstorm was not only two hours earlier than those on the 16th and 17th, the 1kg hailstones on May 18 made it the most severe in Pokhara's history. It is highly likely, therefore, that the cold air intrusion occurring over the entire north Indian subcontinent was significantly more intense at Pokhara. Pokhara's severe convection was enhanced by additional cold air advected from the Tibetan Plateau on the lee-side of the Annapurna region.

The analyses of the two thunderstorms indicate some significant differences. Although the basic ingredients for deep, moist convection and destabilization of the atmosphere were available, there were additional elements present that enhanced storm severity, time and duration of the storms, type of convection, hail size and in mountainous terrain, where initial convection takes place. It is unlikely that the time and severity of the Pokhara hailstorm could have been forecast. Very sudden, cold air aloft, plus sufficient low level moisture, turned routine late morning mountain slope convection into a dangerously, violent hailstorm. The duration of the Pokhara hailstorm was between 15 and 20 minutes. The black thunderstorm cloud that suddenly emerged from behind Sarangkot moved extremely fast towards the southeast, while the southern half of the sky remained clear.

Pokhara, like Thori is a known location of moisture convergence and receives some of the highest precipitation in Nepal. The May 18 Pokhara storm, unlike the Thori hailstorm was not enhanced by moisture advection, but by very cold air aloft from upper tropospheric levels. The Thori hailstorm occurred close to midnight, at the convective edge of a propagating MCS, initiated from elevated convection and fuelled by a combined moisture supply from a fast nocturnal low level jet and the Bihar surface heat low.

Stability Indices for both storms were high, with CAPE values calculated from the surface of at least 7000J/kg for Pokhara. Predicted updraft speeds were estimated to be 117m/sec and predicted hail size was 6cm. Gorakhpur upper air data was missing for May 18 and Pokhara SI were calculated from the surface with upper data that was averaged from May 17 and 19. Actual upper air temperature values advected from the Tibetan Plateau towards Pokhara may have been lower than those used for SI calculations, resulting in even higher instability and CAPE values. Stability indices calculated from the surface for Thori 11UTC May 3 yielded CAPE values of more than 8000J/kg. CAPE calculations for the midnight Thori thunderstorm, with convection beginning at 925hPa and using Gorakhpur upper air data averaged from 11UTC May 3 and 00UTC May 4, yielded values of close to 5000J/kg. Maximum potential updraft speeds for Thori, like those for Pokhara, were close to 100m/sec.

In complex mountainous terrain, such as the Himalayan Range, forecasting severe thunder and hail storms will remain a challenge, even if more upper air data become available. The hailstorm analyses for Thori and Pokhara in this study attempted to outline and describe storm characteristics that may not have been previously noted, but may also provide some guidance for future research and severe thunderstorm forecasting in Nepal.

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APPENDIX 1

Pokhara Airport Wind Data for May 1 – 25, 2012

By 2012 the DHM had installed an automatic weather station at the Pokhara Airport.It is assumed that the wind speed and wind direction during the pre-monsoon month of May at the Pokhara Airport is not likely to undergo significant change. The airport is located in highly complex terrain and would not have been built there if wind speed and directions had not been reasonably consistent. With the DHM Pokhara Airport wind data missing for 2005, this study did an analysis of wind data collected by the DHM at the Pokhara Airport for the period May 1 to May 25, 2012. In all likelihood the 2012 wind data closely resembles the 2005 wind data. Wind patterns clearly reflect the diurnal Mountain-Valley wind flows behaviour.

