Rare meteorological events over the North East (NE) part of India: An analysis in the background of atmospheric dynamics of the Sub Himalayan zone

M Devi *[1,2,3], A.K. Barbara[1,2], A. Medhi[3], S. Das[3], and S. Patgiri[3]

[1]Department of Physics, Gauhati University
[2]Electronic Scientists and Engineers Society, Assam, India
[3]S.T. Radar Centre, Gauhati University

Abstract

The paper presents an analysis of two rare meteorological phenomena : (i) an unseasonal hailstorm over Guwahati (26.12^0 N, 91.7^0 E) and (ii) a snowfall event experienced after a gap of 50 years in Shillong (25.578^0 N, 91.89^0 E) of North East (NE) part of India. The aim is to identify the sources of the events with wind speed, direction, their respective shears and the lifting index as inputs along with the implicit atmospheric parameters like temperature, humidity, and their spatial and temporal variations. The other components of the study are pollutants and their contributions to resultant temperature both in the growth of hailstorms and snowfall. Finally, the analyses are presented by examining the role of wind flow patterns to the respective zone from the Sea and Sub Himalayan Terrain (SHT) along with the relevant physics. The data sources comprise the observed atmospheric parameters from embedded systems placed at the University as well as those collected from radiosonde by the India Meteorological Department (IMD), the model derived atmospheric variabilities from the website, and the trajectory model for wind direction.

Keywords : Rare meteorological events Hailstorm and Snowfall , Wind speed and wind direction shear, pollutant, SHT , NE Zone

1 Introduction

In whatever modes, we study the meteorological status either in short-term variations in the atmospheric parameters in case of weather or long-term changes of such variabilities extending for 30-40 years in case of a climate, researchers always welcome new inputs, especially for understanding rare and unexpected phenomena. Because these events are inherent potential tools for offering more additional inputs in the quest for understanding unsolved problems in atmospheric dynamics. In such issues, sudden and unexpected growths of worst weather situations do carry much significance.

*corresponding author:md555gu@gmail.com

The implicitly associated atmospheric parameters in weather situations are the temperature, humidity, potential temperature, and their resultant variations both in temporal and spatial fields right from the earth's surface to the troposphere and beyond. The wind flow pattern even beyond tropopause in altitudes and thousands of km along the spatial and radial distances are equally important factors contributing to the growth and control of weather events.

One of the key regions of the atmosphere controlling weather is the Planetary Boundary Layer or Atmospheric Boundary Layer(PBL/ABL), the lowest part of the atmosphere) covering $100m$ to $2km$ above the ground and is therefore influenced by the near-earth. environments. The typical depth of the PBL is 1 km during the day and goes down to $100m$ during night hours, beyond this zone lies the free atmosphere. PBL is the important zone to provide dynamics of the lower atmosphere like convection, inversion, and the wind components which have a strong role in weather modification because of the direct influence of the earth's surface on it [Moeng and Sullivan, 1994]. The PBL is also the major contributor of heat and moister necessary for the growth process of many weather phenomena like hailstorms, and thunder and PBL schemes like YSU, MYJ, and MYNN using object-based methods tailored to thunderstorms are available for providing short-term storm prediction [Potvin et al., 2020]. The role of PBL in weather systems however is complex as the situations depend on many factors including topography, ground, and environment of the surrounding locations.

Equally important is the contribution of the free atmosphere above the PBL in weather modification. In this zone, mixing is supposed not to be influenced by ground conditions as such, but is more complex because of the forcing from the lower region and also from the above beyond the tropopause, thereby modifying the gradient of temperature and humidity profiles that might show either strong convection or duct or inversion in between. Because of such situations, the free atmosphere also possesses significant importance on the status of aerosols and pollutants, which may undergo free movement or may trap in between, resulting in the growth process of instability leading to many meteorological hazardous phenomena. Therefore, the aerosol or more strictly anthropogenic part of it is one of the key factors in triggering such events.

The next important but equally effective parameter coming into play in any weather phenomenon be it precipitation, thunderstorms, cyclone, or hails, is the moisture and its available content in the air, along with the contributions of aerosol and anthropogenic pollutants to it, because anthropogenic sources may either increase or decrease the strength of a storm and associated precipitation as a result of their radiative and CNN activities [Cotton et al., 2007; Emanuel, 2017; Gray, 1988]. Therefore, an association of pollutants with any worst weather situation like a cyclone [Devi et al., 2014a,b, 2021], thunderstorm [Devi et al., 2020], hail, and snowfall [Feng and Hu, 2007] remain one of the most complex atmospheric dynamics affecting even the health-related issues [De Sario et al., 2013; Fischer et al., 2008].

The paper examines here two rare events that occurred in the NE region, of India in 2021 & 2022, the snowfall event and hail storm phenomenon respectively, in search of identifying the involved input parameters.

2 Brief background of the study region in relation to worst weather situations: Hail storms and Snowfall

A hail storm originates in the background of a thunderstorm which may be made up of a single cell (pulse type) in the hot ground with available moisture content because such an environment can provide maximum energy for the storm to build -up. A storm of this type grows in presence of vertical wind shear the strength of which controls the storm intensity. If the atmosphere is very moist, the storm can lead to flash flooding or precipitation. Hail is a type of precipitation and is formed when drops of water freeze together in the cold upper regions of thunderstorm clouds. Therefore, the formation of hail has to have a thunderstorm background with a relatively hot temperature at the ground, cold at the high altitude, and availability of water in the atmosphere. Snow and snowflakes grow in cold weather, while the growth of hail is greatly inhibited by cold surface temperatures.

These phenomena of hail and snow are thus associated with a similar atmospheric background but with qualitative variations in the strength of these variabilities and receive special attention in their anomalous occurrences be in the type or in a temporal pattern.

The NE topography and meteorological status are complex with Sub Himalayan Terrain (SHT) extending to the zone, and the flow of precipitation to the region is contributed by humid air circulated both from the Bay of Bengal (BOB) and Arabian Sea (ARB), though the main source of precipitation to NE is from the BOB. Further, long hops of airflow are also entering the zone far beyond $30^0 - 40^0$ N and $80^0 - 90^0$ E along the path of SHT, making the atmospheric dynamical environment more complex. Therefore, it is essential to track the air route to identify the source of the precipitation along with the possible flow of anthropogenic pollutants that contributed significantly to the weather system.

With this background, the paper aims to analyze the following two rare meteorological phenomena that occurred in the NE region of India in identifying the parameters involved in the process and to understand possible Physics and dynamics leading to the events.
These events are:

1. Strong hail storms in the month of early February i.e., on 5.2.2022 over Guwahati (26°11′03″N Longitude: 91°44′44″ E Elevation above sea level: $59m = 193ft.$), an event not seen in the last few decades.
2. Snowfall in Shillong ($25.5788°N, 91.8933°E$ $1520m$ above the sea level), 22 December 2021, an event that occurred after a gap of 50 years.

3 Analysis

We will present first the case of a Hailstorm event in Guwahati that occurred on February 5, 2022.On this day, a sudden unseasonal hail storm hit Guwahati, at around $1500hrs - 1530hrs$ that covered the greenery, a totally unexpected scene over Guwahati, especially in early February. The storm accompanied by the unusual hail lasted for about 20 minutes.

A few basic parameters necessary for understanding such phenomena are (a) temperature (b) rate of change of temperature with time and altitude, (c) humidity,(d) wind speed & direction and respective shears and their flow pattern with altitudes, and (e) pollution level in the environment. These aspects will be discussed in the following articles.

