Journal of Geosciences, Earth and Planetary Systems

PRIME OPEN ACCESS

Volume 2, Issue 1

Research Article

Date of Submission: 25 Feb, 2026
Date of Acceptance: 24 March, 2026
Date of Publication: 01 Apr, 2026

Impact of Hailstorm Encounter on Aviation Services in Jammu & Kashmir Region

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Citation: Singh, N., Khushi, Yadu, M., Pradhan, S., Parihar, S., et al. (2026). Impact of Hailstorm Encounter on Aviation Services in Jammu & Kashmir Region. *J Geosci Earth Planet Syst, 2*(1), 01-14.

Abstract
This paper presents a detailed analysis of a critical aviation incident that occurred on 21st May 2025, about IndiGo Flight 6E2142 going from Delhi to Srinagar. Flight safety is undeniably the top priority in contemporary aircraft design and operation. Nevertheless, in practice, the performance and safety of aircraft are inevitably influenced by challenging weather conditions, one of which is hailstorms. The aircraft encountered an intense and unpredictable hailstorm, resulting in severe turbulence and causing the plane to make an emergency landing at Srinagar International Airport. Weather conditions, considered as key factors to accidents, can produce interruptions leading to human error and technical failures, despite technological advances. India Meteorological Department (IMD) plays an important role in understanding, monitoring, and forecasting severe weather conditions and phenomena that affect air travel in India. This case study assesses weather patterns and evaluates meteorological conditions through satellite, radar, and Meteorological Terminal Air Report (METAR) observation, which are helpful for pilots as well as forecasters to make prompt decisions.

Keywords: Flight Turbulence, Delhi to Srinagar, Hailstorm, Satellite Observations, IMD, Mountainous Region

Introduction

The evolution of aviation safety has experienced considerable changes from its inception to the current era, primarily driven by technological innovations, enhanced training programs, an increased focus on human factors, more stringent regulations, and a robust safety culture with International Civil Aviation Organization-Directorate General of Civil Aviation (ICAO DGCA) guidelines. Historically, aircraft were prone to mechanical failures, did not include vital safety devices, and frequently faced unforeseen weather conditions. In contrast, modern aircraft are significantly more dependable and secure, with pilots employing advanced technology and thorough safety protocols [1]. In the current aviation landscape, emphasizing safety is essential. Identifying the elements that contribute to aircraft incidents is crucial for ongoing improvements. Weather-related factors greatly impact this sector, frequently presenting unforeseen challenges and hidden dangers for both pilots and air traffic controllers. Many studies investigate the relationship between weather events and aviation accidents together with their mutual influence and methods to prevent their occurrence [2]. Hailstorms represent a major hazard for aviation, as they can interrupt flight operations, lead to human mistakes, cause mechanical issues, and, in certain instances, result in severe accidents. Hailstorms are commonly associated with severe, multicellular convective storms, in which individual cloud cells form and disperse within the cumulonimbus cloud structure. These storms have strong updrafts and downdrafts that generate high turbulence and promote hail formation through the repeated cycling of super cooled water and ice particles. The presence of an anvil-shaped cloud top demonstrates the vertical reach of these systems. Hailstorms are uncommon in India, occurring primarily during the hot summer and pre-monsoon seasons, but they can cause significant damage when they do occur [3].

Thunderstorms can vary significantly, from minor isolated occurrences to large-scale mesoscale systems, making them challenging to predict due to their reliance on both broad meteorological patterns and localized elements such as terrain, land use, and soil moisture levels. Remote sensing technologies, including satellites, radar, and lightning detection, provide a wealth of information on hazards associated with storms, such as hail, wind shear, and lightning—critical risks for flight operations. It is impractical to convey this intricate information directly to pilots for their decision-making processes. One Cumulonimbus Weather Information Management System (CB WIMS) system was introduced to tackle this issue by pinpointing and forecasting specific regions of aircraft hazards, classified as either "moderate" or "severe," with a short-term lead time of up to one hour, thereby improving aviation safety during thunderstorm events. The author has created the CB WIMS strategy not to provide a detailed description of thunderstorms, but to pinpoint the hazards that aircraft may face in thunderstorm conditions [4]. Thunderstorms are short-lived mesoscale weather phenomena that significantly impact society, particularly in sectors like aviation and agriculture. The sparse distribution of full-time observatories along with the limitations in the synoptic network result in many thunderstorm events being unreported which causes inaccuracies in climatological records.

Operational forecasting benefits from enhanced knowledge about thunderstorm characteristics which includes their frequency and intensity together with their diurnal patterns and duration to improve air safety and reduce societal risks [5]. Low-visibility conditions such as fog, dust, smoke, and haze significantly impact aviation, leading to flight delays, cancellations, and diversions, with serious economic consequences for airlines and inconvenience for passengers. The Indo-Gangetic Plains (IGP) in northern and northeastern India are especially susceptible to thick fog during the winter months. Dense fog poses a major challenge for flight operations in Delhi, especially at Indira Gandhi International (IGI) Airport. Studies conducted from 2011 to 2016 indicated that nearly 653 hours of heavy fog led to an estimated economic impact of about 3.9 million USD for airlines due to delays, diversions, and cancellations [6]. Fog significantly hampers visibility, particularly during critical flight operations like take-off and landing, which frequently leads to operational interruptions and increased safety risks. Besides fog, other adverse weather conditions such as wind shear, thunderstorms, icing, storms, and snow can drastically affect aircraft operations at various stages of flight-from initial take-off and climb to cruising, descent, and final landing. The existing weather conditions pose challenges for pilots when it comes to visually recognizing the runway, increasing the risk of diversion cancellation and delays. These challenges highlight the necessity for improved aviation weather safety technologies and the implementation of stringent operational protocols to bolster flight safety and minimize disturbances. Increasing fog occurrences pose big problems for aviation and transportation. Timely and reliable prediction is required to mitigate the associated socioeconomic impacts. Fog characteristics and associated meteorological conditions at Kempegowda International Airport, Bengaluru (KIAB), Karnataka, India are investigated in this work. Results indicate that fog takes place most frequently in December, then in January, and generally forms between 1800 and 0300 UTC, which indicates that radiation fog is the dominant type. Between 0400 and 1700 UTC fog is not generated. During fog events, winds mainly come from the east or southeast [7]. Storms and the meteorological factors that influence aviation, such as wind gusts, thunderstorms, runway visual range, and volcanic ash, are atmospheric occurrences that have a detrimental impact on human life. It is crucial to comprehend the mechanisms behind the formation of these meteorological events and to forecast the weather prior to the occurrence of these atmospheric phenomena, as well as to implement appropriate precautions for the aviation sector [8].

