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Pre-Monsoon Thunderstorms in Nepal

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***Abstract*— *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 might explain their severity. 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.*
Keywords—Pre-Monsoon Thunderstorms, Heat Lows.

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.

Bihar Surface Heat Low and Humid Air Transport

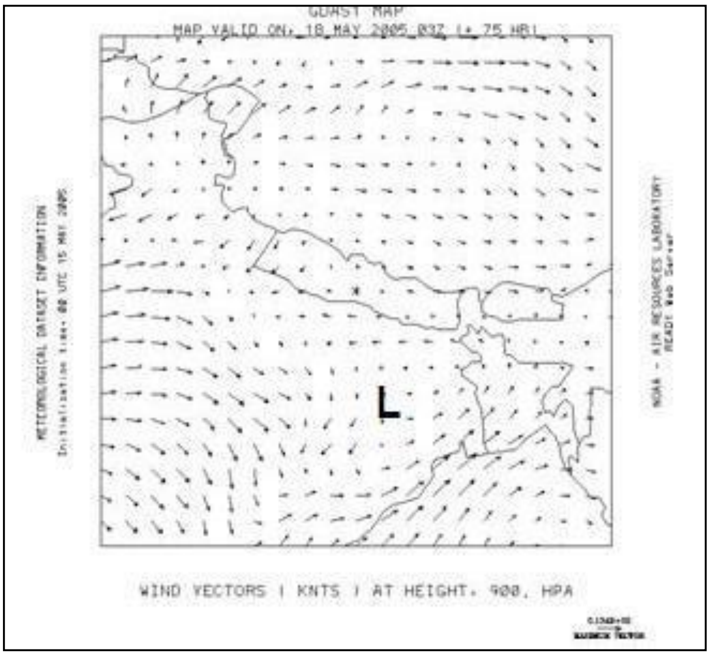

Fig.1: The 900hPa wind vectors for 03UTC, 0845NST May 18 and the surface heat low just south of Patna. Source NOAA ARL Archives.

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Figure 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.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 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 21.6C is indicated.

Table.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 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.

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 *(Rao 1981, Pant and Rupa 1997, Laing and Fritsch 2007, Mandhar et. al., 1999).* 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.

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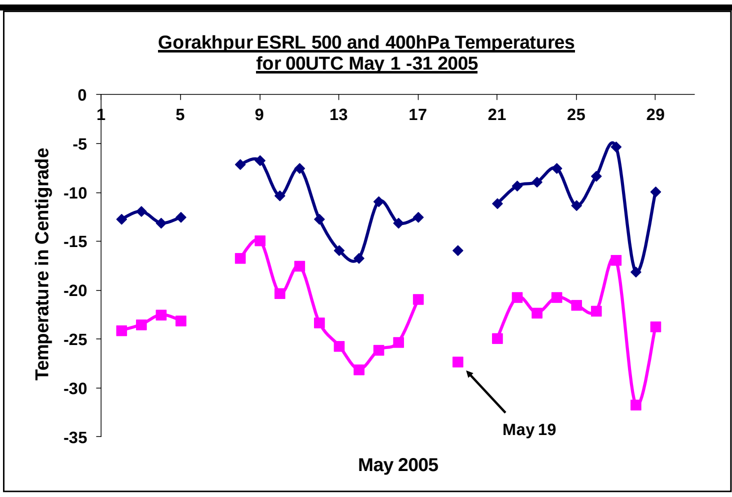

Fig.2: Gorakhpur 00UTC 400hPa (bottom line) and 500hPa (top line) temperatures in Centigrade for May 2005. May 5, 6, 7 and 18 are missing. Source: ESRL

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 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 -16.7ºC on May 8, to -27.3ºC on May 19 and -31.7ºC on May 28. The 500hPa temperatures varied similarly, from -7.1ºC on May 8, to -15.9ºC on May 19 and -18.1ºC 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.