3.1 Temperature at the ground level and higher attitudes

3.1.1 Surface Temperature

The diurnal variation in surface temperature profiles before and after the hail-storm event along with the humidity level received from a highly sensitive temperature and a humidity sensor placed at Gauhati University is presented in Figure. 1 covering mainly Day 5 and Day 6. A record of warm background

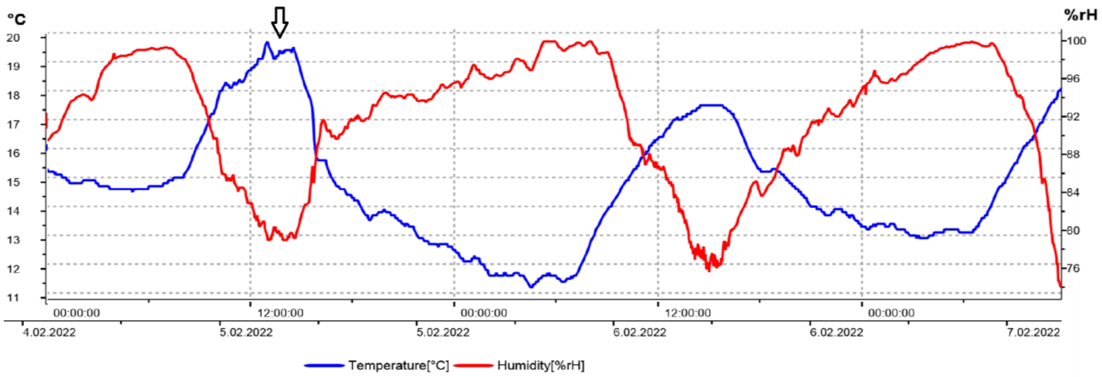


Figure 1: Displays the sensor outputs of surface temperature and humidity from February 4 to 6, 2022. The presence of a relatively warm temperature in the humid background on February 5 as seen in the profile, a few necessary conditions for the development of a hailstorm.

with temperature 19 °C and 20 % high humidity status on 5^{th} February compared to the 6^{th} of February is suggestive of a suitable onset of a storm-like phenomenon. However, these conditions alone cannot be preludes to the onset of a storm event, because we see from diurnal temperature records covering February 3 to 7 (Figure. 2) that though February 5 was a relatively warm day with a surface temperature of more than 18°C as prevailed during noon, there are also days with similar background temperature around the period. Therefore, more in-depth analyses on temperature /humidity especially their altitude variations need to be carried out along with other involved parameters, for identifying the involvement of such parameters with the onset of a storm.

3.1.2 Altitude variation of temperature

The modes of change in temperature with the height from the surface to the tropopause, offer the index of atmospheric system stability or otherwise. The decrease in temperature with height to the tropopause though is well expected, its rate of change with altitude or an inversion provides the Physics and dynamics of the system. On February 5th while the surface environment was warm (Figures. 1 and 2), the temperature variations with altitudes (Source: Vantusky Figure. 3) present a lowering of its value from $4.5km - 6km$ all throughout the day i.e., from 0230 hrs to the end of the day (20:30 hrs) with a more significant decrease during 11:30 hrs - 14:30 hrs (prior to and beginning of the storm) compared to the normal day figures as displayed in the altitude variations of temperature of Figure 3 covering days from February 1 to 6, 2022.

As a measure to assess the reliability of this model's predicted values, the radiosonde profiles over Guwahati are then presented in Figure. 4, for a normal day environment (3.2.2022) and also for the hailstorm day collected by the India Meteorological Department (IMD). Important to identify here two aspects of the hailstorm day profile even in the morning hours (when radiosonde data are available):

1. Presence of a high surface temperature on 5^{th}, even warmer compared to the non-event day value, and
2. Cooling was rapid beyond $5km$ on a hailstorm day compared to a normal day.

The lapse rate at higher altitudes (beyond $5km$) is $-8°C/km$ on this day while its normal average

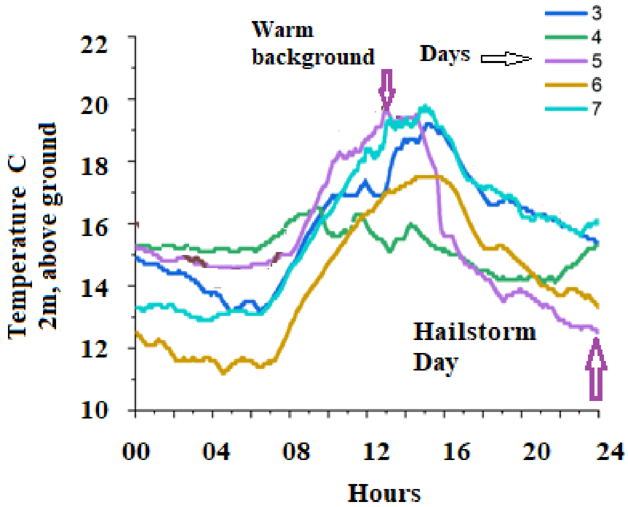


Figure 2: Diurnal temperature profiles from February 3 to 7, 2022. One can note the presence of a relatively warm environment on the hailstorm day, February 5, 2022, before the storm starts.

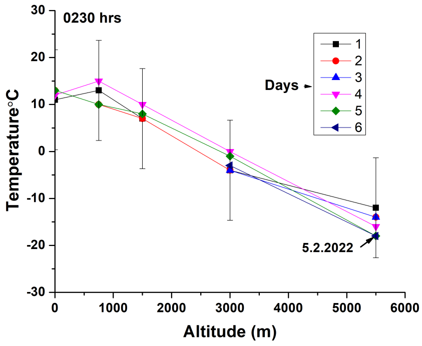
rate lies around $-5.5°C/km$. The temperature status on February 5 thus supports the presence of a Level of Free Convection (LFC) a necessary condition for a storm in conformation to the basic definition of a free layer in which the temperature falls at a rate of approximately $10°C/km$, provided it is free of clouds.

3.2 Wind Speed and Direction

In general, wind speed increases with height above ground due to fewer obstructions from artificial constructions but more due to low potential friction in the atmospheric medium. Therefore, speed increases with altitudes and is assessed by the term wind gradient. However, there are deviations from these normal features when instead of increasing the speed, the wind velocity may get frozen with height or may slow down or may increase its speed with altitudes compared to the normal day status. These variations being associated with factors like temperature inversion, and growth of the frontal zone, the wind profile carries the important parameters to identify the formation of a class of worst weather situations. Similar is the role of wind direction variations in identifying weather status as these changes in directions are dependent on strong temperature inversions or density gradients.
Therefore both speed shear and direction shear are features to be analysed in understanding the growth processes of a Storm be it thunder or hail.

3.2.1 Wind speed, direction, and shear features on hailstorm day

The wind profiles from radiosonde over Guwahati presented in Figure. 5 for (a) an average (especially no storm status) and (b) the hail storm day 5.2.2022, provide a basic difference in the speed achieved at higher altitudes on the hailstorm day. The initial speed on February 5 though falls on the average trend (or even less in magnitude, Figure. 5), the speed increases beyond 8 km altitude compared to that from



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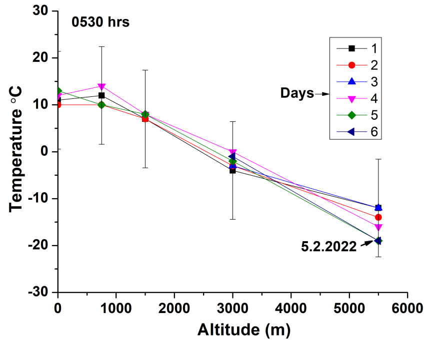

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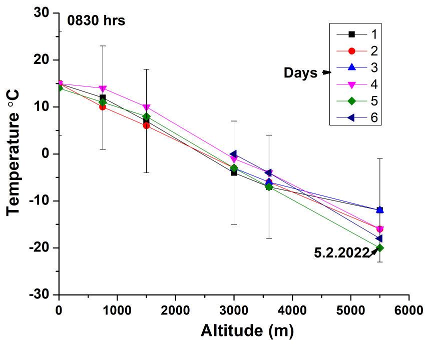

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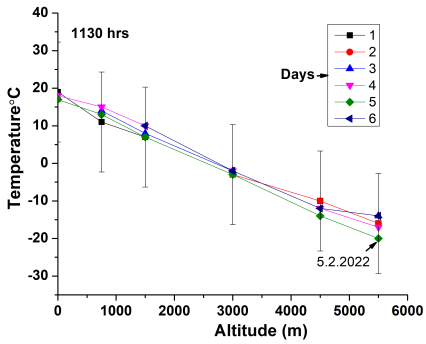

