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ORIGINAL PAPER

Hailstorms over India during the summer season

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Abstract
Hailstorm activity over India is seasonal and mainly occurs from March to June. The present study analyzes the diurnal spatial pattern of hail event occurrence and its intensity based on the hailstorm data of the India Meteorological Department surface observatories during March to June for the years 2014–2021. The study indicates that in all months, unlike thunderstorm events, hail events were clustered around the afternoon temperature maximum, becoming insignificant in the post evening hours. Spatially in March, hail events were mostly confined to the Himalayas. Their frequency increased in April throughout the Indian region with significant increase over the plains of India. In May, the frequency of hail events gradually decreased in the Himalayas, but persisted over the plains of India, becoming insignificant thereafter throughout the Indian region in June. Small hail events (<1 cm diameter hailstones) preferentially occurred in the Himalayas. Moderate (1–1.9 cm diameter hailstones) to severe hail events (≥2 cm diameter hailstones) were rarer and more uniformly distributed throughout the Himalayas and plains of north and central India. They occurred later in the day as compared to small hail events. The steep decrease in frequency of small hail events beyond April indicates that with the increase in the height of the freezing level as the months progressed, ordinary thunderstorms were less able to form significant hail particles that travelled to the ground without melting, through a progressively warm sub-cloud layer of air. On the other hand, moderate to severe hail events form in tall and deep thunderstorm cells, with significant cloud fraction above the freezing level and strong updraft velocity. Such deep thunderstorm cells occur as a result of strong large scale low to middle tropospheric thermodynamic and dynamic support, are less frequent and peak during afternoon to evening hours. As the season progresses, the warming of the subcloud layer significantly affects the size of hail particles reaching the ground. The warming atmosphere and changing character of the mesoscale convective systems in June subdued most of the hailstorm activity over the Indian region.

1 Introduction

Hailstorms have only lately been recognized as a significant form of severe weather in the tropics (Frisby and Sansom 1967). This is mainly because, unlike the hailstorms of the middle latitudes which occur predominantly in large scale organized mesoscale convective systems (MCS) or supercells (Schumacher and Rasmussen 2020), hailstorms in the tropical regions such as India tend to occur from less organized and shorter-lived convection (Kulkarni et al. 2015). Hence many such events go unrecorded. One of the deadliest recorded hailstorms of all time occurred near Moradabad in north India, on 30 April 1888 and killed 246 people, and over 1600 sheep and goats (Cerveny et al. 2017). In addition to human losses and damage to infrastructure, hail has huge potential for damage of "rabi" field crops in ripening stage (planted in October/November and maturing in March to May) as well as fruit orchard crops at different stages of their life cycle over India (Swaminathan 1962; Rao et al. 2014; Chattopadhyay et al. 2017). These studies indicate that hail also causes damages leading to life loss for livestock including open grazing sheep, goat, cattle as well as poultry. Moreover, hail events also result in mass mortality of wildlife over India (Narwade et al. 2014). On account of their potential for devastation, analysis of these events is essential, in order to develop disaster mitigation strategies.

Cecil and Blankenship (2012) used a combination of 37-GHz channel and 85-GHz channel of the passive microwave sensor Advanced Microwave Scanning Radiometer (AMSR)-E on board the Aqua satellite, to objectively estimate severe hailstorm climatology over tropical and subtropical regions. Their findings for the Indian subcontinent

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indicate that hailstorm frequency was highest over east and east central India and adjoining Bangladesh during the March to June period and thereafter over Pakistan and adjoining northwest India in July and August. An arc along the foothills in northern Pakistan was noted to be particularly active from mid-June through mid-August. This frequency distribution and seasonal migration resembles the seasonal maxima and shift of distribution of MCS, over east India during the March to May period to over northwest India during the June to August period (Romatschke et al. 2010). Roy et al. (2023) further expanded this study to over the east and northeast Indian region using Tropical Rainfall Measuring Mission (TRMM) and Global Precipitation Measurement (GPM) satellites' Precipitation Radar (PR) and Microwave Imager observations. Their observations indicate that the hail-producing convective cores of MCS are taller and broader than non-hail MCS and are more sensitive to synoptic forcing over northeast India. However, this distribution of hailstorms from both studies is not borne out by ground-based observations of hail over the region as discussed below. One reason may be that convection in the tropics with very deep layers of graupel and small hail (as in tropical MCS) especially during the monsoon season, may allow storms to easily produce the low microwave brightness temperatures that are typically associated with large hail in the subtropics (Ni et al. 2017). Such thunderstorms in the tropics are associated with an increased probability of cloud-to-ground lightning but not hail (Murugavel et al. 2014 for lightning climatology as an example). Hence such an algorithm only diagnoses the suspected presence of hail aloft but not at the ground. Also, such small hail generally melts upon passing through a progressively warm sub-cloud layer of air as the season progresses.

Uniform model-based global analysis of hailstorm activity was carried out in studies using the UK Met Office global model analyses data (Hand and Cappelluti 2011) and using daily ERA-Interim reanalysis data (Prein and Holland 2018). In the former, a convection diagnosis post-processing tool was used for diagnosing hail from model vertical profiles of temperature and humidity products. If the parcel convective available potential energy (CAPE) is greater than 50 J Kg^{-1} (equivalent to a peak vertical velocity of 10 m s^{-1} at cloud top under the assumptions of parcel theory i.e., ignoring entrainment, etc.) and Cloud Top Temperature is less than − 20 °C with a cloud depth greater than 3500 m and a base below 5000 m above ground level, then the potential for hail is assessed. Prein and Holland (2018) on the other hand, used a probabilistic relation composed of four predictors—a joint predictor between maximum CAPE and freezing level height (FLH), CAPE as a single predictor, and surface to 3 km storm-relative helicity (SRH0-3), and vector shear (VS0-3). Both studies presume that the environments that lead to large hail are consistent worldwide. While both studies very well capture the hail maximum over the eastern Himalayas and adjoining plains, the climatology of hail due to Hand and Cappelluti (2011) also indicates that there is a maximum of hail all along the Himalayas. It also captures the occurrence over the plains of north and central India during the March to May period, as noted by ground-based observations. However, both methods also predict a maximum of hail over northwest Indian plains especially during the monsoon season (June to September) which is similar to the findings from satellite-based algorithms but not confirmed by ground-based observations. Since CAPE is dependent on the temperature and moisture of the lowest troposphere, neither algorithm accounts for the individual effect of the temperature and dryness of the sub-cloud layer air on small sized hail. For these reasons, ground-based observations remain the most reliable source of information of occurrence of hail over the Indian region. However, a major finding from satellite and model-based studies is the clear demarcation of the hailstorm occurring zone along the windward side of the Himalayas and over the adjoining plains of the Indian subcontinent from the Tibetan plateau which is on the leeward side of the mountains.