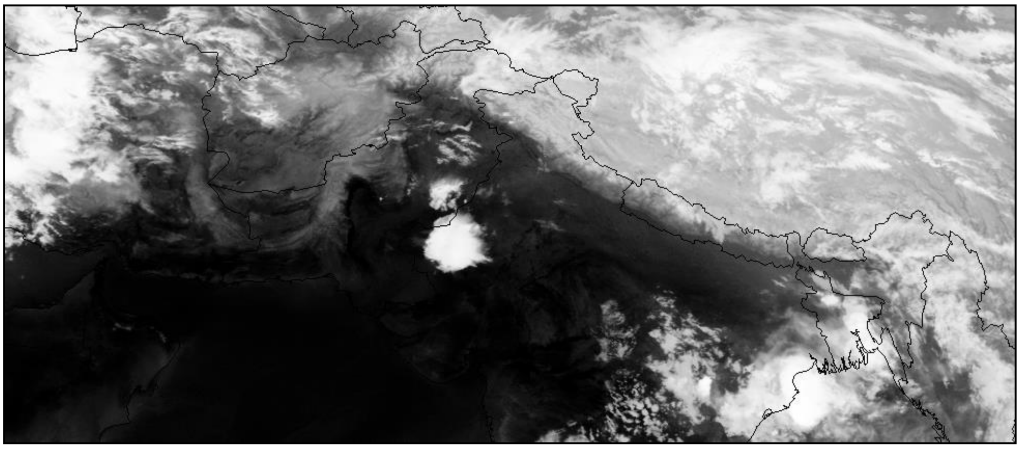

Fig.3: 19UTC May 2 (045NST) May 3, 2001 IR image of a thunderstorm cluster over the Thar Desert. Source: U of Dundee Receiving Station

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. A lone thunderstorm cluster (Figure 3) over NW India at 045NST, May 3, 2001 illustrates a likely small, synoptic disturbance at high tropospheric levels enabling elevated convection to be initiated. 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.

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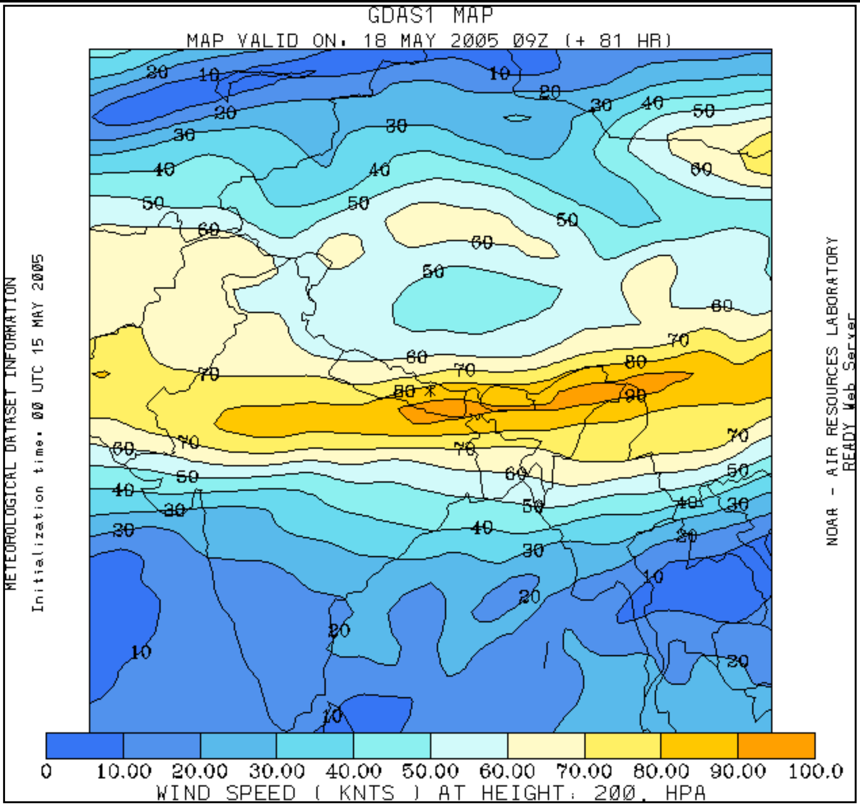

Fig.4: 200hPa wind speed for 09UTC May 18,2005. Source: NOAA ARL Archives.

Figure 4 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.

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 Tarai. From there, the well-documented diurnal Mountain-Valley Circulation (*Ohata et. al., 1981*) 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.

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, channelling 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 (*Makela et.al., 2013*). 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 (*Rosoff et. al., 1998*).

It is thought that all thunderstorms produce hail which, at sea level usually melts on the way down. In high, elevated

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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).

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 Tarai. 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.