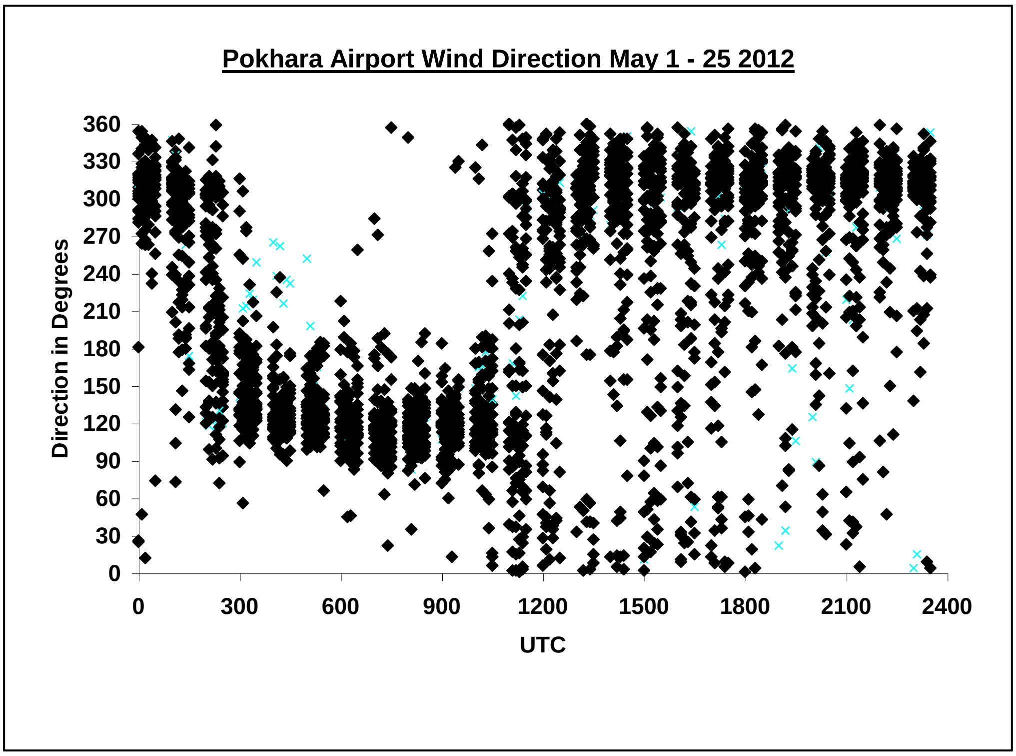


Chart 1. Wind Direction in degrees at Pokhara Airport, May 1-25, 2012. Source DHM

The above analysis (Chart 1) indicates the wind direction at the Pokhara Airport for May 1 to May 25, 2012. The direction is in degrees; data points were recorded every ten minutes. Time is UTC; 00UTC is 0545hrs Nepal Standard Time. Based on Chart 1, the prevalent wind direction during May from 00UTC (0545NST) to 03UTC (845NST) is from 270 to 345 degrees, occasionally shifting to its daytime direction, between 90 and 160 degrees almost an hour earlier at 02UTC (745NST). Daytime wind direction has settled mostly by 03UTC (845NST) and continues until approximately 11UTC (1645NST), a total of 8 hours. The rather abrupt switch in wind direction (the so-called transition period), from a daytime up-valley southerly and southeasterly direction to a mostly northerly and northwesterly direction, characteristic of thermally initiated flows in mountainous terrain, begins occurring between 1130UTC (1715NST) and 12UTC (1745NST). A wind direction, between

270 and 345 degrees is maintained consistently from 12UTC (1745NST) to 02UTC (745NST), a total of 15 hours.