Figure 1 depicts the map of India showing Indian States, Union Territories and its neighbouring countries Bangladesh, Nepal, Bhutan, Myanmar and Pakistan while Fig. 2 displays the location of stations whose data have been used in the study. Long period datasets from Indian observatories have records of hailstorm days. Initial studies have noted hailstorm frequency maximum over the north Indian plains (Frisby and Sansom 1967; Court and Griffiths 1986). Later studies based on more recent and larger datasets indicate that hailstorm days over the Indian subcontinent are most frequent over the Himalayan region, with highest frequency of occurrence over Nepal and adjoining regions of Uttarakhand in the western Himalayas and in the eastern Himalayas in Sikkim (Chowdhury and Banerjee 1983; Ramamurthy 1983) or over Assam and adjoining valleys of northeast India (Philip and Daniel 1976; Singh et al. 2011a; Rao et al. 2014). Frequency of hailstorm days was observed to decrease southwards across the plains of India. A less intense peak in frequency of hailstorm days occurs over Western India in Maharashtra (Chattopadhyay et al. 2017) or over east central India (Jharkhand) and central India (Vidarbha) (Philip and Daniel 1976; Ramamurthy 1983; Rao et al. 2014). Kumar (2017) indicated that hailstorms are most frequent over the western Himalayas (Jammu and Kashmir), followed by east and northeast India (Bengal, Mizoram and Tripura) followed by western India (Maharashtra). A review of existing literature on the intra-annual trends in occurrence of hailstorms indicates that over the Indian region, the hailstorm day frequency peaks during March to June (Chowdhury and Banerjee 1983; Kumar 2017). As mentioned earlier, the hailstorms during this period are also the most severe in terms

Fig. 1 Indian map showing Indian States, Union Territories and its neighboring countries Bangladesh, Nepal, Bhutan, Myanmar and Pakistan

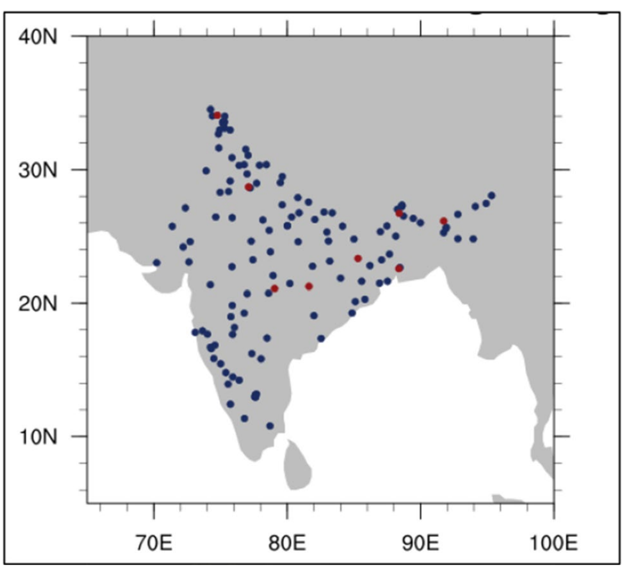


Fig. 2 Location of hail event reporting stations (the stations whose freezing level height is plotted in Fig. 8 are marked red)

of damage potential. Very few studies have attempted the diurnal analysis of hailstorm events on an all India scale on account of non-availability of consistent observations. The few regional studies that are available indicate that over the Indian region, they mostly occur in the afternoon, peaking around 17 IST (Indian Standard Time = UTC + 5:30 h) (Chowdhury and Banerjee 1983; Das et al. 2010).

Another aspect of the analysis of hailstorm events is their severity on account of size. Studies investigating the effect of a warming climate on North America indicate that severe thunderstorm potential is likely to increase resulting in fewer hail days, with more frequent occurrence of larger hail (Brimelow et al. 2017). This aspect of hailstorm activity has not been sufficiently investigated for the Indian region. Reports of severe weather in a country, and its impact on daily life are intimately connected to the forecast and warning process (Doswell 2003). The perception of hail as a severe weather event during March to June has caused the India Meteorological Department (IMD) to initiate a special Forecast Demonstration Project (FDP) during March to June every year. Special effort is made to predict hail events as well as obtain reports of details of hailstorm occurrences (including their size) from IMD observatories during March to June period every year (Sen Roy et al. 2021). The detailed observations obtained through this countrywide drive, allow a more detailed analysis of hailstorms for the Indian region during 2014–2021. The purpose of this study is to analyse the diurnal pattern of hailstorm occurrence and its size variation over the Indian region as well as its evolution during March to June from these ground-based observations.

2 Data and methodology

IMD has 141 full time observatories which provide around-the-clock observations of hailstorms and other weather throughout the Indian region. Following World Meteorological Organization (WMO) standards for recording present and past weather at and around a station in SYNOP code (WMO 1995), hail over the station is encoded by the numbers 96 and 99 (hail with thunderstorm). The information is available on Global Telecommunication System (GTS) throughout the world at 00, 03, 06, 09, 12, 15, 18 and 21 UTC which corresponds to 0530, 0830, 1130, 1430, 1730, 2030 and 2330 IST respectively. During the last few years, IMD observatories also report the details of the hail events (time of occurrence of hail and the hail size measured along the maximum dimension of the largest hailstones during the event) in the daily digital Monthly Meteorological Register. This information is stored in the National Data Centre of IMD at Pune. A combination of both datasets was used in this study during the period of eight FDP seasons (March to June) from 2014 to 2021. As per the available data, 135 stations reported a total of 663 hailstorm events during the study period. The data was tested for the regularity of reporting and 100% data was received from these stations during the period of consideration. However, the hail size information was not received for all events. This is mainly because this information is sometimes not available to the forecaster, unless the event happens very close to the observatory. Of the total of 663 reports of hailstorms, 451 reports were accompanied by information of size. In view of the importance of this information to the scientific community, the hail size information in these reports is also analysed in detail in this study.

For studying the diurnal occurrence of these events, the day has been divided into eight 3-hourly periods i.e. morning hours (0530–0830 IST), forenoon hours (0830–1130 IST), noon hours (1130–1430 IST), afternoon hours (1430–1730 IST), evening hours (1730–2030 IST), early night hours (2030–2330 IST), late night hours (2330–0230 IST) and early morning hours (0230–0530 IST). The total number of hail events during 8 years for each three hour period of March to June is displayed in Fig. 3. The frequency of hail occurrences increased from March to April and decreased thereafter during May and June. In all months, the hail events are most frequent during the 1430–1730 IST period. If one considers a threshold of at least 10 hail reports (highlighted with black horizontal line in Fig. 3) during every 3 h interval of the day in a month, a significant number of hailstorms occurred during the 1130–2330 IST during April, 1130–2030 IST period during March and May and during 1430–1730 IST in June. Outside of these respective periods, there were single event reports at a few stations spread out over the country. These counts were too low to derive rigorous statistical conclusions. Station data of hailstorm occurrence in each of the 3 h periods during 1130–2030 IST in March and May, during 1130–2330 IST in April and during 1130–1730 IST in June were bilinearly interpolated on to a regular grid over India using inbuilt extrapolation functions of NCAR Command Language [NCL (version 6.4.0) 2017] and are displayed in Figs 4, 5, 6 and 7. The data displayed indicates total number of events during the period, rather than average number every year.