Classification of Thunderstorm Types

Daytime or late afternoon thunderstorms occurring in the Nepal Himalayas above 3000m asl are predominantly single cell. 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 have been observed. Thunderstorms along the Tarai in Nepal are known to be violent and destructive. Convective activity is likely to 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 5 and 6 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 5). 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 6).

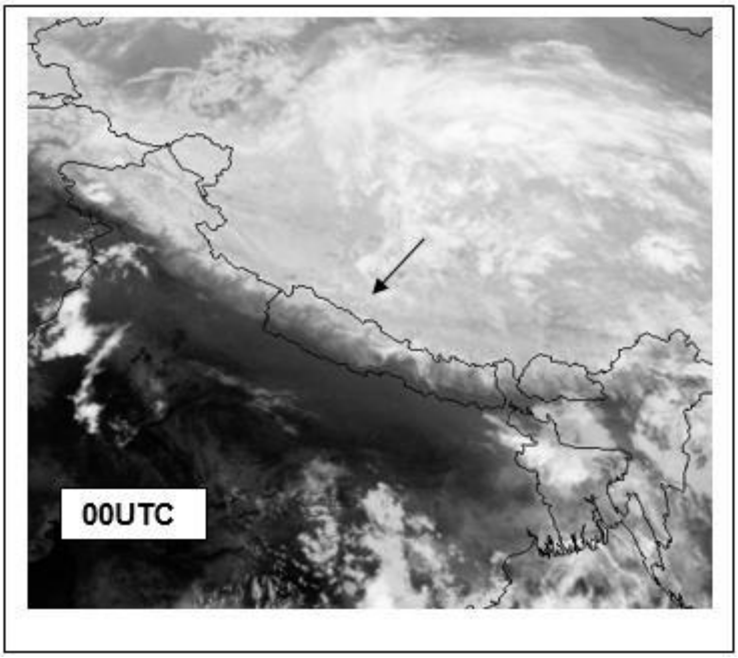

Fig.5: Archived Infrared image of 00UTC (0545NST) May 3, 2001.Source: U of Dundee Receiving Station.

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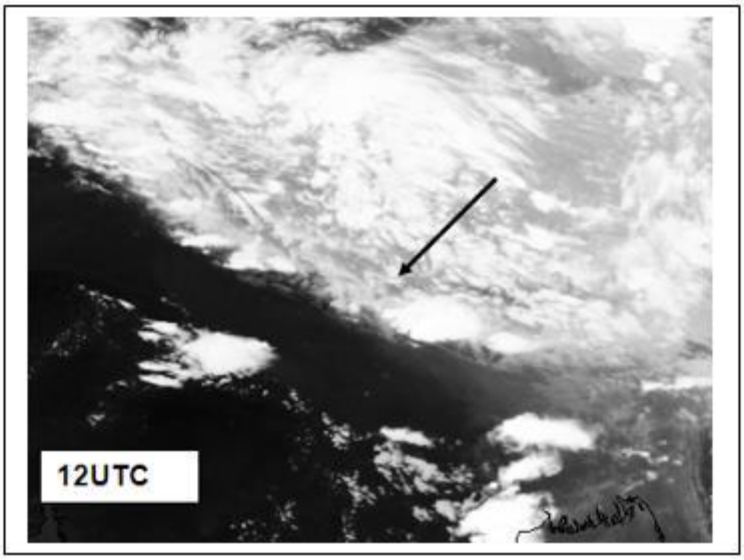

Fig.6: Archived Infrared image for 12UTC (1745NST) May 18, 2005. Source: Unervesity of Dundee receiving station.

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 6 is 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 5). The arrow indicates the northern tip of the Kali Gandhaki 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.

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 vapour 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 -40ºC. Large hail is formed in the strong updrafts and regions of supercooled water in severe convective storms between levels of -10ºC and -30ºC. 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 vapour inside the cloud behaves like a glue when the hailstones collide and causes them to fuse (Knight et al) or 2. Hailstones are solid ice and very high inside the cloud will bounce away from each other during collisions, but those that are in the process of falling and melting have a very thin layer of super cooled water on the surface. 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.

Strong Updrafts and Windshear

Extreme buoyancy from high CAPE values determines 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 (*Knight et. al., 2005*). Hail falling in elevated terrain spends less time in warmer temperatures near the surface and is less likely to evaporate or melt.

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 (*Knight et. al., 2005*). 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.

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