Meteorological conditions significantly impact aviation, marine, and land transportation, with weather playing a critical role in aviation safety and operational efficiency. Accurate knowledge of weather parameters enhances flight planning, fuel management, and passenger safety. Key meteorological factors affecting aviation include wind shear, gusts, turbulence, low visibility, low ceiling, and various forms of precipitation-all of which can disrupt flight operations, especially during take-off, landing, and de-icing procedures. The operational challenges and fuel consumption increase as well as safety hazards emerge when wind shear combines with turbulence and low visibility along with precipitation conditions. Machine learning and AI technologies can enhance observational data quality and numerical weather prediction models to produce precise forecasts which lead to safer aviation operations [9]. The western Himalayan area of Jammu and Kashmir experienced substantial climatic changes because of global warming together with climate change. Over the last twenty years, Jammu and Kashmir has endured a disturbing rise in extreme weather occurrences, which resulted in fatalities and significant economic losses in horticulture and agricultural production. The research uses weather information obtained from Srinagar station along with Kupwara station and Qazigund station, which covers the period from 1980 through 2019, to investigate precipitation and temperature patterns. The investigation studies the increasing number of risky weather events, which include flood events alongside drought intervals and seasonal modifications. The study demonstrates that the Himalayan ecosystem shows significant sensitivity to small climatic fluctuations. The environmental changes in the region result in glacier retreat and shortened winters and reduced snowfall and extended summers, together with increasing temperatures that create major threats to both natural surroundings and socioeconomic balance. The study highlights immediate requirements for understanding and addressing climate change effects, which threaten vulnerable mountain areas, including Jammu and Kashmir [10].

The main global challenge today is climate change because global warming combines with precipitation changes to affect the environment. The Intergovernmental Panel on Climate Change (IPCC) documented a global temperature increase of 0.85°C from 1880 to 2012 together with precipitation pattern changes which show rising rainfall in Northern Hemisphere mid-latitudes and falling rainfall in other parts of the world [11]. Weather-related factors significantly affect aviation safety, passenger comfort, scheduling, and operational efficiency. To tackle these challenges, new electronic sensor systems are being developed and used, especially in the U.S. Some key examples include Doppler-based systems like the Doppler Weather Radar, Terminal Weather Radar, and Airport Surveillance Radar with weather features. These systems improve the detection and analysis of severe weather conditions, such as wind shear and turbulence. Other useful technologies include the Low Level Wind Shear Alert System, Doppler Wind Profilers, and Automated Weather Observation Systems. Combining these tools with satellite data greatly enhances aviation weather monitoring and forecasting [12]. The Instrument Landing System (ILS) is a vital ground-based navigation aid that enables precision approach and landing, especially under poor visibility. Category III (CAT III) ILS is particularly important as it allows aircraft to land safely in near-zero visibility, significantly enhancing flight safety, reducing delays, and improving airport capacity. Its adoption has greatly improved operational efficiency in modern aviation [13]. In recent years, advancements in drone (UAV) and radar technologies have significantly expanded their applications in aviation and remote sensing. Drones, due to their precision, on-demand deployment, and low cost, offer advantages over satellites and aircraft for tasks like flight path monitoring, crop assessment, and terrain mapping. Imaging radar systems, such as Synthetic Aperture Radar (SAR), enhance drone capabilities for obstacle detection, flight safety, and environmental monitoring. Accurate flight attitude and position estimation is crucial for high-quality remote sensing data, reliable comparisons over time, and integration with GIS for detailed flight-based mapping and analysis [14].

The aviation sector in India plays a crucial role in boosting economic growth and social progress, along with improving connectivity. India's aviation sector has rapidly recovered post-COVID-19, with significant growth in air traffic and projections to become the world's third-largest air passenger market by 2030. However, adverse weather conditions-such as fog, thunderstorms, and dust haze-continue to cause flight delays, cancellations, and operational disruptions, leading to financial losses and reduced airport efficiency. As the industry grows, the impact of weather-related challenges on infrastructure, costs, and service reliability becomes increasingly significant [15]. The registered airlines in India transport over 50 million passengers and 1.1 million tons of cargo each year on their domestic and international flights. The transportation sector enables tourism activities and personal travel while providing businesses with quick mail delivery and cargo services. The air aviation industry depends on a broad ground-based infrastructure, which consists of airport facilities together with air navigation systems and regulatory services. India maintains an expanding aerospace manufacturing industry that works on aircraft systems alongside maintenance operations and electronic components. Worldwide, the air transport sector supports approximately 56.6 million jobs and contributes more than USD 2.2 trillion to the global GDP. In India, the swift increase in passenger traffic has led to significant modernization initiatives, including the construction of new airports and the implementation of state-of-the-art security and navigation technologies. India ranks as the 9th largest market in aviation, with 121 million domestic travellers and 41 million international travellers. Over 85 international airlines have flights to India, whereas Indian carriers serve more than 40 nations. Major airports, including Delhi, Mumbai, Chennai, Bengaluru, and Kolkata, handle upwards of 77 million passengers annually, leading to a total airport traffic in India exceeding 109 million passengers and 1.4 million tons of cargo [16]. Study looks at hailstorm patterns in four regions of India from 1981 to 2015. It highlights their climate and weather features. Unseasonal hailstorms in March and April 2014 and 2015 caused significant damage to rabi and horticultural crops. Maharashtra was the hardest-hit state, facing the highest frequency and likelihood (91-95%) of hailstorms. We often linked these events to weather conditions like north-south windbreaks and westerly systems. The findings have supported the creation of timely Agromet Advisories under the Gramin Krishi Mausam Sewa (GKMS) project by IMD and its partner institutions to help reduce agricultural losses [17]. The study highlights how full-time current weather observatories at airports and selected IMD Class I and II stations provide high-quality data to create an improved thunderstorm climatology. The restricted number of available observatories limits the spatial resolution inside meteorological subdivisions. The establishment of one full-time weather observatory in each district becomes essential because thunderstorms produce critical effects that include aviation hazards together with infrastructure damage and loss of life and agricultural benefits and more.

Data and Methodology

Satellite Details

In this analysis, we used data from the (Indian National Satellite System) INSAT-3DR, which was launched in September 2016, is the successor to INSAT-3D, which is owned and run by ISRO. The meteorological payloads on INSAT satellites give real-time weather data and help with weather forecasting and monitoring. It is a geosynchronous spacecraft equipped with various payloads, featuring primary weather instruments such as an imager and a sounder, Data Relay Transponder (DRT) & Satellite-aided Search and Rescue (SRS). INSAT-3DR's Imager Payload has an imager that collects data in six spectral bands: Visible (VIS), Shortwave Infrared (SWIR), Mid-Wave Infrared (MWIR), Water Vapour (WV), and two Thermal Infrared (TIR) bands. Similarly, the Sounder Payload of INSAT-3DR is a complex 19-channel instrument specifically crafted to measure vertical profiles of atmospheric temperature and humidity at various pressure levels. It has 18 infrared channels and one visible channel, which makes it possible to make different types of maps for the atmosphere that are important for predicting the weather and sending out alerts for disasters. INSAT-3DR imager and sounder have different products which are utilising for analysis and forecasting purpose within that we have utilised few products like from Imager: Outgoing Longwave Radiation (OLR), Cloud Top Brightness Temperature (CTBT), Visible (VIS+IR1BT SANDWICH) & DAY/NIGHT Microphysics and from the Sounder: Cloud Top Temperature (CTT) & Lifted Index (LI) (IMD INSAT-3DR Data User Handbook https://mosdac.gov.in).