The ANELFA (Association Nationale d'Etude et de Lutte contre les Fléaux Atmosphériques) scale was introduced to categorize hailstones in terms of their size to define their

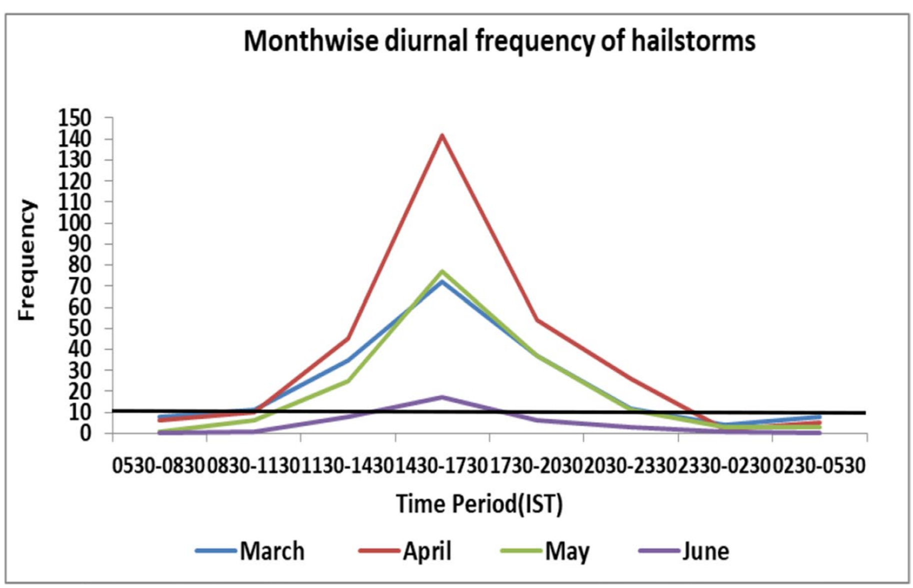


Fig. 3 Diurnal distribution of total number of hail events during March to June (the horizontal black line corresponds to the threshold of 10 hail events)

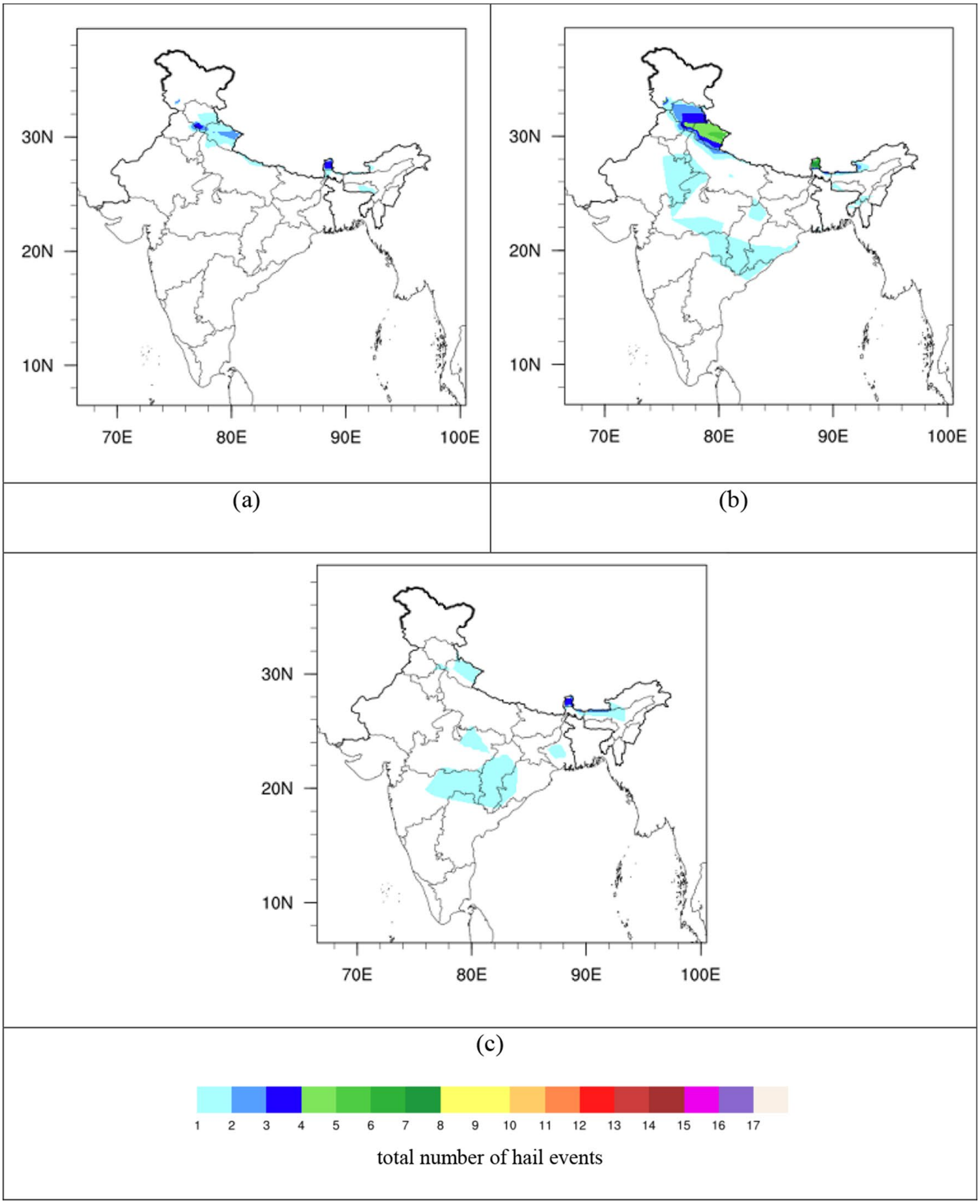


Fig. 4 **a–c** Diurnal spatial distribution of total number of hail events during. **a** Noon (1130–1430 IST), **b** afternoon (1430–1730 IST), **c** evening (1730–2030 IST) during March

severity (Dessens et al. 2007). It is based on more than 3000 point hailfalls measured by hailpads over a 16-year period in France. The class number of a hailfall is determined by the integer value of the largest measured hailstone diameter in each event in cm or by equivalence with current objects: A0 (<1 cm), A1 (1–1.9 cm), A2 (2–2.9 cm), A3 (3–3.9 cm, A4 (4–4.9 cm) and A5 (≥ 5 cm) for pea, grape, pigeon's egg, walnut, hen's egg, orange respectively. This scheme is increasingly being adopted by various climatological studies of hail severity (Baldi et al. 2014). For the purpose of analysis of severity of hail in this study, we limited ourselves to the first three categories of the ANELFA scale. These are: small or light hail (<