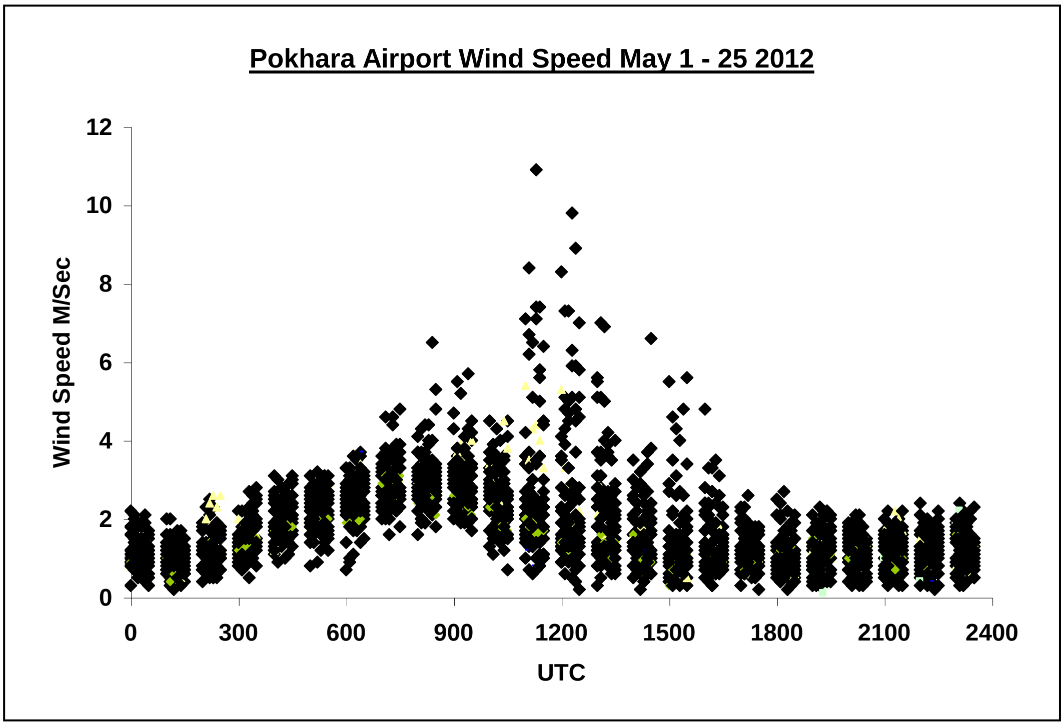


Chart 2. Wind speed in meters/second at Pokhara Airport from May 1 –25, 2015. Source, DHM

Wind speeds as indicated in Chart 2 from 00UTC (0545NST) to approximately 02UTC (0745NST) range from 0.3 to 2.4 m/sec; direction is from 270 to 345 degrees (see chart 1). By 03UTC (0845NST) at the approximate onset of daytime up-valley winds, speeds are seen to increase slowly, reaching up to 2.7 to 5 m/sec by midday. Maximum daytime winds of 3 to 6 m/sec occur between 830UTC (1415NST) and 11UTC (1645NST), from a 90 to 160 direction. The 6 to 11 m/sec wind speeds seen in the above chart between 11 and 13 UTC (1645 and 1845NST) occurred on May 21. By 12UTC (1745NST), wind speeds generally return to the slower nighttime speeds of 0.3 to 2.2 meters/sec from a 270 to a 345 degree direction.

APPENDIX 2

Satellite Information

Meteosat Indian Ocean Data Coverage Imagery

The Meteosat Visible and InfraRed Imager (MVIRI) is a high resolution radiometer with three spectral bands. The MVIRI acquires radiance data from the full earth disc during a 25-minute period. This is followed by a five-minute retrace and stabilisation interval, so that one complete set of full earth disc images is available every half-hour. The radiometer operates in three spectral bands:

Available Near Real-time Products	
	Description
	Infrared 11.5 MVIRI spectral channel over black and white background The Thermal Infrared (IR) band is used for imaging by day and by night, and also for determining the temperature of cloud tops and of the ocean's surface. This band corresponds to peak re-emission of radiation from the Earth's surface and atmosphere, according to their temperature. As with the VIS band, the atmospheric gases are fairly transparent in this region.
	Infrared 11.5 MVIRI spectral channel over color background
	Visible 0.7 MVIRI spectral channel over black & white background The Visible (VIS) band (0.45 to 1.0 µm) is used for imaging during dayight. This band corresponds to peak solar irradiance; furthermore the atmospheric gases are fairly transparent to incoming and outgoing (reflected)

solar radiation in this band.

Visible 0.7 MVIRI spectral channel over color background

Water Vapour 6.4 MVIRI spectral channel over black and white background
The Water Vapour (WV) absorption band (5.7 to 7.1 µm) is used in determining the amount of water vapour in the upper troposphere. It takes advantage of the strong absorption of emitted terrestrial radiation by atmospheric water vapour. In this spectral region, the atmosphere is very opaque if water vapour is present, but transparent if the air is very dry.