OLR

OLR represents the amount of thermal infrared radiation emitted by the Earth and its atmosphere into space. It is measured in Watts per square meter (W/m^2). The OLR product is derived from thermal infrared channels (primarily

10.8 μm) of the Imager sensor. OLR Product Features: Temporal Resolution: Every 15–30 minutes. Spatial Resolution: ~4 km at nadir.

Data Format: Available as Level-2 geophysical products in HDF5 format. Lower OLR values typically indicate high, thick clouds (e.g., thunderstorms, hailstorm or tropical cyclones), while higher values suggest clear skies or low clouds [18] Significance of OLR: Enables real-time monitoring of - deep convection (e.g., thunderstorms, monsoon systems), diurnal variations in cloud cover, tropical cyclone development, critical for weather forecasting, climate studies, and hailstorm/ thunderstorm nowcasting. OLR anomalies help in studying heatwaves, ENSO events, and drought monitoring (https:// www.mosdac.gov.in/, https://psl.noaa.gov/)

CTBT

CTBT measures the thermal radiance at the uppermost layers of clouds. This is done using thermal infrared sensors that capture the radiation released by different surface elements, including clouds. The cloud top represents the highest part of a cloud—signifies the maximum height of its visible section. This measurement is typically expressed in either meters above the Earth's surface or as the equivalent pressure level in hectopascals. CTBT indicates the temperature a perfect black body would need to reach in order to emit an equivalent amount of radiation as that of the cloud top. Generally, lower CTBT values suggest greater cloud heights and point to more vigorous convective activity along with severe thunderstorms. This is due to the fact that cooler temperatures are usually found at higher levels in the atmosphere [19].

Applications

CTBT data is crucial in multiple areas, including weather forecasting, climate studies, and the observation of extreme weather events such as thunderstorms (https://www.ospo.noaa.gov/).

Visible (Vis+Ir1bt Sandwich)

Visible (VIS) band reflects sunlight, illustrating cloud patterns, textures, and shadows. It captures intricate details such as towering cumulonimbus clouds, overshooting tops, and anvil clouds. On the other hand, Infrared (IR1BT): This band shows the brightness temperature of cloud tops measured in degrees Celsius. It indicates the altitude of clouds, their intensity, and colder temperatures signify higher elevations and stronger convection. The VIS+IR1BT Sandwich product is a combined satellite image that integrates two essential elements: VIS band, typically at 0.65 μm, which captures sunlight reflected by clouds, and the Infrared Band (IR1/IR1BT), usually at 10.8 μm, that displays the brightness temperatures of cloud tops. When combined: You can see the shape and judge the intensity in a single image. The Bright white clouds in VIS + cold colours in IR (red/purple) show very high, reflective, and active storm clouds, likely with hail or turbulence. Bright cloud + cold IR colours = very strong storm cell.

Purpose

The aim is to deliver a more enriched visualisation of storm structures, which is especially beneficial for identifying severe convective systems, such as hailstorms, thunderstorms, turbulence zones or cyclone (https://www.star.nesdis.noaa.gov/star/index.php) [20].

Day/Night Microphysics

Day/Night Microphysics is a colour-enhanced RGB composite product that uses thermal infrared bands to highlight the microphysical characteristics of clouds and surface features under all lighting conditions. It creates the image by combining the colours - Red, Green & Blue. These colour bands represent different factors like Red - Depicts the difference between 2 Thermal IR, Green - indicates the difference between thermal infrared and mid-range infrared, while Blue - indicates the intensity of a single thermal infrared signal. It uses a device called Radiometer that measures the properties of radiation by studying the radiation's interaction with matter.

Day time Microphysics - By combining information about the cloud brightness, cloud particle phase, size and cloud top temperature it can be interpreted.

Night time Microphysics - It is designed for monitoring the elevation of fog and stratus clouds at night time [21]. It utilizes cutting-edge imaging methods to uncover details that are typically Unnoticeable to visible-light observations, providing a thorough perspective of the Earth's atmosphere irrespective of lighting conditions. This makes it an essential resource for weather assessment, climate research, and atmospheric studies (https://www.eumetrain.org/).

CTT

CTT is the brightness temperature of the top of a cloud, measured by infrared sensors on-board satellites. It indicates how cold or warm the top of the cloud is, which helps infer the cloud's height and intensity. CTT is giving more accurate information through its spatial and temporal variations. Measures of CTT: The IR1 band (10.8 μm) measures the radiated energy from the Earth's surface and clouds. Colder brightness temperatures indicate higher and thicker clouds (usually convective), while warmer temperatures suggest low or no clouds. It provides continuous monitoring over India every 15 minutes. Helps in nowcasting (short-term forecasting) of Hailstorms-Hail forms in tall clouds with tops reaching below -60°C or lower, where super cooled water and ice crystals can exist, Thunderstorms-CTT helps identify cumulonimbus clouds with strong vertical growth, and Cyclones-The eye and convective bands of tropical cyclones are easily visible with CTT imagery [22]. It can be used with other parameters like OLR, VIS+IR Sandwich, and Day/Night Microphysics for more accurate hail detection. This allows continuous and wide-area monitoring of cloud development over India and nearby regions (https://www.researchgate.net/journal/Journal-of-Applied-Meteorology-and-Climatology-1558-8432).

LI

LI is a thermodynamic stability index used in meteorology to assess the potential for thunderstorms, instability of the atmosphere and predict the convective development. It is calculated through a formula

$$LI = T_{env} - T_{parcel}$$

Where

Tenv is the temperature of the environment at 500 hPa (about 5.5 km above sea level) Tparcel is the temperature of a parcel of air lifted adiabatically (without heat exchange) from the surface up to 500 hPa. The calculation of LI is very much useful in predicting the hailstorm as it can indicate the vertical instability that shows the strong upward motion in the atmosphere and also if the value of LI is negative it will indicate that the surface air parcel will be warmer than the surrounding air aloft, and will continue give rise to a necessary condition for deep convection. While LI alone gives a quick estimate of instability, it’s often used with Convective Available Potential Energy (CAPE), Dew Point, and CTT for a multi-parameter hail risk assessment.