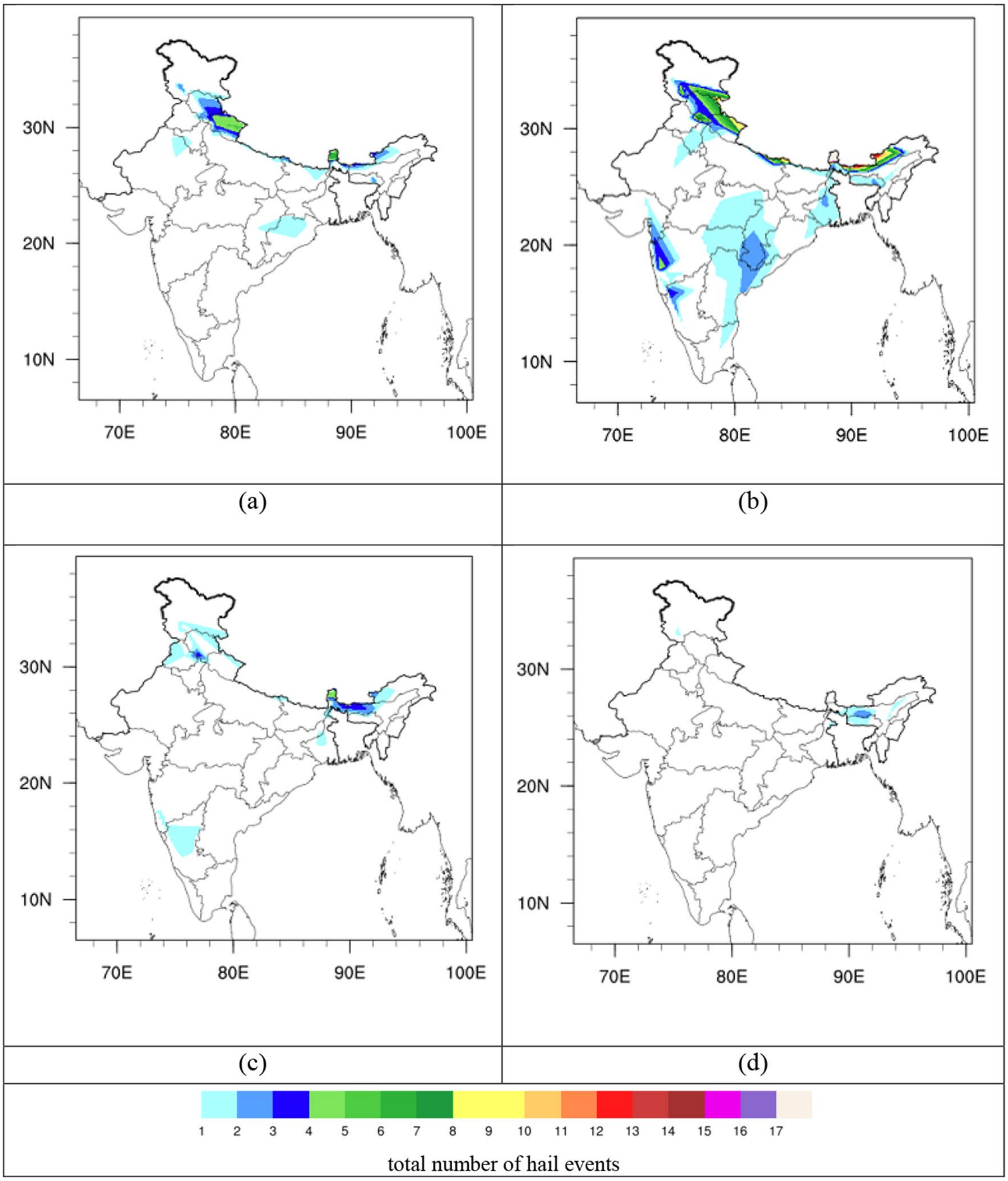


Fig. 5 a–d Diurnal spatial distribution of total number of hail events during. **a** Noon (1130–1430 IST), **b** afternoon (1430–1730 IST), **c** evening (1730–2030 IST), **d** early night (2030–2330 IST) during April

1 cm diameter), moderate hail (1–1.9 cm diameter) and severe hail (≥ 2 cm diameter). This last category of the ANELFA scale is the same as the severe hail criterion for the United States (Johns and Doswell 1992). In all, 62% of the reported events of known diameter were small hail events, 27% events were moderate hail events and the remaining 11% events were severe hail events. Figures 8, 9 and 10 display respectively the diurnal, temporal and spatial characteristics of the small, moderate and severe hail events during the 4 months period of March to June.

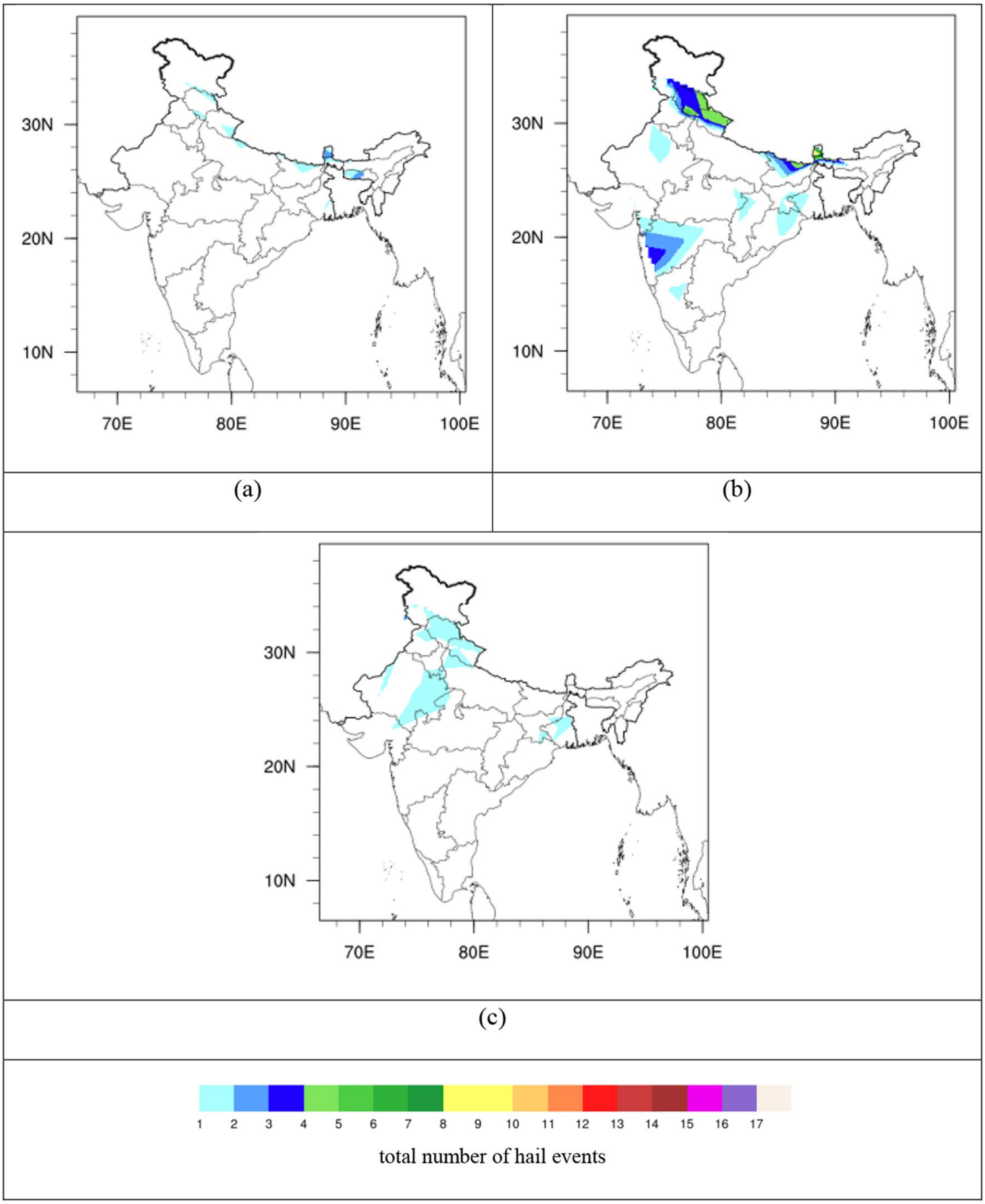


Fig. 6 **a–c** Diurnal spatial distribution of total number of hail events during. **a** Noon (1130–1430 IST), **b** afternoon (1430–1730 IST), **c** evening (1730–2030 IST) during May