APPENDIX 3

From Kathmandu Post Archives

Ktm Post Article 15 May 2001

KTM Post Report

BIRGUNJ May 14

People of Thori, a remote village adjoining Chitwan district, are wondering as to why the Chief District Officer CDO in Parsa has been unable to visit their village even 10 days after the worst incident of devastation that occurred in their village.

The Chief District Officer has also been unable to read three separate memorandums sent by local VDC Office, Ilaka Police office and some local people about the incident

Brihaspati, 40, of Thori says he has not seen such a devastating incident in his life. People of Thori say it is an irony that the Chief District Officer who has been entrusted with the responsibility of protecting the life and property of local people has not visited the site so far after such a massive destruction and regards the incident as a minor one.

When Chief District Officer Dolakh Bahadur Gurung was asked why he did not visit the damaged site, he said he was too busy with different programmes. He informed that he wanted to visit on Sunday, but he had to attend an interaction programme organized by PABSON about the problems encountering different schools.

When he was told about the extent of damage, he was surprised. He said, "Is this true? I will then visit that village tomorrow."

He also admitted that he had received three reports, but he had not been able to read them due to lack of time. People have written to him demanding relief assistance. They have also sent a memorandum to the prime minister requesting him for relief assistance.

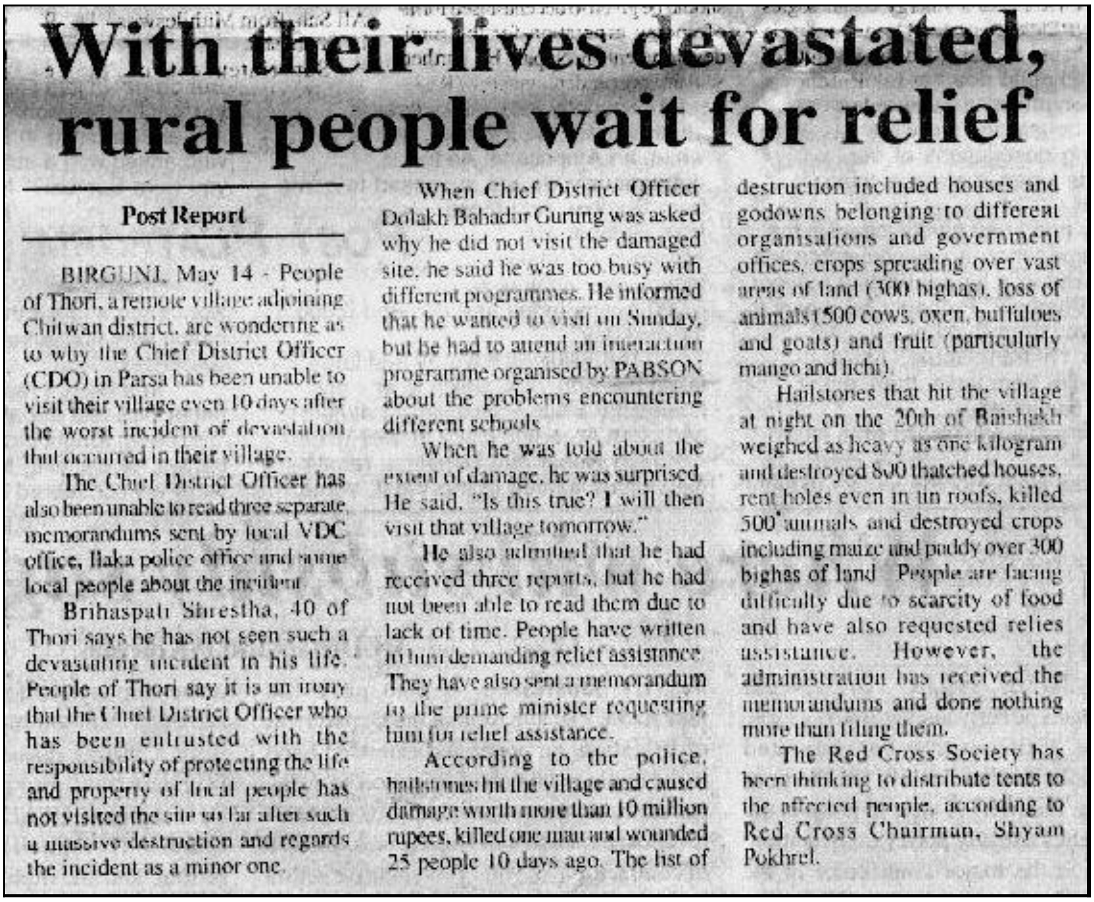
According to the police, hailstones hit the village and caused damage worth more than 10 million rupees, killed one man and wounded 25 people 10 days ago. The list of destruction included houses and godowns belonging to different organizations and government offices, crops spreading over vast areas of land. 300 bighas, loss of animals, 500 cows, oxen, buffaloes and goats and fruit (particularly mango and lichi).