Results and Discussion

Analysis of Outgoing Long Wave Radiation on May 21, 2025

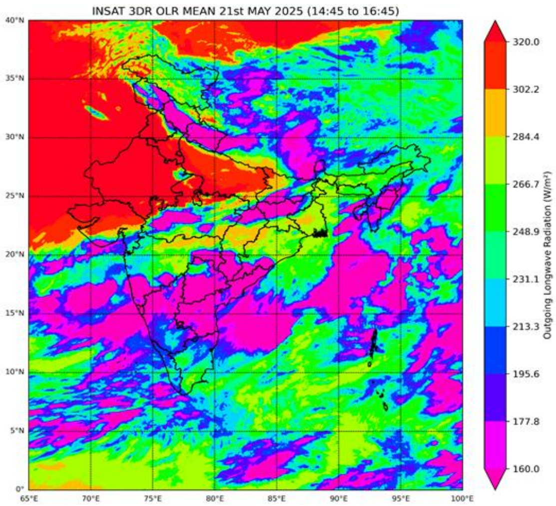


Figure 1.1: Representing The Mean Plot of OLR (21 May 2025, 14:45-16:45 IST)

The above picture, Figure. 1.1, shows an average of 2.5 hours of outgoing longwave radiation that was recorded on May 21, 2025 (14:45 to 16:45 am). The satellite image shows that the sky was mostly cloudy before the flight left for Srinagar. The purple belt in the upper northern part of the Srinagar Valley shows that there has been very little outgoing longwave radiation due to the cloud formation. This is because it is associated with high, thick and cold clouds. Satellite radiation climatology says that low OLR values mean that there are deep, cold, high-altitude cloud tops. These phenomena are typically associated with cumulonimbus cloud systems (Cb), which are recognised for causing turbulence, hail, and convection instability.

This observation is supported by the research conducted by Schumann and Graf (2013), which demonstrated how aviation-related cirrus clouds and upper-tropospheric dynamics can influence the OLR areas. Their research indicates that contrail-induced cirrus clouds and deep convection zones lead to both spatial and temporal reductions in OLR due to increased optical thickness and cooler cloud tops. The decrease in OLR corresponds with areas of intense convection and turbulent vertical motion, which are often related with embedded turbulence. This indicates that cloud formation was happening swiftly, supported by strong convection and the existence of towering clouds (cold cloud tops), likely Cumulonimbus clouds. Such clouds are typically linked to hail storms and thunderstorms, which can potentially generate hail if the vertical uplift and super cooled water are sufficiently well built.

Analysis of Cloud Top Brightness Temperature on May 21, 2025

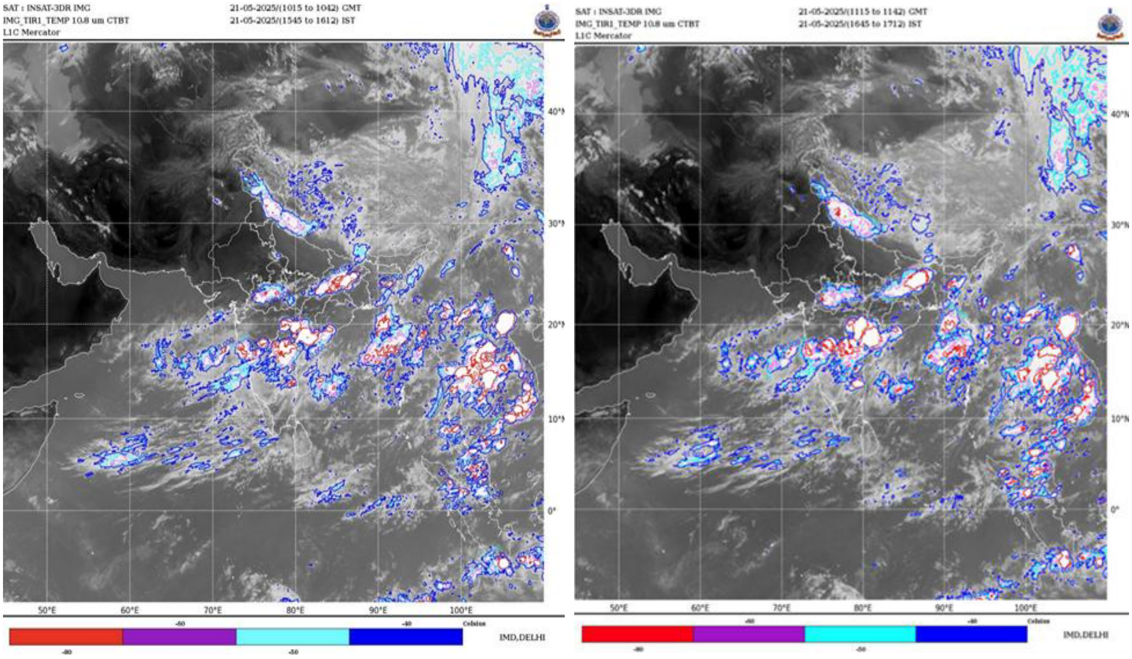


Figure 1.2: Movement of Cloud Top Brightness Temperature (CTBT)(21 May 2025, 15:45-16:12 To 16:45-17:12 IST) (https://satellite.imd.gov.in/)

The CTBT, illustrated in Figure 1.2 at 15:45 IST, offers valuable interpretations into pre-convective development insight. The high cloud tops and thermal signatures suggest that any flight around or over this region (e.g., Delhi to Srinagar) was highly likely to encounter turbulence, hail risk, or CB clouds (cumulonimbus). The CTBT shown in figure 1.2 illustrates the movement and the presence of cumulonimbus clouds exhibiting significant vertical growth. A prominent cold cloud mass over and slightly south of Srinagar. These clouds feature cold tops (typically < -50°C), which are prominently displayed in the image as purple, or cyan. With the help of CTBT we can track the growth and movement of thunderstorm cells. Areas of extremely low temperatures (≤ -80°C, Indicated in red, these features often represent overshooting tops, a hallmark of strong updrafts capable of producing hail in the higher sections of clouds as they move northward in the Srinagar region as shown in fig 1.2 .

As outlined by Me infrared-based brightness temperature observations are important for detecting convective hazards, especially cumulonimbus clouds and overshooting tops with temperatures below -80°C. The CTBT images presented in Figures 1.2 align with these findings, revealing cold-topped cloud formations that may indicate the potential for hail and turbulence along the Delhi–Srinagar route [23].