3 Results and discussion

3.1 Diurnal distribution of hail events

During March (Fig. 4a–c), significant number of hailstorm events (3–4 events in 8 years) started occurring from the noon hours (1130–1430 IST), mainly over the eastern Himalayas (Sikkim) bordering Nepal and western Himalayas (Himachal Pradesh) (refer to Fig. 1 for geographical locations). Subsequently during the afternoon hours (1430–1730 IST), the frequency of hailstorms further increased, with 6–7 events recorded mainly over the eastern (Sikkim) and western Himalayas (Uttarakhand and Himachal Pradesh). Thereafter, there was overall reduction

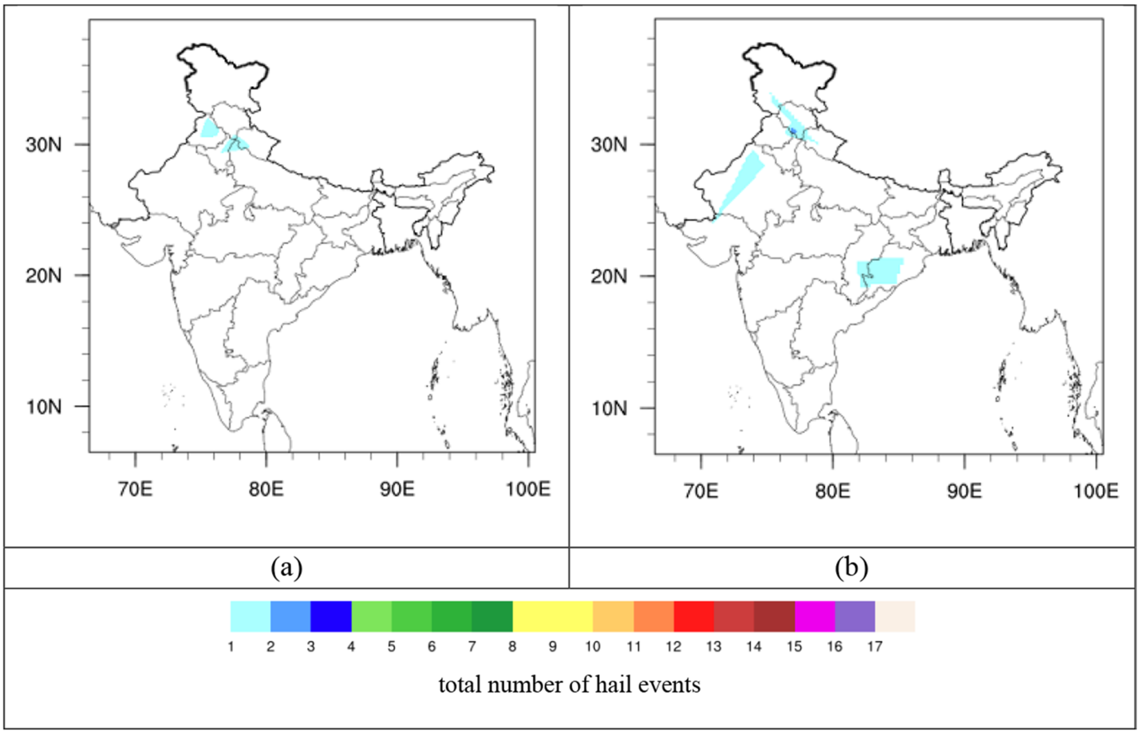
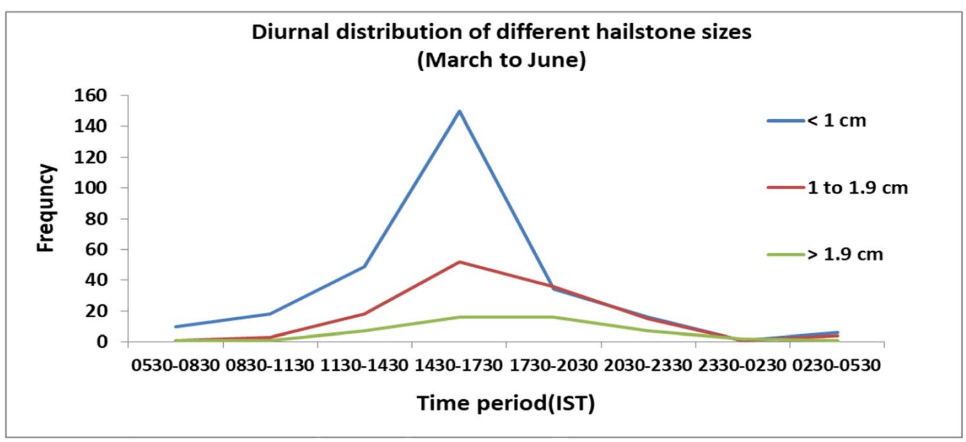


Fig. 7 **a**, **b** Diurnal spatial distribution of total number of hail events during. **a** Noon (1130–1430 IST), **b** afternoon (1430–1730 IST) during June

Fig. 8 Diurnal distribution of total number of small, moderate and severe hail events



in frequency of hailstorms during the evening hours (1730–2030 IST) throughout India except over Sikkim in the eastern Himalayas where 3–4 events continued to occur. Infrequent hailstorms (1–2 events) were also recorded during the afternoon (1430–1730 IST) and evening (1730–2030 IST) hours over the plains of central India. Hailstorm occurrence became insignificant over the Indian region thereafter.