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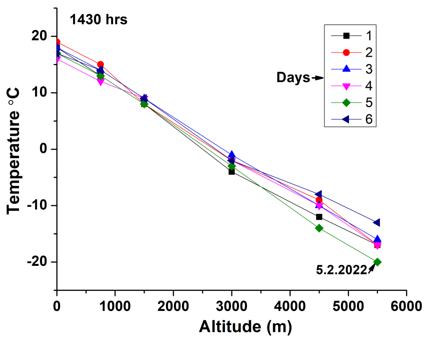


(e)

Figure 3: Display temperature variations with altitudes from February 1 to 6, covering hailstorm day (5.2.2022) over Guwahati. Note that the temperature at higher heights is lower on this hailstorm day (marked by an arrowhead) compared to that on average days, though the ground level temperature was maintained at a warm level. (Data source: Vantuskey with extrapolation/interpolation)

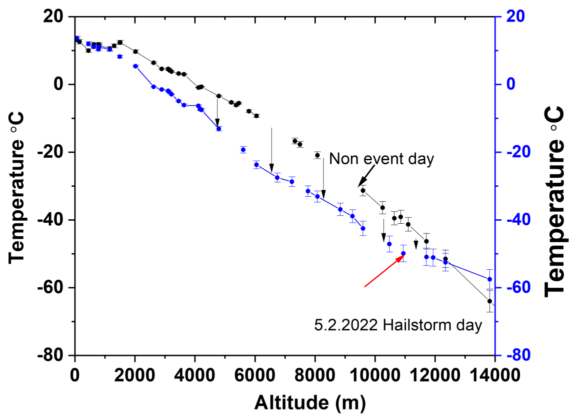


Figure 4: Radiosonde temperature profiles over Guwahati (0600 hrs LT): (a) a Nonevent condition. and (b) 5.2.2022 hailstorm day. Note a sharp fall in temperature on February 5 at heights between $5 to 8 km$, by about $-10°C$ and $-15°C$ compared to the clear day temperature.

no storm day (Figure. 5) and attained the velocity of $100 knot$ at $12/13 km$ compared to $80/85 knot$ on no storm status. The speed shear on the hail storm day is then calculated and the presented display in Figure. 6b shows that the shear though not strong at lower altitudes but started increasing from $8 km$ to reaching almost two times that of no storm environment (Figure. 6b). This status is for 06:00 hrs (LT) when radiosonde data are available. But in absence of radiosonde profile during the storm onset period of around 11:30 hrs, we go for model evaluated wind speed data (source: Vantusky) and note that beyond 5 km altitude wind speed increased to $100 km/hr$ on hailstorm day, in conformation to the radiosonde data.

The wind direction does not undergo significant changes on the hailstorm day (Figure. 7), except with the track changes from the south (S), south-west(SW), and to the SSW components within altitude ranges from $5 km$ to $7 km$ (Figure. 7a), a slight deviation in the direction from the average westerly (W) wind flow pattern (Figure. 7b). The wind direction shear magnitude is also not strong as displayed in Figure. 8a, with its marginal spread on this day by about $25 m/km$ within $4 km$ to $6 km$ altitudes compared to no storm day shear profiles (Figure. 8b).

3.3 Humidity: Altitude variations during Hailstorm day and in No storm environment

Humidity decreases with altitude because air becomes thinner and any deviation from this trend is therefore the basic interest from physical and dynamical explanations relevant to any worst weather situation. In this aspect, we have already presented in Figure 1 that humidity at the ground level just before the onset of the storm was 12% to 15% higher than the no-storm day. However in absence of radiosonde data available during the onset periods of the storm we present here humidity profiles of Guwahati taken by IMD at 06: 00 hrs (LT) of (a) the storm day and (b) a no storm day, (Figure. 9). As usual, the humidity shows a decrease with altitude (Figure. 9a) for a no-storm day, displaying that it reaches a minimum level of 3% - 5% at a height of around $10 km$. But on the storm day, there is a deviation, here the initial decay of humidity level from surface to $4 km$ was faster at a rate of 4% reaching almost zero value at $4 km$ height (Figure. 9b) compared to the normal day rate of decrease of 1.5%, but then there is a sudden increase in humidity level from almost 0 (a very rare event) to 7%, thereby an

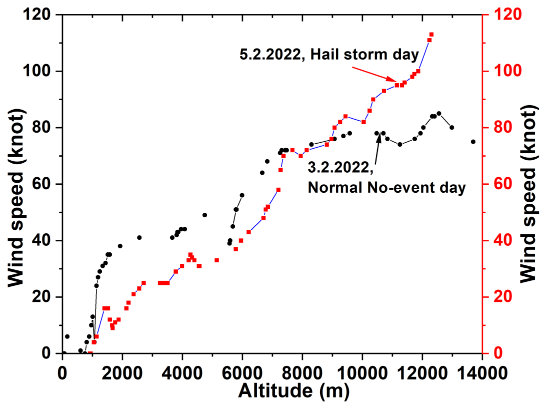


Figure 5: Wind speed profiles over Guwahati (06:00 hrs LT) (a) 5.2.2022 (storm day) (b) 3.2.2022 (no storm environment)

increase in its value by more than 600% from $4km$ to $7km$ altitude compared to a marginal increase (by 50-60) % within this range of altitude during no storm or clear situation. From a very dry environment to sudden accumulation of humidity as noted on February 5 is significant at $5km$ to $7km$ altitudes because such features generally occur on interference either by cold or hot front making a wide difference in a temperature gradient (Figure. 9c and Figure. 9d).

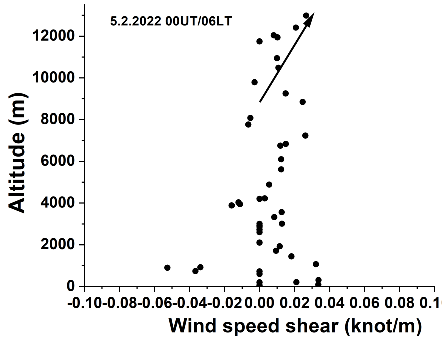
3.4 Lifting Index

The Lifting Index (LI) is one of the indices of identifying atmospheric instability. Because this parameter is derived by computing the temperature that the air would possess at the ground if it were to be lifted to higher altitudes ($5.5km$ generally) and by comparing the temperature with respect to the actual temperature at that height. In other words, it provides a temperature difference between the ground (say) and an air parcel lifted adiabatically to a height ($5.5km$ or in pressure $500hPa$), The negative value of LI is an indication of instability and more the negative values the stronger will be the updrafts and may lead to Thunder Storm. Figure 10 displays the magnitude of LI in the different diurnal environments of February 5 supporting that from 0900 hrs onwards, the situation favours lifting an adiabatic parcel up but the strength attained zenith during 11:30 to 15:30 hrs.
Gauhati hailstorm time meteorological features thus can be summed up as shown in Table. 1.

4 Discussion

Table. 1 shows that on day 5th the temperature, wind, and humidity parameters, as well as due point temperature and lifting index, deviated from the normal day character both in temporal and altitude frames. These features are necessary to look for in association with the growth of the hailstorm.

Hail storms are more frequent in temperate latitudes than in poles and tropical environments and therefore the occurrence of such an event at a place like Guwahati is not unusual, but the time of occurrence is the issue here, i.e., the early February when meteorological environments do not support the growth of such events as will be brought in to discussion here.