Hailstones that hit the village at night on the 20th of Baishakh weighed as heavy as one kilogram and destroyed 800 thathchd houses, rent holes even in tin roofs, killed 500 animals and destroyed crops including maize and paddy over 300 bighas of land. People are facing difficulty due to scarcity of food and have also requested relief assistance. However, the administration has received the memorandums and done nothing more than holding them?

The Red Cross Society has been thinking to distribute tents to the affected people, according to Red Cross Chairman, Shyam Pokhrel.

APPENDIX 4

News Paper Highlights



With their lives devastated, rural people wait for relief

Post Report

BIRGUNJ, May 14 - People of Thori, a remote village adjoining Chitwan district, are wondering as to why the Chief District Officer (CDO) in Parsa has been unable to visit their village even 10 days after the worst incident of devastation that occurred in their village.

The Chief District Officer has also been unable to read three separate memorandums sent by local VDC office, Ilaka police office and some local people about the incident.

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Hailstones that hit the village at night on the 20th of Baishakh weighed as heavy as one kilogram and destroyed 800 thatched houses, rent holes even in tin roofs, killed 500 animals and destroyed crops including maize and paddy over 300 bighas of land. People are facing difficulty due to scarcity of food and have also requested relies assistance. However, the administration has received the memorandums and done nothing more than filing them.

The Red Cross Society has been thinking to distribute tents to the affected people, according to Red Cross Chairman, Shyam Pokhrel.

nal Daily ❑ 20 May, 2005 ❑ पृष्ठ ४ ❑ मूल्य दुई रुपैया

प्रकृतिको पटक-पटकको प्रहारले सिंगो काहूँ शोकमग्न

महिना दिनको अन्तरालमा दुई होनहार किशोरको मृत्यु

❑ भेषराज आचार्य

पोखरा, ५ जेठ। पोखरा उपत्यकासँगै सिमाना जोडिएको शान्त काहूँ गाउँ पटक-पटकको प्राकृतिक बज्रप्रहारका कारण यतिबेला मर्माहत बन्न पुगेको छ।

प्राकृतिक प्रकोपले सोझा गाउँबासी माझबाट होनहार दुई युवाहरु खोसेर लगेपछि उनीहरुका आफन्तमात्र होइन, पुरै काहूँबासी नै यतिबेला मर्माहत भएका छन्।

गत महिना प्राकृतिक प्रकोप चट्याङमा परी १४ वर्षीय किशोर अमृत लामिछानेको मृत्यु भएपछि मर्माहत बनेका काहूँबासी पुनः बुधबार हावाहुरीसहित आएको असिनाको प्रहारबाट अर्का होनहार किशोर महेश आचार्यको मृत्यु भएपछि झनै मर्माहत भएका हुन्।