The increase in the total number of hailstorms in April as seen in Fig. 3, is reflected in the overall spatial pattern too (Fig. 5a–d). Significant number of hailstorm events (6–7 events in 8 years) started occurring from the noon hours (1130–1430 IST), mainly over the western Himalayas (Uttarakhand) and eastern Himalayas (Sikkim) (refer to Fig. 1 for geographical locations). However unlike in March, hailstorm occurrences were more widely distributed throughout the upper reaches of the eastern Himalayas (north Assam and Arunachal Pradesh) during the noon hours (1130–1430 IST). Some hailstorm events (1–2 events) were also recorded over the northwest Indian plains and east India during the noon hours (1130–1430 IST). The frequency increased throughout the region

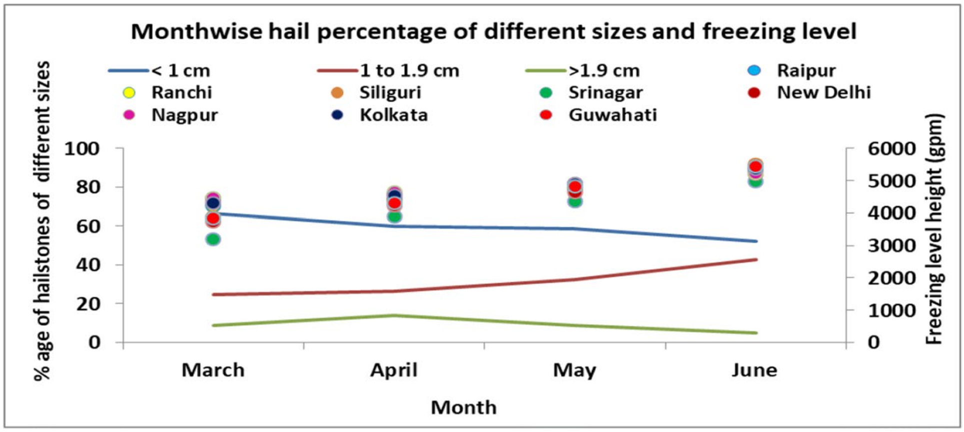


Fig. 9 Monthwise percentage of small, moderate and severe hail events (of total) and climatological freezing level height

during the afternoon hours (1430–1730 IST) with maximum values of 7–8 events well distributed mainly along the Himalayan ranges from the Kashmir valley to Uttarakhand in the western Himalayas increasing eastwards, and about 12–14 events in the eastern Himalayas, especially over Assam. Also unlike March, the diurnal maximum of hailstorm occurrence during April was recorded mainly over the eastern Himalayas during the afternoon hours (1430–1730 IST). The frequency of hailstorms also increased over the plains, with twin maxima of 4–6 events over west and 2–3 events over east peninsular India. The hailstorm frequency reduced during the evening hours (1730–2030 IST), becoming insignificant over most parts of the country except the eastern Himalayas (Sikkim) and adjoining northeast India where 3–6 events were recorded and western Himalayas (mainly Himachal Pradesh) having 3–4 events. The hail activity over eastern Himalayas and adjoining northeast India continued till early night hours (2030–2330 IST) with 2–3 events.

During May (Fig. 6a–c), hailstorms during noon hours (1130–1430 IST) mainly occurred over the eastern Himalayas (Meghalaya and Sikkim) (2–3 events). Thereafter, the frequency increased over the western Himalayas (Himachal Pradesh and Uttarakhand) (4–6 events) and eastern Himalayas, with the maxima (9–10 events) over Sikkim during the afternoon hours (1430–1730 IST) (refer to Fig. 1 for geographical locations). Simultaneously, hailstorm frequency increased over the western peninsular India (3–4 events). The frequency decreased significantly thereafter with only isolated hailstorm activity recorded over the Himalayas and plains of India during the evening hours (1730–2030 IST) with 1–2 events.

During June (Fig. 7a, b), hailstorm frequency considerably decreased compared to the previous months. During the noon hours (1130–1430 IST), isolated hailstorm activity (1–2 events) were noted over the western Himalayas. Later in the day, the isolated hailstorm activity continued to occur over the Himalayas (2–3 events) and also over the plains of north and central India (1–2 events) during the afternoon hours (1430–1730 IST).

Studies have noted the requirement of three key “ingredients” for the occurrence of deep, moist convection (Johns and Doswell 1992). These are (1) sufficient low-level moisture, (2) conditionally unstable temperature lapse rates in the low to mid troposphere, and (3) sufficient lift to transport a potentially buoyant parcel to its level of free convection. During the period from March to June, sensible heat in the lower troposphere gradually increases, with lapse rates approaching absolute instability conditions over parts of north India. The other two components namely, sufficient low-level moisture and a weather system to provide sufficient lift to a potentially buoyant parcel are provided by the diurnally varying semi-permanent north–south oriented wind discontinuity across the Indian subcontinent during this season and transient westerly troughs that move over the north and central Indian region (Srinivasan et al. 1973). These factors determine the spatial and temporal diurnal variability of thunderstorms over the India region with early morning maximum over coastal regions and the Himalayan foothills, and late afternoon peak over the plains of India (Sharma et al. 2022). However, unlike the spatial and temporal variability of the diurnal cycle of thunderstorm activity, hailstorm activity is mostly confined to a small period of the day throughout the Indian region in all months, peaking around the diurnal maximum of temperature and preferentially over the Himalayas. Another observation is that the gradual increase in thunderstorm frequency with the progress of summer season from March to June is not reflected in a similar increase in hailstorm activity, which peaks in April, and steeply decreases thereafter. This difference in the intraannual behaviour of hailstorm and thunderstorm activity was noted in previous studies too (Mishra and Prasad 1980).

A major constraint of hailstorm event analyses over India is the mesoscale nature of their occurrence, whose authentic reports of date and time of occurrence as well