Analysis of Visible (VIS+IR1BT Sandwich) on May 21, 2025

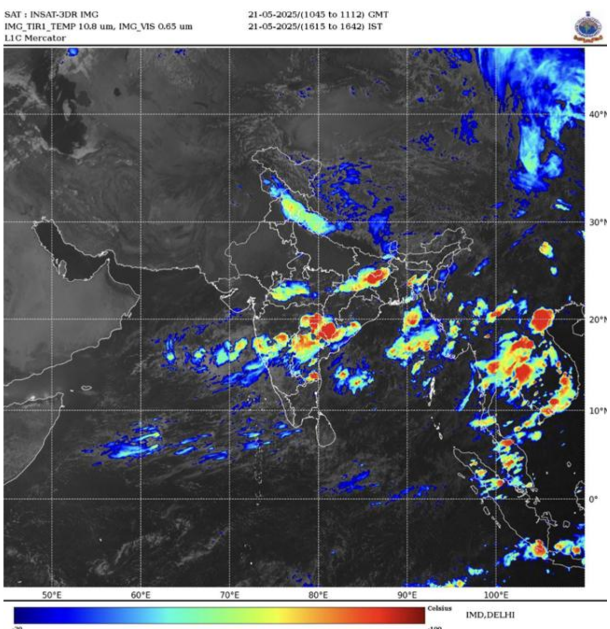


Figure 1.3: This Image Depicts the Vis+Ir1bt Sandwich Product (21 May 2025,16:15-16:42 IST) (*https://satellite.imd.gov.in/)*

The bright white clouds you see in Figure 1.4, over Northern India (particularly in Jammu & Kashmir), represent thick, dense cumulonimbus clouds. These kinds of clouds are hazardous for planes as "Turbulence is concentrated in the updraft region of deep convection. These updrafts can be identified in satellite imagery by their cold brightness temperatures and distinct textural patterns in the visible channel", Bedka et al. (2018). These clouds align with the CTBT image, which recorded the temperatures between -50°C and -70°C, offering strong indication of deep convection and the creation of the hailstorm. In Northern India, especially in Jammu & Kashmir, we notice dense, bright clouds that suggest supportive conditions with the CTBT product (see fig 1.2, earlier image captured around 15:45 IST). The tops of the clouds are observed at temperatures below -70°C, and the expected OLR is less than 180 W/m². This results in the formation of thick cloud cover, which in turn leads to reduced emissions of the radiation. As demonstrated by the combination of visible imagery with IR brightness temperature enables accurate detection of deep convective structures [24]. The bright, highly reflective cloud tops seen over Jammu & Kashmir in Figure 1.4 are associated with infrared-based brightness temperatures varying from -50°C to -70°C. This temperature range typically signals the presence of mature cumulonimbus systems. Additionally, these features correspond with notably decreased outgoing longwave radiation (OLR < 180 W/m²), aligning with research indicating that dense, vertically developed cloud systems inhibit the emission of terrestrial radiation. The combined data from Visible, CTBT, and OLR verifies the presence of severe convective weather. This encompasses hailstorms, intense rainfall cells, and turbulence zones, all of which are critical for aviation. Furthermore, it indicates the likelihood of hail-producing storms, particularly around Srinagar and its surrounding areas.

Analysis of Day/Night Microphysics on May 21, 2025

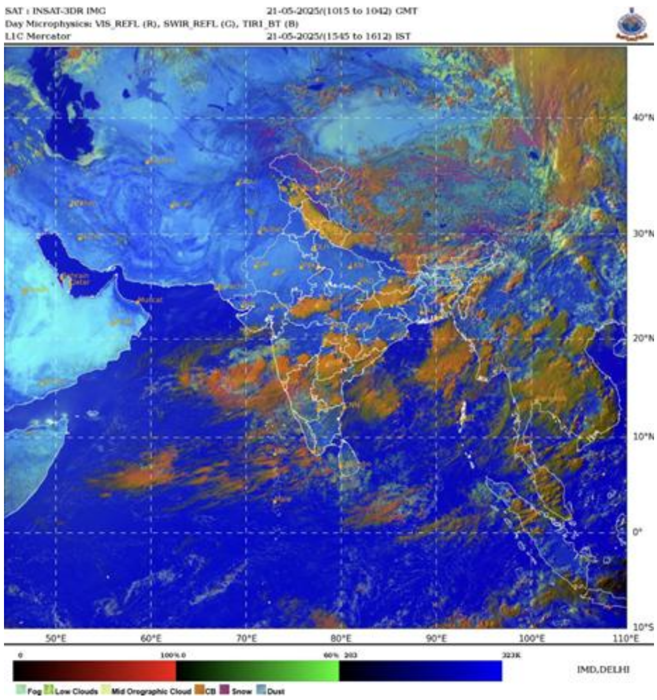


Figure 1.4: Day Microphysics RGB Image from Insat-3dr (21 May 2025, 15:45–16:12 IST) Showing Intense Cumulonimbus Cloud Development Over Jammu & Kashmir (*https://satellite.imd.gov.in/*)

The Day Microphysics image (Figure 1.5) from INSAT-3DR reveals the presence of deep convective systems over Northern India, particularly in Jammu & Kashmir. The Bright Orange zones Located over Jammu & Kashmir represent the creation of the cold, thick cumulonimbus clouds filled with ice. These clouds appear this way because they scatter sunlight strongly SWIR and also have very cold cloud tops in IR channel. According to these features are typical of hail-producing storms, as large ice particles (hail) scatter satellite signals in a similar way [25]. These clouds are optically thick and vertically developed which gives rise to thunderstorm and hailstorm. The combined analysis of the Day Microphysics RGB image (Figure. 1.5), OLR data, and CTBT fields provide a strong multi-sensor confirmation of a hail-producing thunderstorm system on May 21, 2025. In Jammu & Kashmir, the areas highlighted in orange in Fig. 1.5 indicates the presence of dense cumulonimbus clouds, with low OLR values of less than 180 W/m² and cloud-top brightness temperatures below -70°C, both of which point to significant convective updrafts. According to Hueso et al. (2020) such cloud creation are signs of convective cores capable of producing hail, as the presence of suspended ice particles creates strong scattering effects. This analysis based on satellite observations reinforces the conclusion that flight 6E2142 experienced turbulence in a high-risk environment for hailstorms [25].

Analysis of CTT on May 21, 2025

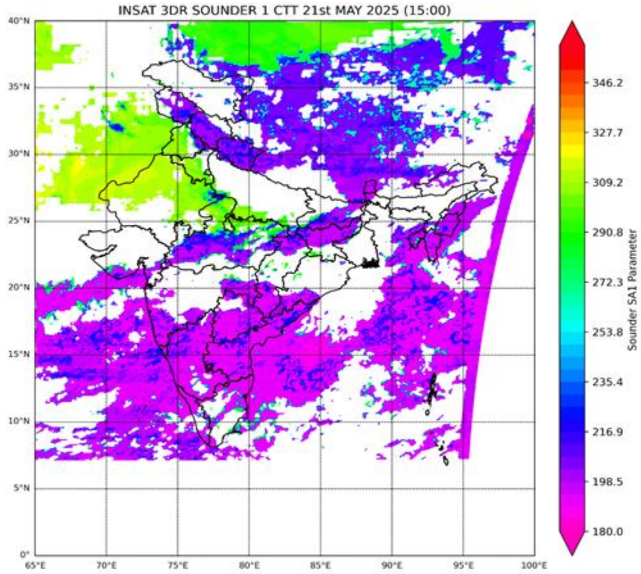


Figure 1.5: Cloud Top Temperature of (21st May 2025, 15:00 IST)