चट्याङबाट मृत्यु हुने अमृत लामिछाने

असिनाबाट मृत्यु हुने महेश आचार्य

गत बैशाख १० गते भारी वर्षासँगै परेको चट्याङमा परी गाविसको वडा नं. [illegible] लामिछानेथरका पुण्यप्रसाद लामिछानेका १४ वर्षीय छोरा अमृत लामिछानेको निधन भएको थियो।

[illegible] बुधबार परेको असिनाबाट सोही गाविस वडा नं. ८ मचारीका रामजीप्रसाद आचार्यका जेठा छोरा महेश आचार्यको पनि निधन हुँदा सिंगो गाउँ यतिबेला शोकमग्न बनेको छ।

पोखरा औद्योगिक क्षेत्रमा कार्यरत रामजी आचार्य विगत केही वर्षदेखि पोखरा उप-महानगरपालिका वडा नं. १२ कुँडहरस्थित प्रगतिटोलमा बस्दै आइरहेका थिए।

पोखराकै कुमुदिनी होम्स्‌बाट यसपालीमात्रै प्रवेशिका परीक्षा दिएर घरमै बसेका रामजीका जेठा छोरा महेशको बुधबार अपरान्ह हावाहुरीसँगै आएको असिनाको प्रहारले निधन भएको थियो।

आफ्नै घरमा रहेको पसलमा बसिरहेको बेला असिना पर्न थालेपछि पसलमा घाम छेक्न झुण्ड्याइएको पाल झिक्न लाग्दा असिना महेशको टाउकोमा वर्षिएको थियो। असिनाको प्रहारपछि टाउको समाउँदै केहीबेर बेञ्चमा बसेका महेशले कोठाभित्र गई आफैले एक गिलास पानी समेत पिएको उनको परिवार बताउँछन्।

पानी पिएपछि मलाई चक्कर लाग्यो भन्दै खाटमा गएर सुतेको केहीबेरमै वान्ता गर्न थालेपछि परिवारले महेशलाई ट्याक्सीमा राखी गण्डकी अस्पताल पुऱ्याएको केही बेरमै चिकित्सकले मृत घोषणा गरेका थिए।

परिश्रमी र मेहनती स्वभावका महेश अध्ययनमा पनि त्यत्तिकै लगनशील भएको उनले अध्ययन पुरा गरेको कुमुदिनी होम्सका कक्षा शिक्षक बोधराज ढकाल बताउनुहुन्छ।

बोलीबचनमा मिठास, साधारण लवाई र अनुशासित महेशले प्रवेशिका परीक्षामा ७० प्रतिशतभन्दा बढी अंक ल्याउने अपेक्षा राखिएको शिक्षक ढकालले आदर्श समाजसँग भन्नुभयो।

एसएलसीको परीक्षापछि पनि घरमा त्यसै बस्न राम्रो हुँदैन भन्दै महेशले नै किराना पसल राख्न कर गरेपछि बैशाख २८ गतेदेखि पसल सुरु गरिएको परिवारका सदस्यहरु बताउँछन्।

२०४४ साल फागुन ४ गते जन्मिई भर्खर १८ बसन्तमा टेकेका मृतक महेशको बिहीबार अपरान्ह रामघाटस्थित सेती नदीमा दाहसंस्कार सम्पन्न गरियो।

उता स्थानीय पोखरा-११, फूलबारीस्थित भाष्कर मेमोरियल बोर्डिङ स्कुलमा कक्षा ९ मा अध्ययनरत अमृत लामिछाने पनि पढाइमा निकै तेज रहेको विद्यालयका प्रिन्सिपल माधवी बाँस्तोला बताउनुहुन्छ।

यसरी महिना दिनको अन्तरालमा गाउँका दुई होनहार किशोरलाई प्रकृतिले खोसेपछि सिंगो काहूँ गाउँ नै यतिबेला शोकाकुल बन्न पुगेको छ।