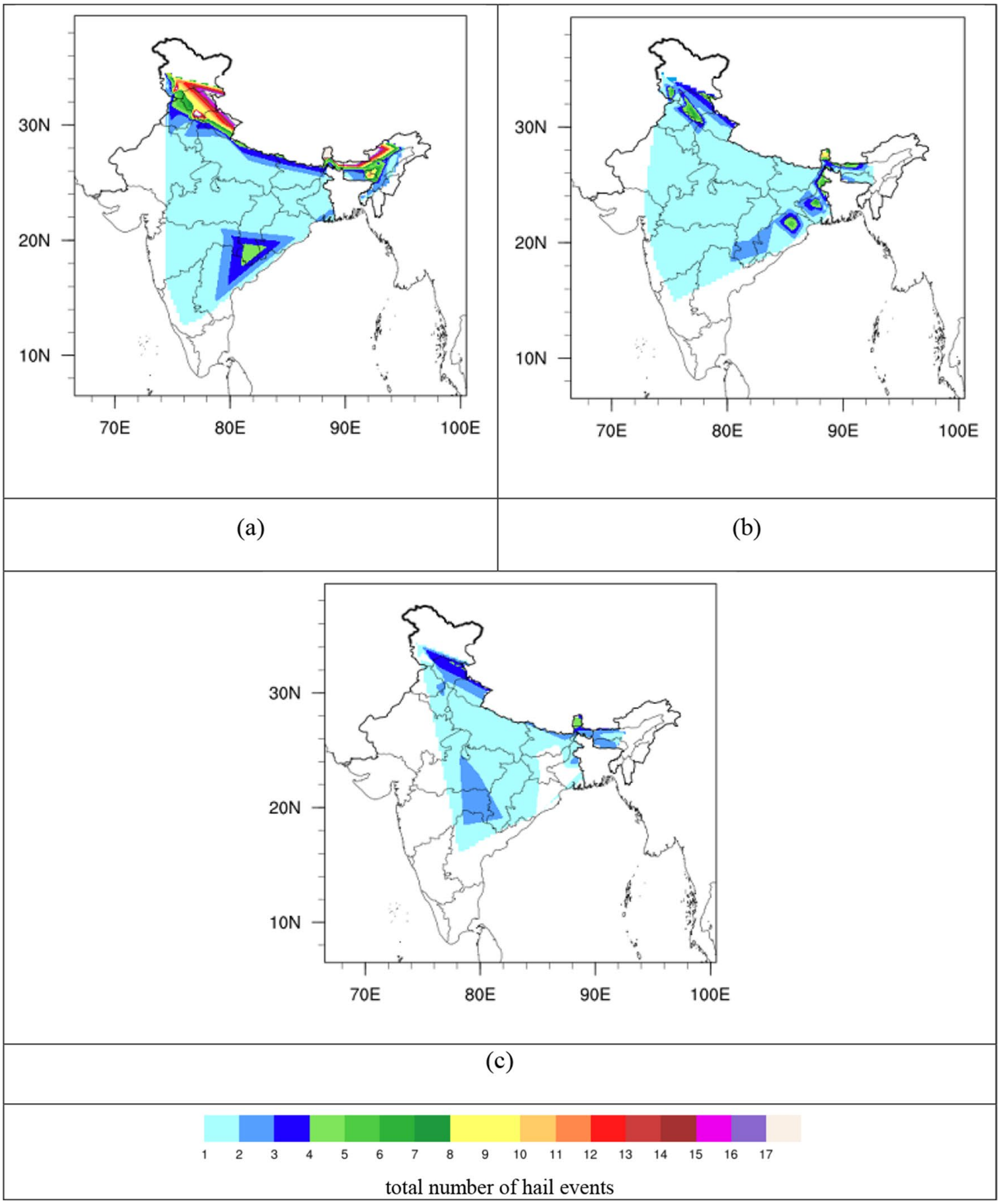


Fig. 10 **a**–**c** Spatial distribution of total number of hail events during March to June of 2014–2021 with **a** having hail size <1 cm, **b** having hail size 1–1.9 cm, **c** having hail size >2 cm

as size details are available only from observatory reports. Upon comparison with previous ground-based hailstorm studies, it is noted that the hailstorm spatial maximum noted in the present study in all months over the Himalayan region, and over Assam and adjoining valleys of northeast India (refer to Fig. 1 for geographical locations) especially in April coincides with the previous findings (Philip and Daniel 1976; Chowdhury and Banerjee 1983; Ramamurthy 1983; Singh et al. 2011a; Rao et al. 2014). There is indication of the second, less intense peak over west and east central India too as noted in previous studies (Philip and Daniel 1976; Ramamurthy 1983; Rao et al. 2014; Chattopadhyay et al. 2017), especially when hailstorm activity increased over the entire region in April. However, the hailstorm frequency maximum over the north Indian plains noted in the older studies (Frisby and Sansom 1967; Court and Griffiths 1986) is not confirmed in the present study. To investigate whether the results derived in this study are significant, they were compared to model derived hailstorm climatology as well as from ground-based reports of other countries of southeast Asia—Nepal and Bangladesh. Saha and Quadir (2016) and Raihan et al. (2020) noted that climatologically, thunderstorms with hail are most frequent over northeast Bangladesh, which border the eastern Indian Himalayas and adjoining valleys of northeast India, where this study noted the hailstorm maximum in all months. Gautam et al. (2021) noted that eastern Nepal, bordering the eastern Indian Himalayas is more prone to hailstorm activity than western Nepal. In terms of peak period of occurrence during the afternoon hours (1430–1730 IST) noted in this study; it matches very well with previous results over east and northeast India and Bangladesh (Chowdhury and Banerjee 1983; Yamane and Hayashi 2006;). The late evening maximum over parts of northeast India in April is consistent with the findings of Das et al. (2010). The results of hailstorm distribution also matches the model derived climatology (Hand and Cappelluti 2011).

3.2 Intensity of hail events

Figure 8 displays the diurnal frequency of occurrence of hail events (by size) during the March to June period. As already mentioned, small hail events comprised the majority of the observatory reports (279 reports or 62% of the events). Moderate events were less frequent (124 reports or 27% of the events), while severe hail events were least frequent (48 reports or 11% of the events). The frequency of small and moderate hail events peaked during the afternoon (1430–1730 IST), in phase with the diurnal maximum of temperature. While frequency of small hail events were slightly skewed towards the noon hours (1130–1430 IST), moderate hail events were skewed towards afternoon hours (1430–1730 IST). Severe hail events peaked later in the day during evening hours (1730–2030 IST) over the Indian region.

The climatological freezing level height of a few selected stations throughout India during March through to June is displayed in Fig. 9. The locations of these stations are marked in red in Fig. 1. With the increase in solar heating from March through to June, there is gradual increase in the freezing level height over all the stations. The monthly percentage of different sizes of hail for the entire Indian region during March through to June is also displayed in Fig. 9. In terms of size, the fraction of small sized hail events decreased gradually from March to June. The fraction of severe hail events initially increased from March to April, but decreased thereafter in May and June. However, the fraction of hail events with moderate hailstones gradually increased from March to June. In absolute terms, small hail events increased from 80 events in March to 128 events in April and decreased thereafter (60 events in May and 11 events in June). Moderate hail events gradually increased from 30 events in March to 53 events in April and decreased thereafter to 32 events in May and 9 events in June. Severe hail events initially increased from March (10 events) to April (28 events), but decreased thereafter in May (9 events) and June (1 event). Hence for all sizes, there was a sharp increase in frequency from March to April. The decrease thereafter in May was sharper for small and severe sized hail events as compared to moderate hail events. This shift towards occurrence of larger hailstone events (moderate range in this study) with increase in the freezing level height and also in hailstone size distribution within single hail events is also noted in previous climatological studies over other regions: for France (Dessens et al. 2015).

Figure 10a–c displays the spatial distribution of the three categories of hailstorms (small, moderate and severe) for the 4 months. Small hail events (Fig. 10a) occurred preferentially over the Himalayas, with the upper reaches of the Indian Himalayas (north Himachal Pradesh, north Uttarakhand, Sikkim, upper Assam and north Arunachal Pradesh) accounting for the majority of the events, with Sikkim (Gangtok) in eastern Himalayas recording 48 events and Himachal Pradesh (Shimla) in the western Himalayas recording 27 events. These events were less frequent, southwards over the Himalayan foothills and plains of India. However, there is a second maximum of much less intensity over the plains of east central India (5 events). Moderate hail events (Fig. 10b) were more uniformly distributed over the Himalayas and plains of India. While their frequency of occurrence showed a maximum over the Himalayas (with Sikkim in eastern Himalayas recording 11 events (Gangtok) and Himachal Pradesh in the western Himalayas recording 8 events (Shimla)), their frequency was equally high over the east Indian plains (6 events in Bengal (Sriniketan)). They preferentially occurred along the foothills of the Himalayas, and further south over Bengal and Odisha. Severe hail events (Fig. 10c) were infrequent throughout India, with similar frequency over the Himalayas (Sikkim (Gangtok) with 5 events and Kashmir valley (Kukernag) with 4 events), and over the plains of north and central India.