The INSAT-3DR Sounder image for 21st May 2025 at 15:00 hrs IST reveals crucial insights of cloud dynamics over the Norther Indian zone, specifically in Jammu and Kashmir region, which is also the focal region of analysis. The colour-coded CTT scale to the right of the image indicates brightness temperatures ranging from ~180K (magenta) to ~346K (red). In the southern and central parts of J&K, we can see dominant magenta and blue shades which are associated with CTT values ranging between 180K to 235K, these cold CTT values are often linked with cumulonimbus cloud and deep convective cloud tops that indicates strong updrafts that reaches into the upper troposphere and can severe weather phenomena such as hail, lightning, turbulence etc. The presence of very low cloud top temperatures supports a well-built system for the hailstorm environment. According to the strength and structure of updrafts and the development of hailstorms are highly sensitive to both environmental conditions-such as vertical wind shear and atmospheric instability, play an important role in determining the intensity and predictability of hailstorms [26]. The internal microphysical processes, including growth and ice nucleation. In this context, the magenta coloured zones over Jammu & Kashmir in the image strongly suggest the presence of intense updrafts and a highly unstable atmospheric profile, aligning with the physical processes detailed by These features likely existed prior to the IndiGo flight 6E2142 take-off, thus this image validates satellite-based thermal IR observations in the early detection of hazardous convective systems over mountainous terrain [26].

Analysis of LI on May 21, 2025

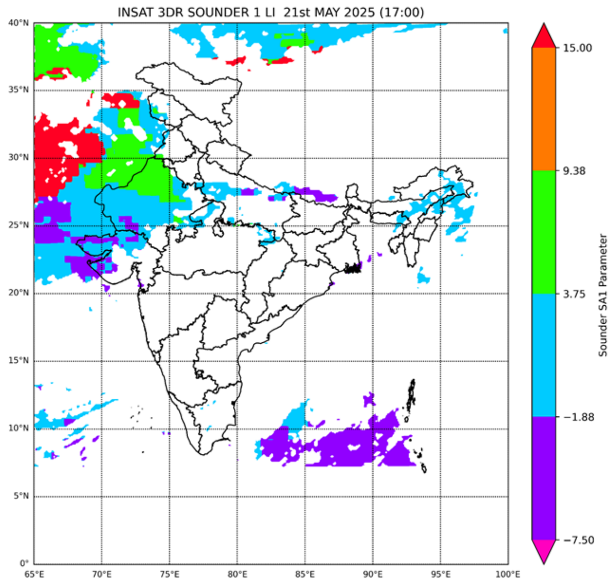


Figure 1.6: Lifted Index of (21st May 2025, 17:00 IST)

The INSAT-3DR-derived LI Figure 1.6 (21st May 2025 at 17:00 IST) over the study region showed strong negative LI values over J&K, confirming the occurrence of the very unstable atmosphere. This thermodynamic environment is consistent with the examined ice features observed by earlier satellites over deep convective cloud tops and is indicative of a microphysical environment highly favourable for hailstorm and severe convective storm production. This along with

CTT warns of the strength of satellite derived inputs for predicting hailstorm hazards, with emphasis on sensitive fields such as aviation. At 15:00 IST, the CTT showed large areas of cold cloud tops (<235K), along with blue and magenta zones of deep convection and powerful vertical updrafts, complementing this, a highly unstable atmospheric profile was also shown by the LI at 17:00 IST LI values over Jammu & Kashmir ranged from 3 to less than -1.88, indicating strong atmospheric instability. LI values below -1.88 are strongly associated with severe convective events, including large hail, strong updrafts, gusty winds, and heavy precipitation, according to results [26]. Supporting this, found that strongly negative LI values were consistently present on recorded hail days in a radiosonde-based climatological study over Belgrade [27]. When combined with exceptionally low CTT < 235 K, the occurrence of such instability over Jammu & Kashmir on May 21, 2025, provides a combined confirmation of a convective system favourable to hail formation. Together, these findings not only validate the observed incident but also highlight the operational relevance of satellite-derived products in early warning frameworks for severe weather detection and aviation safety. These indicators establish a relation to predict hailstorm.

Parameter	Threshold	Significance
OLR	< 200 W/m?	Strong outgoing longwave radiation blockage due to thick clouds - indicates deep convection
CTBT (10.8 µm)	Extremely low temps (< -60°C) indicating high, cold tops	Cold tops in CTBT correlate with tall clouds in visible images. Together, confirm vertical depth and storm intensity
Visible (VIS+IR1BT Sandwich)	VIS: High reflectivityIR1BT: < -60°C	Enhances detection of overshooting tops and dense cores of convective clouds associated with hail.
Day/Night Microphysics (DMP)	Bright Orange / Pink cores	Identifies thick ice cloud layers and particle size variations; bright cores show hail/cloud ice mix.

Table 1: Imager Products

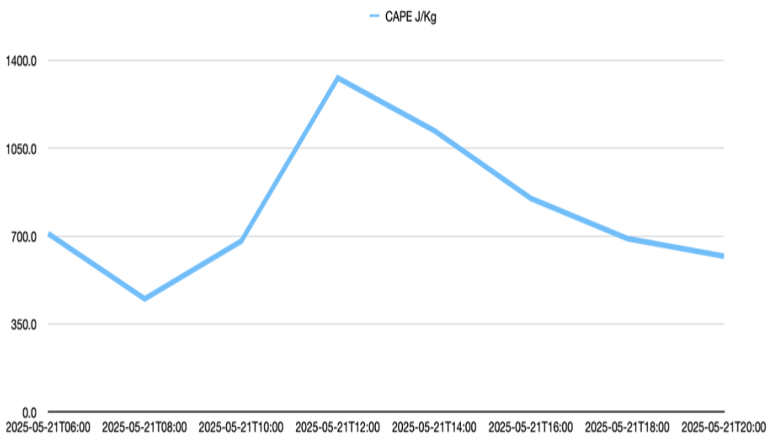
Parameter	Threshold	Significance
CTT	< 220 K	Cold cloud tops
LI	< -3	Strong instability

Table 2: Sounder Products

Graphs Representing The Cape, Wind, Cloud Cover & Rh

Cape

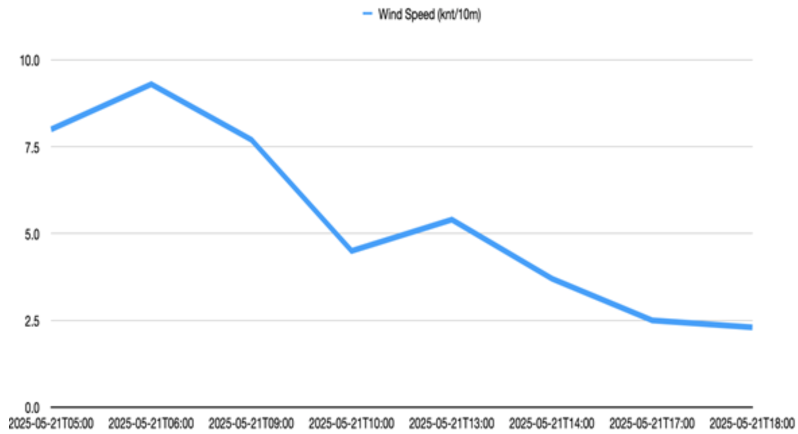
According to the 21st May 2025 CAPE curve the most significant atmospheric instability occurs at 12:00 IST which aligns with later satellite observations regarding hail-conducive convection. The thermodynamic conditions over J&K appeared favourable before the hailstorm event because of the increasing energy profile thus CAPE became an essential parameter for hailstorm risk assessment together with LI and CTT.