Samadhan National

वर्ष ३ अंक २२८ २०६२ जेठ ५ गते बिहिवार

08/19/2014

पोखरामा विनाशकारी असीना वर्षा

एकको मृत्यु, दर्जनौं घाईते, लाखौंको क्षति

■समाधान सम्वाददाता

पोखरा, ४ जेठ ।

बुधबार अपरान्ह ३:४५ बजे पोखरामा परेको विनाशकारी असीना वर्षाबाट एक युवकको मृत्यु भएको छ । असीना वर्षाबाट दर्जनौं घाइते भएका छन् भने लाखौं रुपैयाको क्षति भएको छ ।

पोखरा उपमहानगरपालिका वडा नं. १८ कुँडहरका १८ वर्षीय युवा महेश आचार्यको असीनाले लागेर मृत्यु भएको हो । आफ्नै निवासमा रहेका आचार्यमाथि एक्कासी असीना बर्सिएको थियो ।

आफ्नै फसलमा पाल टाँग्दै गर्दा असीना लागेर घाइते भएका आचार्यको पश्चिमाञ्चल क्षेत्रीय अस्पताल पोखरामा उपचार हुँदाहुँदै मृत्यु भएको हो । उनको टाउको र मुखमा गम्भीर चोट लागेकी थियो ।

असीना लागेर घाईते भएका मध्ये पाँच जना पश्चिमाञ्चल क्षेत्रीय अस्पताल पोखरामा उपचारार्थ भर्ना भएका छन् । कुँडहरकै जमुना [illegible]को अवस्था गम्भीर छ । उनको टाउको र नाकमा चोट लागेको छ । असिनाकै चोटले लेखनाथ नगरपालिका ८ शिशुवाकी ३० वर्षीया [illegible] पाण्डेको आँखा फुटेको उनकी [illegible] सम्भना अर्यालले समाधानलाई बताइन् । स्कूलबाट फर्केका आफ्ना [illegible] असिनाबाट जोगाउन खोज्दा आँखा फुटेको थियो । पाण्डेको हिमालय अस्पतालमा उपचार भैरहेको छ ।

अन्य घाइतेहरुमा पोखरा-१४ चाउथेका पाँच वर्षीया सुनिता श्रेष्ठ, चितवन घर भई पोखरा विजयपुर बस्ने १५ वर्षीय सुवास थापा र लेखनाथ ५ की ३५ वर्षीया बालकुमारी रानाभाट अस्पतालमा भर्ना भएका छन् । अन्य सामान्य घाईतेहरुले निजी अस्पतालमा उपचार गराएका छन् भने कतिपयले घरमै उपचार गराएका छन् ।

५ मिनेटमात्र भएको ठूला-ठूला असीनावारीले पोखरामा आतंक मच्चायो । सडकमा हिडेका अधिकांश गाडीका शिशा फोडिएका छन् भने गाडी कुच्चिएका छन । घरको उपल्लो छतमा राखिएका अधिकांश सोलार सिस्टम फुटेका छन् । तरकारी बाली तथा अन्य बालीमा ठूलो क्षति पुगेको छ ।

"मैले मेरो जीवनमै यस्तो विनाशकारी असीना परेको देखेको थिईन ।" पृथ्वीचोक निबासी पार्वता पौडेलले समाधानसित भनिन्-"असीना पनि यति ठूला हुने रहेछन् ।"

पोखरामा दैनिकजसो तीन बजेपछि पानी पर्ने गर्छ । अन्य दिनमा जस्तै सामान्य पानी पर्ने लक्षण थियो । तर पानी परेन, एक्कासी असीना पर्न थाल्यो । एक्कासी डर लाग्ने आवाज गर्दै असीना पर्न थालेपछि सडकमा हिडेका मानिसहरुमा हाहाकार मच्चियो ।

प्रत्यक्षदर्शीका अनुसार आधा किलोसम्मका असिना परेका थिए । असीना पर्न थालेपछि मान्छेहरु घरमा पसेर जोगिए पनि सवारी साधन भने जोगिएनन् । सडकमा पार्किङ गरेर राखिएका मोटरसाईकल र गाडीहरु क्षतीग्रस्त भएका छन् । "तरकारीमा पुगेको क्षतिको लेखाजोखा छैन ।" कृषक सविता भण्डारीले समाधानसित भनिन् ।