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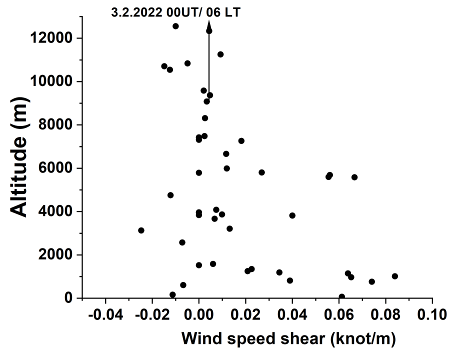

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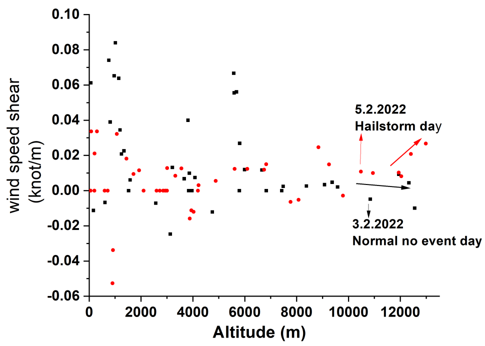


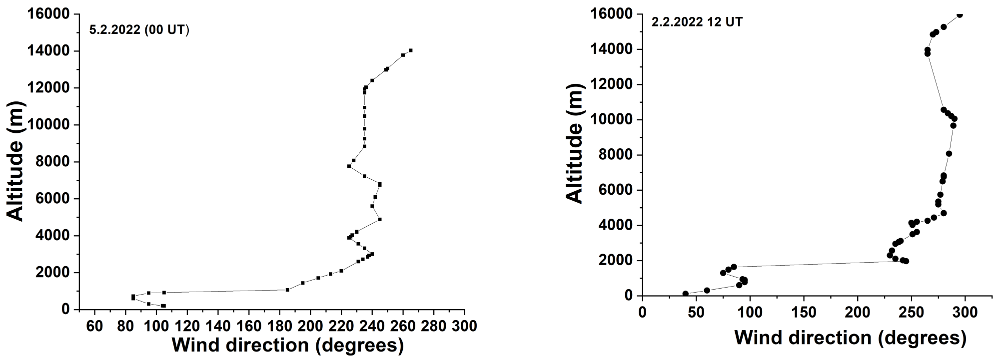
(c)

Figure 6: Wind speed shear over Guwahati (06:00 LT) : (a) 5.2.2022 and (b) 3.2.2022 ,(c) the same that of (a) and (b) but in the superimposition of the two profiles.

We have observed that in this event as summarized Table. 1, a warm ground condition prevailed and the humidity level was high from 11:30 to 14:30 hrs within the PBL. Radiosonde profile also shows the presence of high humid status at this level even in the morning hours. The high humid status at the PBL is important in triggering instabilities in the atmosphere. One such effect of a very moist and humid PBL is that the moist adiabatic lapse rate will cause the cooling of a rising parcel of air to be small, therefore the relatively less cooling up to $2km$ as observed on February 5 (Figure. 4) might be associated with such effects. Further, the decrease of the temperature beyond 5 to $7km$ altitudes as observed in this case is not unexpected when low-level moisture is available (Figure. 9) to lift the parcel up because the amount of moisture in the storm dictates the lifting process of the rising parcel.

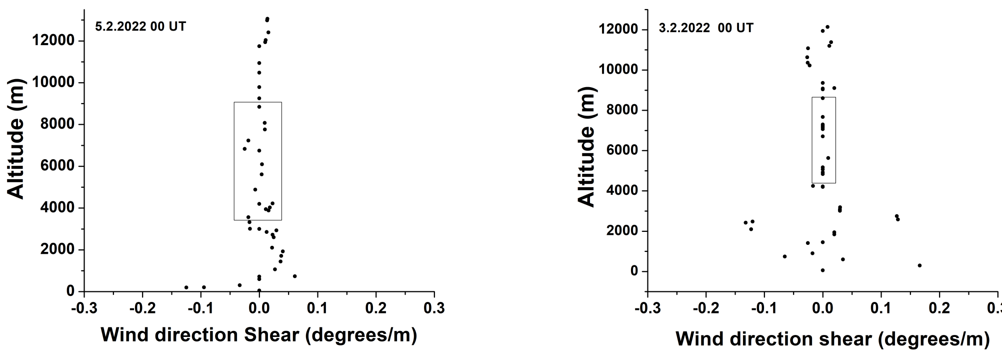
Thus when the temperature, humidity, wind speed & direction profiles are concerned, the situation favors for a thunderstorm that grows in the warm background in presence of Lifting mechanisms, and high humid environment at the PBL level. Thunderstorm occurrence profiles of this day confirm the growth of this activity from 08:30 hrs reaching a peak in the afternoon (around 14:30 hrs) and gradually from 17:30 hrs (Figure. 11) its strength started to decay.

Therefore, the environment over this region has developed conditions suitable for triggering thun-



(a) (b)

Figure 7: Altitude profiles of wind direction over Guwahati: (a) 5.2.2022 and (b) 2.2.2022



(a) (b)

Figure 8: Wind direction shear : (a) February 5 hail storm day, (b) no storm day (06: 00 LT)

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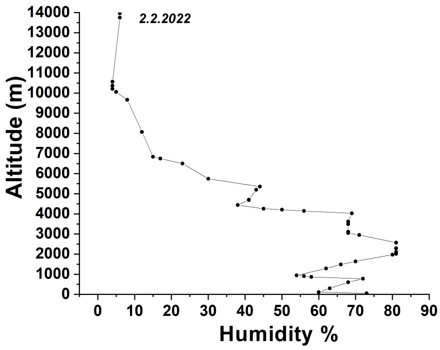

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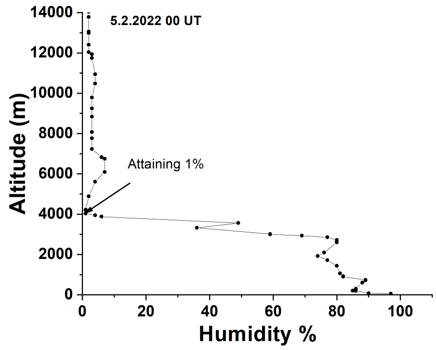

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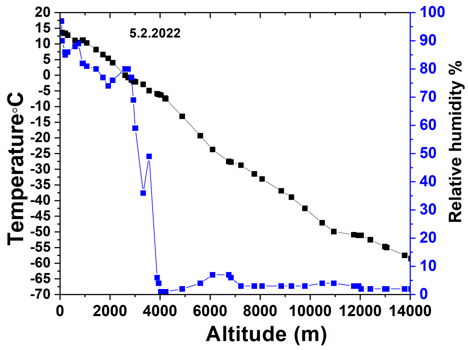

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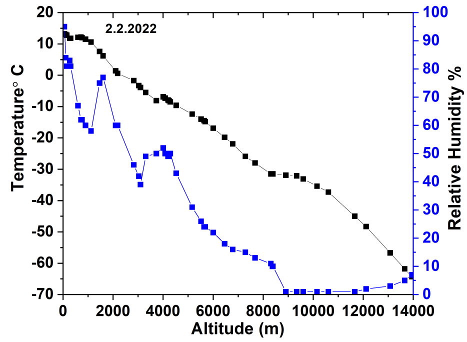


(d)

Figure 9: Humidity profiles : (a) No storm day and (b) 5.2 022 hail storm day. Note an increase in humidity from $4km$ to $7km$ altitude after attaining almost 0% humidity at $4km$ on 5.2.2022, while there was an overall gradual decrease in humidity content on no storm day, (c) A sharp fall in humidity on February 5^th along with a fall in temperature within $5km$ to $8km$ range (see the gradient) and (d) in normal day situation.