Hence, we may summarize the above findings for the severity of hail over the Indian region as follows: (1) Peak frequency of occurrence shifts towards later hours with increasing hailstone size, which is noted in all months (March to June monthly figures not shown). (2) While total number of hail events of all sized hailstones follow the general trend of increase from March to April and decrease thereafter, the decrease in May compared to April was sharper for small and severe hail events, as compared to moderate sized hail events. (3) When correlated with the gradual increase in the freezing level height, it is noted that the frequency of occurrence of larger sized hail events were less affected by the increase in freezing level height compared to small hail events. (4) Small hail events preferentially occurred over the Himalayas. With increase in hailstone size, their frequency of occurrence was more equitably distributed throughout the Himalayas and north and central India.

Hailstones form within convective storms that have regions containing supercooled liquid water and ice and sufficiently strong updrafts (typically, at least 15 m s^{-1}) to support growing hailstones (Knight and Knight 2001). Hence, a large height fraction of the cloud above the freezing level, and proximity of freezing level to the ground, are additional supportive factors for hail to reach the ground. These conditions are present mainly over the Himalayas, especially during March and April when the freezing level is low. Aided by the orographic lift on account of the mountainous terrain, such conditions are met for many thunderstorms over the region, which accounts for the predominance of small hail events over the Himalayas during March and April as noted in this study. The increase in the freezing level height throughout India with the progress of the summer season reduces these optimal conditions and there is a corresponding decrease in hail events as the months progress.

However, the moderate to severe hail events have greater impact in agricultural and human terms. Globally it has been noted that large hail formation is often related to supercell thunderstorms (Moller et al. 1994), strong mesoscale convective systems (Houze 2004), which provide the ideal environmental conditions such as strong and persistent updrafts that exist for 30 min or more which is required for large hail formation (Blair et al. 2017). For well-organized storms, such as supercells and squall lines, strong vertical wind shear can be regarded as an additional, fourth, ingredient. This was demonstrated both in numerical studies (Weisman and Klemp 1982), and in studies of storm environments (Rasmussen and Blanchard 1998; Thompson et al. 2003, 2013).

The fact that convection over India during the period of March to May (pre-monsoon season) is different from the convection during the following monsoon season (June to September) has been noted by many previous studies (Hirose and Nakamura 2002; Islam and Uyeda 2008 for example). On account of the high surface heating and low moisture conditions, a significant fraction of the convection is often of small spatial and temporal scale with thunderstorm cells extending deep into the upper troposphere (Yamane and Hayashi 2006; Roy Bhowmik et al. 2008;). These thunderstorms have significantly less upper level stratiform outflow and peak diurnally during the evening hours unlike the semidiurnal peaking of the larger scale and long lived convection which is more frequent during the monsoon period (Romatschke and Houze 2011; Sen Roy et al. 2019). Radar studies over the plains of India and NWP modelling studies note the presence of supercells with strong rotational component embedded within (Sharma 1967; Singh et al. 2011b) or organization into squall lines (Murthy et al. 2018) during instances of severe hail.

Analysis of moderate to severe hail episodes over the Indian region indicates that they occur due to deep convection associated with strong dynamic and thermodynamic support up to middle tropospheric levels (Mishra and Prasad 1980; Das et al. 2010; Singh et al. 2011a, b; Chattopadhyay et al. 2017; Roy et al. 2023). Deep southward penetration of midlatitude mid tropospheric westerly troughs, coupled with interaction of moist winds from the Bay of Bengal and Arabian Sea in the lower levels along the north–south wind discontinuity across the Indian mainland significantly increases the atmospheric lapse rate as well as vertical shear, thereby causing multiday episodes of widespread and devastating hailstorms over west peninsular India (Kulkarni et al. 2015; Murthy and Latha 2017; Ranalkar et al. 2022); on other occasions over central peninsular India (Pandharinath and Bhavanarayana 1990); and over west central India (Swaminathan 1962). Location of the subtropical westerly jet core aloft (mean position over central Indian latitudes at 200 hPa over the Indian region during this season) is also a favourable factor for triggering severe hail episodes (Chattopadhyay et al. 2017). Strong vertical wind shear is also noted to favour late afternoon to night time severe hail episodes over the valleys of northeast India (Mukherjee et al. 1962; Biswas et al. 2010). High thermal instability and vertical wind shear occur in east and northeast India and Bangladesh during the March to May period, which is favourable for the development of severe mesoscale convective systems during this period (Yamane and Hayashi 2006). During March and April, such events are primarily associated with hail. As the months progress, strong gusty surface squalls become the predominant type of precipitation system (Yamane and Hayashi 2006; FDP Report 2021).

4 Conclusions

During the period from March to June, the Indian subcontinent gradually transits from cold and relatively stable winter season to hot and dry pre-monsoon season and subsequently to hot and moist monsoon season. Unlike thunderstorm activity which increases spatially as well as in terms of frequency throughout this transition during March to June, hailstorm events over India starts occurring in significant numbers from March, increases in April and significantly decreases thereafter. Also, they predominantly occur over the Himalayan region and are concentrated around the local diurnal temperature maximum throughout India.

Two significant diurnal and intraseasonal factors modulate the hailstorm activity. These are (a) increasing sensible heating of the lower atmosphere and (b) the increasing freezing level height throughout the country, which balance each other to gradually (1) increase the frequency and intensity of thunderstorms with hail signature embedded within them and (2) decrease the frequency of events with hailstones observed on the ground. These factors most affect the small hail events, which increased from March to April and decreased gradually thereafter, becoming insignificant by June. On account of low freezing level height from the ground, the frequency of hailstorms was highest over the Himalayas and the adjoining foothills as well as the valleys of northeast India. Frequency of hailstorms significantly increased and peaked over the plains in April, as the intensity of thunderstorm activity increased over this region. Thereafter, the frequency of hail events gradually decreased in the Himalayas, but persisted over the plains of India in May, becoming insignificant throughout the Indian region in June.

The study also indicates that moderate to large hail events tended to occur later in the day during evening to early night hours. Their frequency was less affected by the increase in freezing level height and did not occur preferentially in the Himalayas. With increase in hailstone size, their frequency of occurrence was more equitably distributed throughout the Himalayas and north and central India. Upon comparison with previous studies, one notes that these severe hail events are associated with organized deep convection such as supercells with strong rotational component embedded within them or squall lines formation. Such weather systems are relatively rare and develop throughout India in regions where factors such as strong low to mid-level forcing, moisture supply, and strong vertical shear occur concurrently. Their frequency increases from March to June with a corresponding rise in the frequency of moderate to severe hail events. Such mesoscale convective systems take longer to develop and peak towards late afternoon to evening hours (Sen Roy et al. 2019), thereby explaining the delayed maximum of moderate to severe hail events. As the season progresses, the warming of the subcloud layer significantly affects the size of hail particles reaching the ground. The warming atmosphere in June subdued all hailstorm activity over the Indian region.

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Data availability Meteorological data is available at the National Data Centre of India Meteorological Department (https://dsp.imdpune.gov.in/). It will be supplied as per Government of India rules.

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