Graphs

Wind Index

On 21st May 2025 surface wind pattern exhibits early convergence features together with thermodynamic instability signals which enable deep convective cells to produce hail. The timing aligns with rising CAPE values, low CTT, and strongly negative LI.



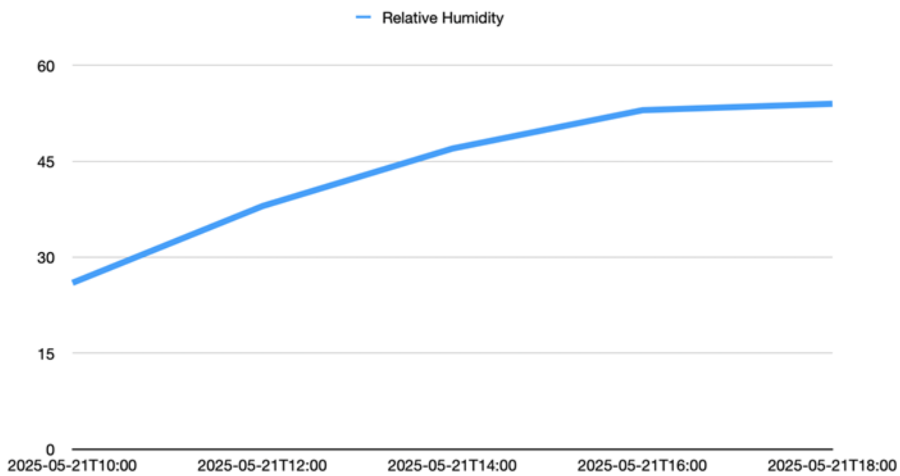
Graphs

Cloud Cover

The sharp increase and peak in high cloud cover over J & K on 21st May 2025 is a strong atmospheric indicator of deep convection, hailstorm potential and wind convergence, this cloud cover approaches to nowcasting the severe hailstorm risks, particularly for aviation hazard assessment in radar-limited, mountainous regions.

RH

This increasing relative humidity trend provided sufficient moisture to support deep convection, vertical cloud development, and hail formation. This progressive rise in RH on 21st May 2025 complements the hailstorm prediction model (https://open-meteo.com/en/docs/ecmwf-api?timezone=GMT&hourly).



Graphs

Radio Detection and Ranging (RADAR) Details

RADAR information includes data collected via RADAR technology. This method utilizes radio waves to detect objects and evaluate their distance, velocity, and other attributes. In the field of meteorology, radar systems emit bursts of microwave energy into the atmosphere. When these pulses encounter precipitation particles such as raindrops, snowflakes, or hail some of the energy is reflected back to the radar antenna [28]. For analysis and forecasting purposes we have utilized the (Maximum Reflectivity–Horizontal (MAX_Z) parameter. Doppler weather radar is an advanced technology that not only gauges the reflectivity of precipitation but also monitors the movement of raindrops or atmospheric particles by utilizing the Doppler effect. This effect demonstrates changes in the frequency or phase of the returned signal, which occurs when precipitation particles move toward or away from the radar. This study makes use of radar data collected from Doppler Weather Radar (DWR) systems, known for providing high-resolution insights into precipitation intensity and atmospheric dynamics [29]. In India, the IMD manages a network of Doppler Weather Radars (DWRs) throughout the country, particularly in areas at risk of cyclones, thunderstorms, and monsoonal events. These radars play an essential role in early warning systems and managing disaster risks.

MAX-Z

Maximum Reflectivity (Horizontal) in radar represents the greatest radar reflectivity measurement recorded at a particular altitude level which radar systems show in horizontal image slices. The radar reflectivity value indicates how strong precipitation and other scatterers are within the radar beam. Radar reflectivity (Z) tracks the radar energy that returns to the radar station after it encounters precipitation or other objects. Radar reflectivity measurements rely on decibels of reflectivity (dBZ) as their standard unit dBZ (decibels of reflectivity), Range: 0 dBZ to > 60 dBZ. (dBZ (meteorology), 2025). Purpose in Weather Monitoring: The strongest echo returns become visible which enables identification of intense precipitation cores and hail potential assessment. The tool enables detection of hailstorms along with convective cells and severe thunderstorms. Aviation operations rely heavily on this parameter because it becomes dangerous when reflectivity values reach above 45 dBZ (https://imdpune.gov.in/training/radar/DWR%20applications.pdf).

Analysis of MAX-Z on May 21, 2025

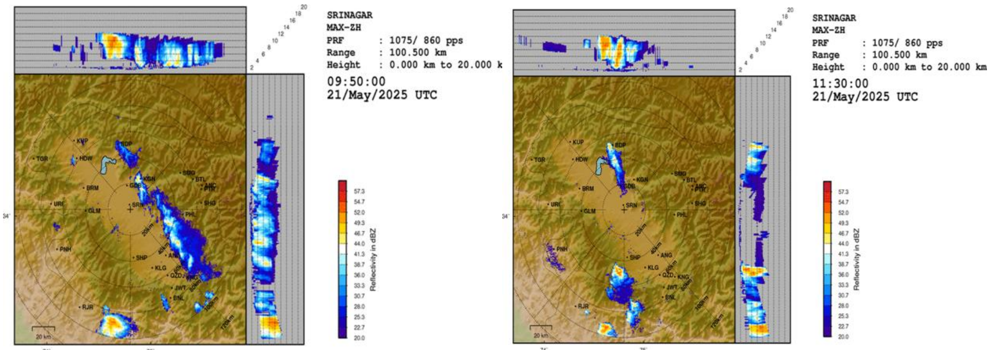


Figure 1.11: Radar Reflectivity of Max-Z On 21st May 2025, 09:50 Utc,03:20 IST, 21st May 2025, 11:30 UTC, 05:00 IST Respectively

The above Figure 1.11 presents the Doppler Weather Radar (DWR) reflectivity data for Srinagar at 03:20 PM (IST), shows a well-defined convective band that covers the southern and central areas within the radar coverage region. The vertical cross-section illustrates that the cloud tops extend up to 12 km, confirming the presence of deep convection. Moving on to, the next image from 05:00 PM (IST) reveals a slight southward movement in the convective activity which displays intensified high reflectivity cores at 49–51 dBZ. The cloud heights measured 12km which shows strong radar reflectivity detection. The Srinagar DWR radar data from 21 May 2025 displays convective reflectivity levels between 49 and 52 dBZ which indicates strong convective activity that may produce hail and intense turbulence. The radar reflectivity measurements at 51 dBZ correspond to heavy precipitation cores that usually occur in deep convective storms with potential hail and powerful updrafts. According to hail-producing convective storms exhibit high cloud heights combined with reflectivity readings exceeding 48 dBZ at altitudes beyond 5 km when strong updrafts generate hail potential [30]. This study found constant cloud tops at 12 km altitude while radar reflectivity values at 51 dBZ verified the intense convection. The 21 May 2025 DWR radar data from Srinagar shows convective reflectivity patterns which match severe convective storm characteristics thus making hail formation and turbulence hazards probable. It also matches the time period and flight path of IndiGo flight 6E2142 which needed to execute an emergency landing after experiencing severe turbulence and hail.