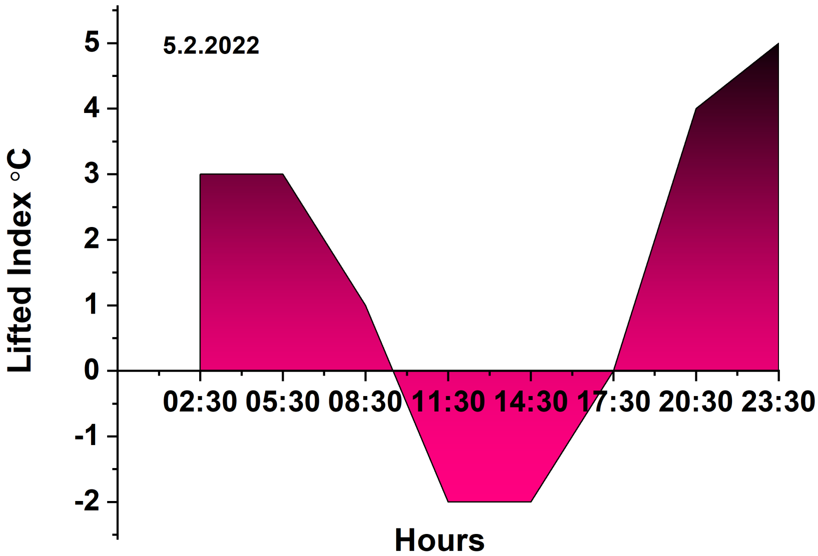
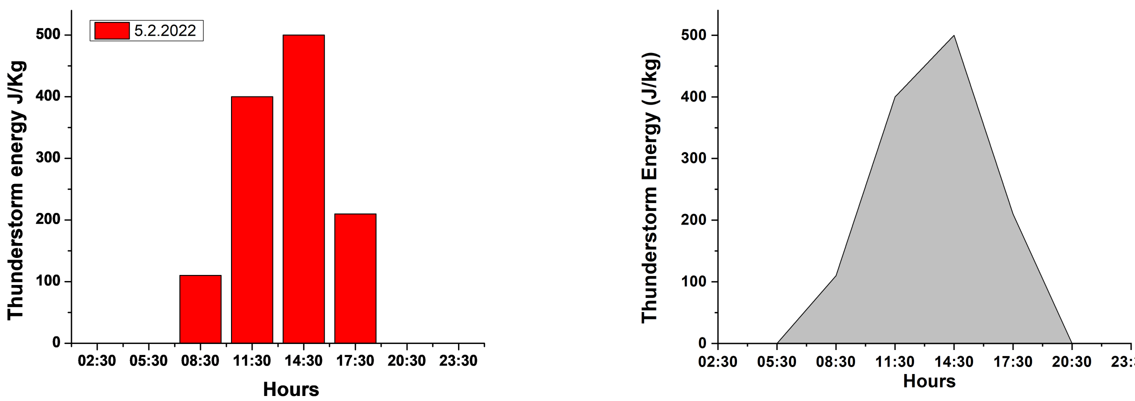


Figure 10: Lifting index on 5.2.2022. Note that from 09:00 onwards the situation favors for lifting an adiabatic parcel up, the strength attained zenith during 11:30 to 15:30 hrs



(a) (b)

Figure 11: Thunderstorm occurrence and strength on 5.2.2022

Table 1: Status of the atmospheric environment on 5.2.2022 Gauhati Hail storm event

Ground Temp (T)	Temp at $(4-6)km$	Humidity (Surface)	Humidity with altitudes	Wind Direction	Due point temp	Wind speed & shear	Lifting index
$19°C$ *Warm*	$10°C$ to $-15°C$ *below normal*	15% *high from the averagre*	(i) Sharp gradient up to $4km$ *high from the average* (ii) Reaches $\sim 0\%$ at $4km$ (iii) Increase from $5km$ to $7km$. *Deviation from normal*	Changing from SSW to SW at $4km - 6km$ from the *usual westward component*	57 °F	At high altitude: Wind speed increases with strong shear ; *Deviation from normal*	$-2°C$ from 11:30 to 14:30 hrs

derstorm activity and we need to look for a few more involved parameters on the issue related to the accompanying hails where one important index is cloud and the types.

It is necessary to refer to this aspect here because the characteristic properties of a cloud not only offer the meteorological environment of the atmosphere but also the physics and dynamics of the background system, therefore, types of cloud are important parameters in association with events like thunder-storm, hails, precipitation, and snowfall. Regarding the cloud categories, the well-known four such types are nomenclature as low $(2km)$, medium level ($2km$ to $6.1km$), high level (goes beyond $6.096km$), and vertically developed cloud. Further, within each category of cloud, there may be a number of forms; such as cumuliform and cumulus Humulus which confine within the lower troposphere, and Cumulus congestus clouds which may extend into the middle troposphere. The most important for the growth of worst weather situations like precipitation, lightning, and thunder events related cloud is the Cumulonimbus which extends all throughout the troposphere and is developed from Cumulus Humulus and Cumulus congestus. Our interest here is in this type of clouds.

On examining the cloud types of high, low, and mid-altitude on the 5th of February we note that the extension of the cloud increased to beyond $7km$ from 11:30 hrs to 14:30 hrs when the thunder started and the formation of hail materializes (Figure. 12), though favorable condition initiated in the morning hours.Thus, the formation of mid-level and high-level clouds from 11:30 hrs to 14:30 hrs suggests the presence of a vertically developed thundercloud. The temperature gradient changes almost by 2 times in the altitude range from $5km$ to $7km$ on February 5th compared to no event day i.e., a decrease in temperature was observed (Figure. 13) in this altitude range. The profiles then show that the lapse rate is faster at higher heights (Figure. 13) on February 5, even in comparison to the entire profile of the day, and faster than that from a no storm day (Figure. 13) and a free strong convective system is grown on 5th February at a higher altitude. Finally, this environment favours the formation of hail when drops of water freeze together in the cold upper regions of thunderstorm clouds with a relatively hot temperature (at the ground) reaching the ground as hails.

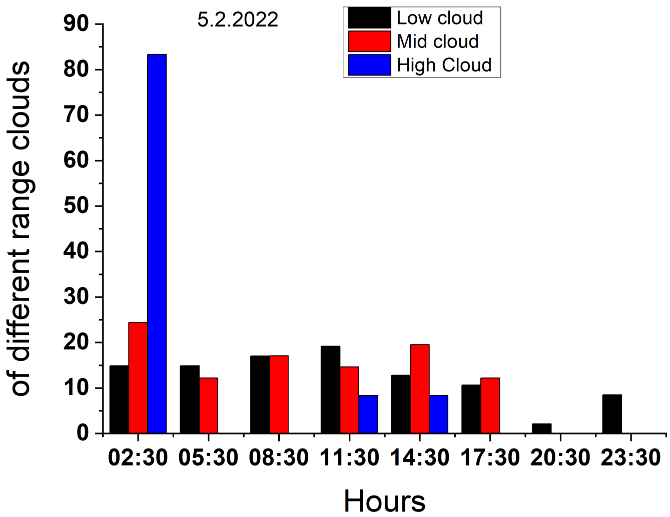


Figure 12: Cloud type and coverages on 5.2.2022 over Guwahati

It is also important to highlight that there is a change in wind direction beyond $5km$ from SSW -SW to SSW (Figure. 7a) unlike in the normal west-ward wind direction of February (Figure 7b) These changes are prominent within $5km$ to $8km$ range, in synchronization in the time and altitude frame of lowering of the temperature down by more than $-10°$ from the normal day (Figure. 4 and Figure. 13). In this aspect, one can review the formation of cloud structure as discussed earlier and perhaps the sources of such formation lie in the SSW component of wind bringing humid air from BOB. The Hypersplit models(Figure. 14) also show that the normally existing West-East airflow path to Guwahati in February (Figures. 14a, 14e, 14f) gets changed on this hailstorm day to SW components thereby bringing humid air from the Bay of Bengal (Figures. 14b, 14c, 14d), the source of cloud formation. Figure. 15 shows the presence of one-day accumulated rain (Source: NOAA) on 5^{th} February and the absence of the same on the next day and of the resultant cold front on providing support for the growth of rain-bearing clouds on 5^{th} February.

But at the same time, we note that the strong supercell formation conditions are not satisfied Because, in an environment where there is strong speed shear and directional shear, supercells are likely to form, and is the best situation in the atmosphere for the evolution of rotating updrafts. In this event of February 5, such a situation is not favored, though speed shear (Figure. 6a) could help in strengthening storm motion by separating up and down draft, the storm rotation could not grow as required to form a supercell because of low wind directional shear (Figure. 8a), though we note a marginal modification in the direction from WWS to SW-WWS that developed at $5-7km$ altitudes along with a cold front.

Another parameter that may contribute to temperature modification leading to a cold background is the level of pollution. Because, pollution has a strong role in modifying the temperature either by an increase or decrease depending on the type of pollutant [Devi et al., 2021]. But its role in the formation

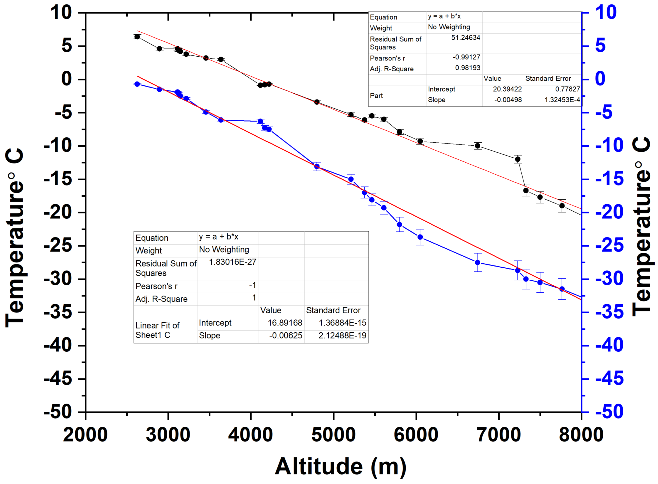
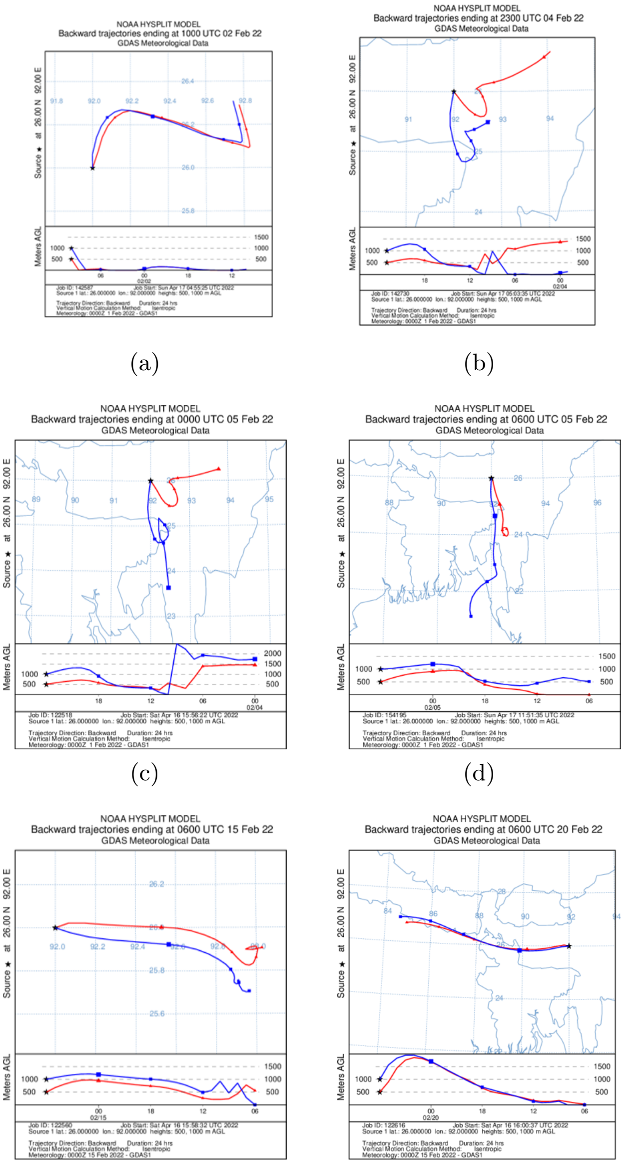


Figure 13: The Temperature decay rate on 5.2.2022 from $2km$ to $8km$ for a normal no-event day and the hailstorm day.

of snowfall is still a debatable issue. because there are studies that show both enhancement and depletion of snowfall levels by pollution. One such report (EPA Offical website of USA climate change indicator: snowfall, data source [Kunkel et al., 2009] Web update: May 2014), shows that the average rate of change in total snowfall from 1930 to 2007 at 419 weather stations in the 48 states of USA, reduces in some parts and increases in some other parts by cleaning of the air. As per this report, while the Pacific Northwest and Midwest of the USA experienced a low in total snowfall but a few regions and some areas near the Great Lakes observe more snowfall than in the past with the reduction of pollution level. [Rosenfeld, 2000] presented that urban and industrial air pollution can stop precipitation by inhibiting cloud droplet coalescence and ice formation. In this aspect, we examine the pollution level over Guwahati on 5.2.2022 the hailstorm day, and observe that the pollution level (2.5 microns) over Guwahati has gone down to less than $20\mu gm/m^3$ on February 5, (Figure. 16), a process started from 23:00 hrs on February 4 that continued till next day and thus, an index suggesting that pollution free air may assist in reducing temperature and thus supporting the formation of hails.In fact, we note that especially at high altitudes of around $5km$, and from 11:30 hrs to 14:30 hrs., the temperature goes down with the decrease in the level of pollution, however (Figure. 17) beyond $60\mu gm/m^3$, the relation breaks down, (a study for us to carry in future). The decrease in temperature may also be contributed by rain-bearing clouds though its intensity was low by only $0.3mm$

In relation to this event, we bring here another rare phenomenon that occurred in Shillong on Dec 22, 2021, the falling of snow after a gap of 50 years. We will not go into all details of meteorological phenomena and their variations in this paper but would present a significant aspect related to pollution and temperature. at Shillong on snowfall day. Coming to the temperature variation with altitudes, a decrease in its value was observed both at the surface and the most significant changes are at higher altitudes (Figure. 18a, 18b) thereby drops of water freeze in the cold upper regions and with a cold temperature at the ground when it reaches (ground) as snow, maintaining it till environment favors The decrease of temperature starts at 08:30 hrs on December 22 and reaches a dip at 14:30 hrs and after 20:30 hrs, the temperature reverted to the normal daily average. If we now look at the pollution level, significant here is the decline in its levels from 0830 hrs (Figure. 19a) on 22.12.2022 and so is the case

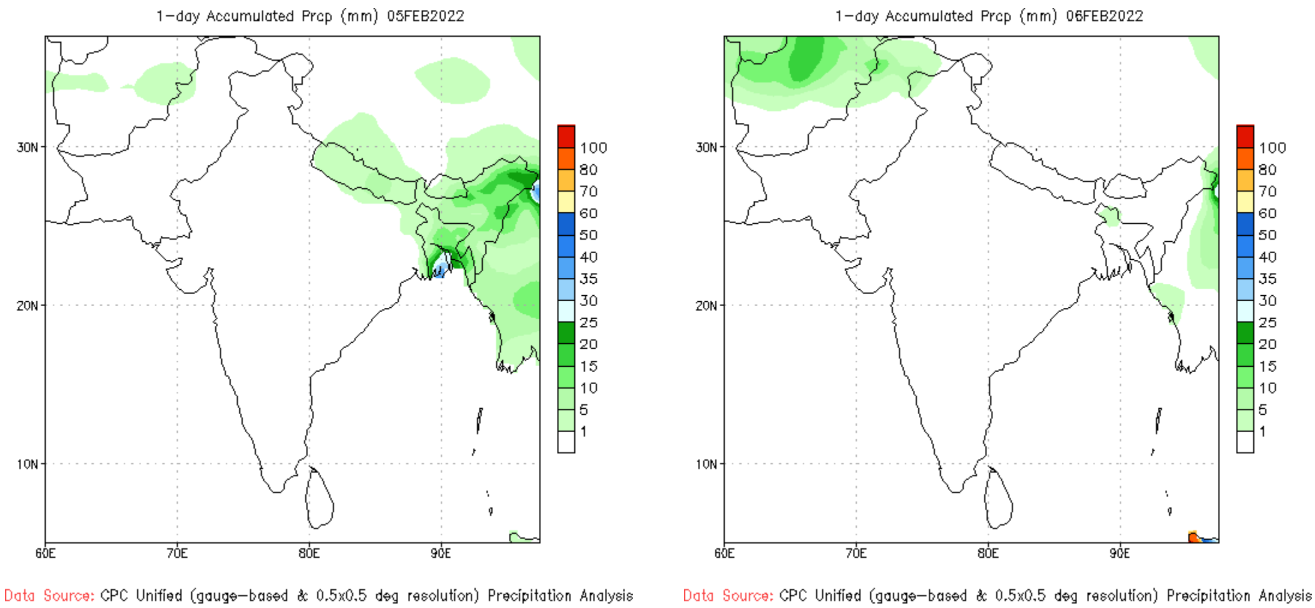


(a) (b)

(c) (d)

(e) (f)

Figure 14: Airflow path to Guwahati on (a) February 2, (10:00 UT) 16:00 LT; (b) February 4 (23:00 UT) /February 5 0400LT (c) February 5 (00:00UT) 06:00 (LT), (d) February 5 (06:00 UT) 1200 LT ; (e) February 15, (06:00 UT) 12:00 LT (f) February 20,(06:00 UT) 12:00 LT . Note that the normal wind flow path gets changed on February 5, instead of the west/east wind flow track, the wind flow is now through the Bay of Bengal on this day.



(a) (b)

Figure 15: One day (a)accumulated rain on February 5, 2022, (b) absence of rain on the next day February 06, 2022 (source: NOAA).

in Guwahati, synchronizing in the time with that of Shillong (Figure. 19b). The pollution level reached a minimum at around 14:30 hrs and so is the temperature. It is difficult though to draw one by one a relation between temperature and purity of air as other parameters like humidity, and cold fronts are also involved in the cooling process, but the association between pollution level and temperature cannot be ignored.

It is also difficult to explain why the pollution level in Guwahati will affect the temperature of Shillong or why pollution and temperature at Guwahati show similar variations as that of Shillong. One issue that may be here is wind direction. The Hypersplit Trajectory forward models (NOAA) as displayed in Figure 14 for 06 UT and 10 UT of 22.12.2021 (as representative cases) show that wind flow from Guwahati (as one of the point sources in the wind flow path to Shillong) has a contribution to the Shillong wind and hence in the environment and thus has an effect on temperature and vice versa. A more explicit analysis of this trend shows that one of the reasons for pollution-free flow is perhaps that the wind trajectory on this day though passed the Sub Himalayan Terrain (SHT) but not through the usual aerosol populated belt but from further north of $32°N$ $85°E$(one of the probable paths) along Bhutan on route to Guwahati as displayed by Hpersplit trajectory model of Figure. 20. This zone ($32°N$ $85°E$) experienced a special wind circulation pattern on 22 Dec 2021 i.e., from the NE, in difference to the normally existing Southwest(Figure. 21), and thus experienced a cold wind field from the north which then reaches Shillong on the route through Guwahati (Figure. 22) in the SE directions as displayed by model predicted wind trajectory of Figure. 20. The wind carries fewer pollutants compared to the one passing through aerosol populated terrain (East-west SHT), thereby resulting in a low pollution level at both the trajectory touching stations as displayed in the figure. However, it is a future project to identify the sources leading to modification in wind flow distribution at higher latitudes and the coupling dynamics between high latitude wind flow and local events in lowering of pollution levels and consequent contributions to temperature, finaly to the growth of snow as well as hail.And to understand the funda-

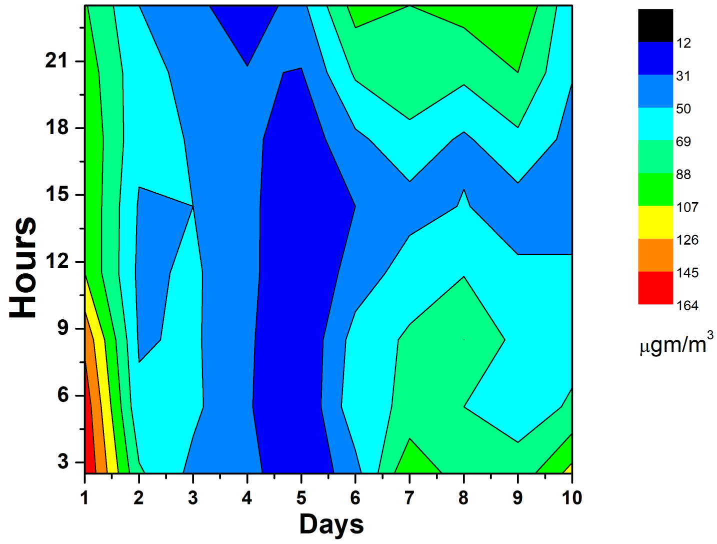


Figure 16: Diurnal profiles of pollution ($2.5 \mu gm/m^3$) over Guwahati, covering days from 1 to 10 of February 2022. Note a decrease in pollution level on 5.2.2022 over Guwahati all through the day.

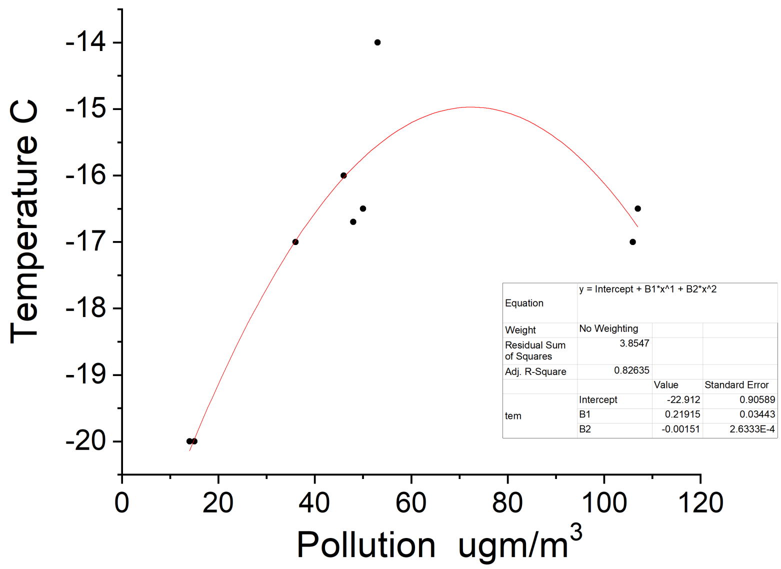
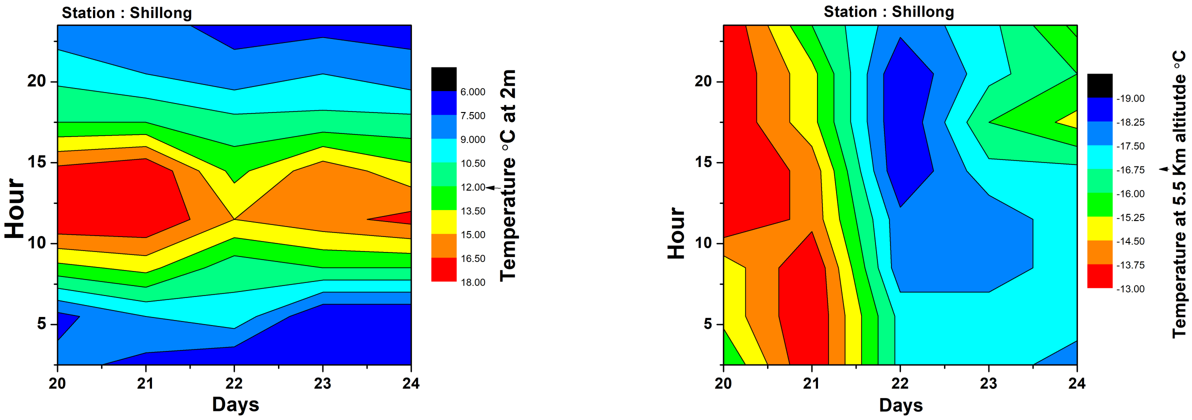
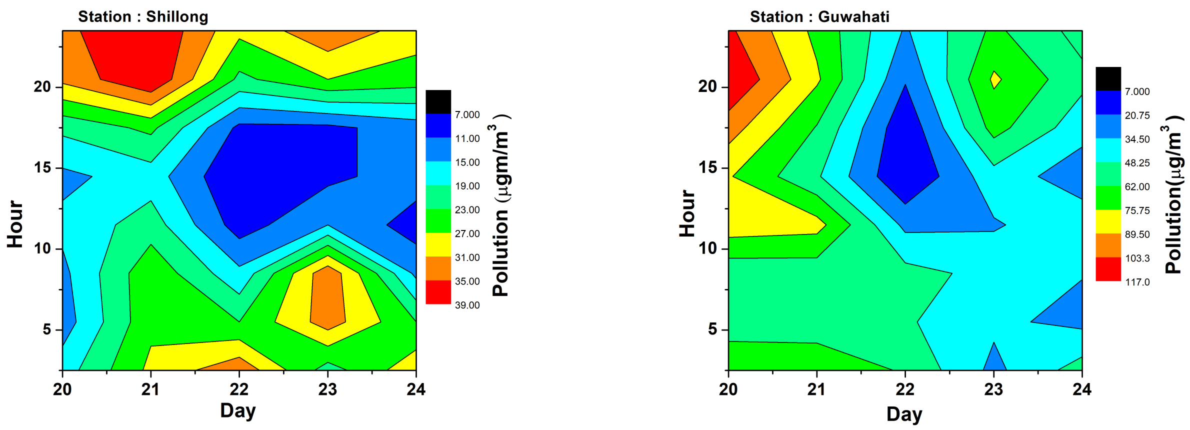


Figure 17: Pollution and temperature (beyond 4.5 km altitudes) on 5.2.2022 over Guwahati



(a) (b)

Figure 18: Temperature variation over Shillong during snowfall day with respect to average no snowfall situation (a) 2 m height (b) 5000m height. A large reduction in temperature at 5.5 km altitude almost throughout the day of December 22 is noteworthy.



(a) (b)

Figure 19: Pollution level (P2.5) in µgm/m3 (a) Over Shillong and (b) over Guwahati, days before snowfall and on the day of snowfall (22.12.2021). A large reduction in pollution level on December 22 both at Shillong and Guwahati is to be noted.

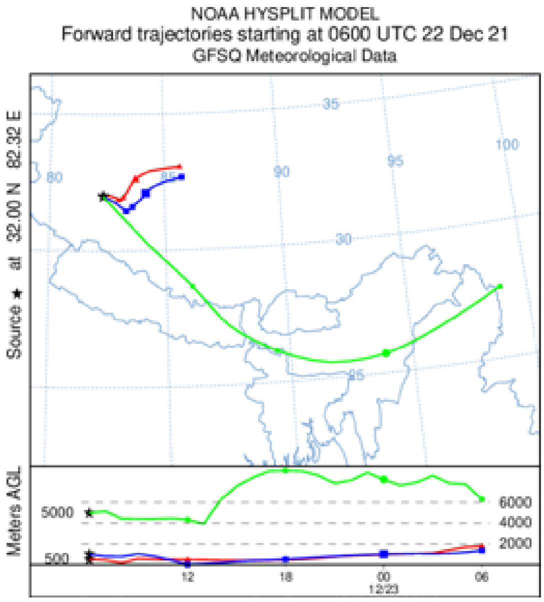


Figure 20: Wind path trajectory from 32°/33°N 82°/83°E to Shillong on the route through Guwahati, December 22, 2021, NOAA Hypersplit trajectory models.

mental issue as to why these phenomena occurred suddenly after a long gap of decades.

5 Conclusion

The paper provides atmospheric environments leading to rare meteorological phenomena the growth of unseasonal hailstorms and unexpected snowfall events recently experienced over the Northeast part of India. The detailed analysis is done in the light of implicitly associated parameters temperature, humidity, due point temperature, wind parameters, and their resultant variations both in temporal and spatial fields right from the earth's surface to the troposphere and beyond. During hailstorms the presence of warm ground temperature (19°C), humidity 20 % above normal, $-2°C$ lifting index, 10 % higher in temperature lapse rate over $5km$ to $7km$ altitude, high wind speed shear of $40knots/km$, and growth of mid-level clouds are supportive to the formation of cold front thus favours the growth of hail when drops of water freeze together in the cold upper regions of thunderstorm clouds with a relatively hot temperature (at the ground), reaching the ground as hails. The role of wind flow direction along with the air quality consisting of humidity carrying cold fronts with it was also shown to have a contribution to the growth process of a storm.

However strong super cell formation conditions are not satisfied, because, speed shear though could help in strengthening storm motion by separating up and down- draft, the storm rotation could not grow as required to form a super cell because of low wind directional shear.

In snowfall events in Shillong, both the ground and high altitude temperature show a drop in values compared to the average, favouring snow to materialize. The contribution of pollution-free air from high latitude cold zone in bringing the temperature down is supportive of the formation of snow. The study

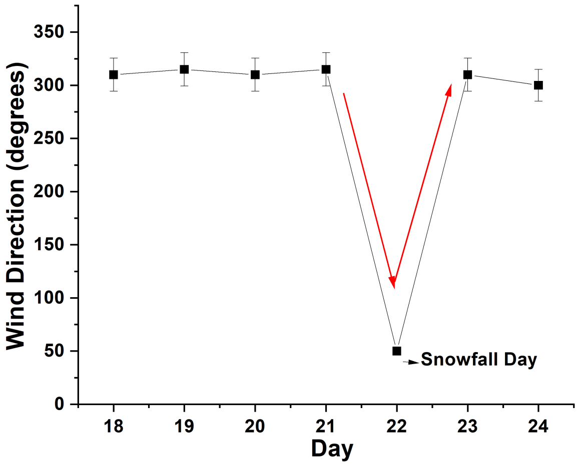
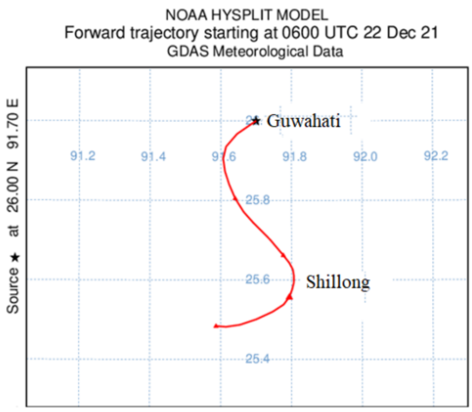
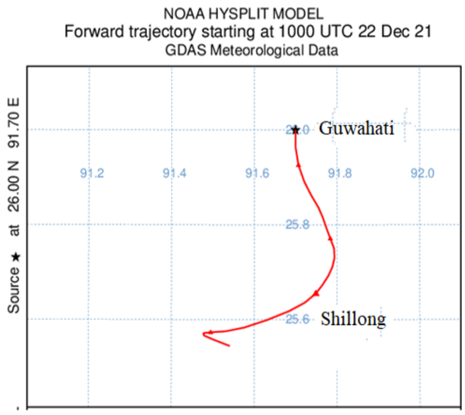


Figure 21: Sudden changes in wind direction from W to N-E on 22.12.2021 (snowfall day) to $30° - 35°N, 80° - 82° - 85°E$.



(a)



(b)

Figure 22: Wind path trajectory to Shillong - Guwahati as a point source, December 22, 2021 NOAA Hypersplit trajectory model (a) 06:00 UT (b) 10:00 UT).

thus presents a reliable conclusion that the atmospheric and meteorological parameters prevailing in the respective periods over Guwahati and Shillong are supportive of the growth of hail and snow but we are yet to understand the fundamental issue as to why these phenomena occurred suddenly after a long gap in periods. This aspect we will deal with as a future project along with coupling dynamics between high latitude wind flow in triggering local events like thunder/snowfall.

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Data availability statement

Global temperature and humidity and met data are available along with a weather map at www.ventusky.com.
Stream flow data are collected from USGS (https://pubs.usgs.gov/fs/2005/3018).
Precipitation profiles of India are from Climate Prediction Centre NOAA.
Temperature and wind profiling are from IMD, Guwahati.