Upper Air Wind and Temperature Assessing Mid-Tropospheric Conditions Over Srinagar

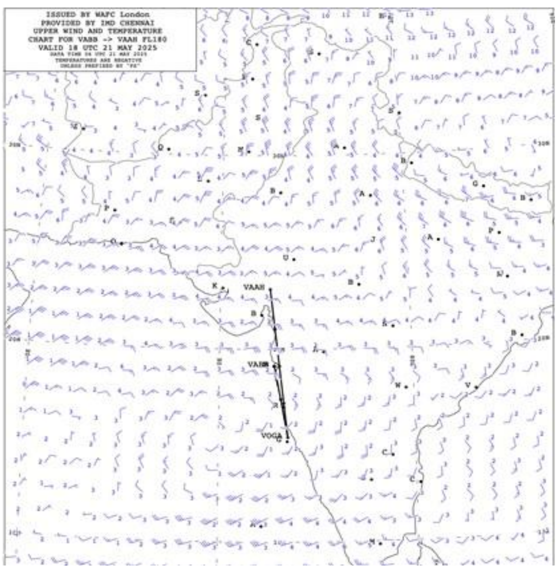


Figure 1 12: Upper Air Wind and Temperature (Valid 18 UTC, 21 May 2025) (Source: IMD OLBS Platform)

Figure 1.12 demonstrates the Upper Wind and Temperature Chart issued by WAFC London and data provided by IMD Chennai, valid at 18 UTC on 21 May 2025. It represents meteorological conditions approximately 18,000 feet (5.5 km altitude), a critical altitude within the mid-troposphere. This chart is part of standardized aviation meteorological products used for flight planning, turbulence forecasting, and hazard nowcasting.

Over Jammu & Kashmir (Srinagar region at ~34°N, 74°E), the chart indicates light to moderate upper winds, with speeds ranging from 5 to 8 knots, mostly from west to northwest. The temperature in the Srinagar region varies between +5°C and +7°C, which is cooler than the same level in southern India. The results point to the presence of cold air at mid-tropospheric levels that could cause atmospheric instability when it blends with warmer, humid air at lower levels. The temperature gradient and the presence of unstable convection are clear signs that cumulonimbus clouds may grow upward, especially over mountains. These kinds of weather are ideal for hail, strong updrafts, and turbulence, which is what flight 6E2142 experienced.

Upper Air Turbulence

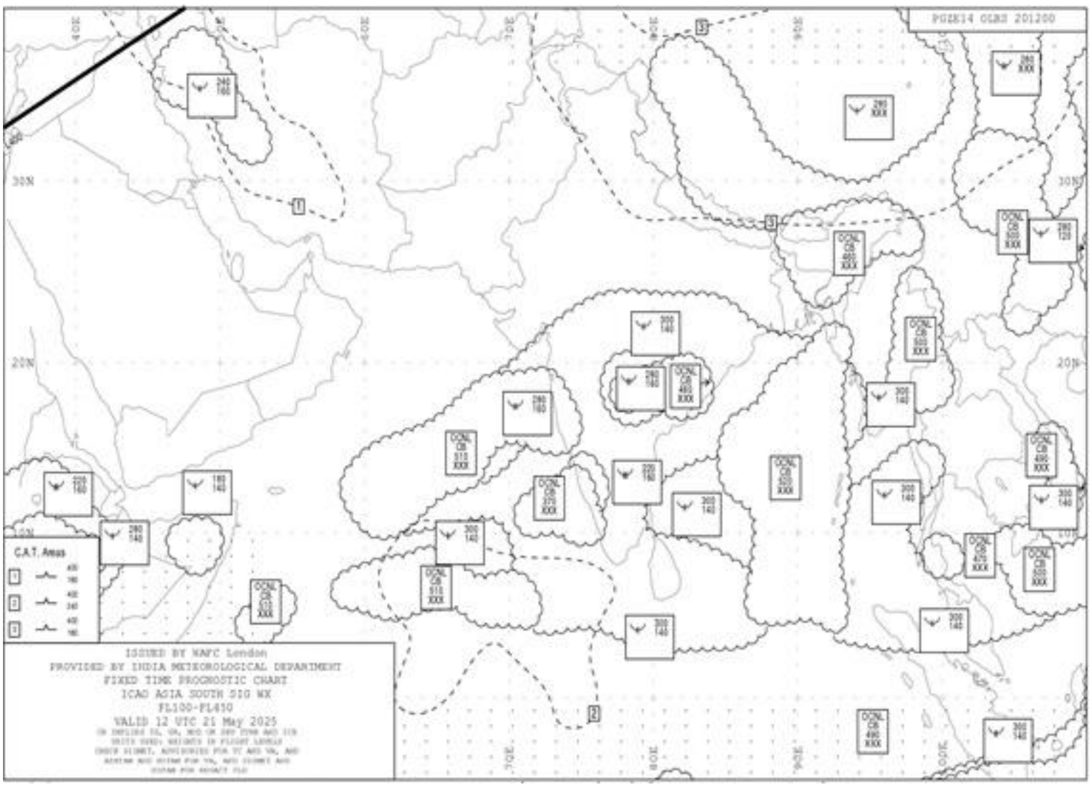


Figure 1.12: Air Turbulence (Valid 18 UTC, 21 May 2025) (Source: IMD OLBS Platform)

Figure 1.12 is showing the upper air turbulence and convective system. It is issued by WAFC London, used for international aviation hazard forecasts and data is provided by IMD Chennai, valid till 18 UTC on 21 May 2025. In the northern region of India, particularly in Delhi to Jammu & Kashmir. The chart shows a large CB (cumulonimbus) cloud cluster between Northern India and the Western Himalayan region, including the flight corridor of 6E2142. The Delhi to Srinagar corridor is covered by cumulonimbus clouds. These clouds are marked between flight levels 160–400 (i.e., 16,000 to 40,000 feet). Various CAT symbols, along with directional wind barbs, indicate wind shear and interactions with the jet stream, heightening the likelihood of severe turbulence. The existence of cumulonimbus clouds (CB) extending vertically up to 40,000 ft strongly suggests the potential for hail-producing thunderstorms. These CB zones are encircled with jagged lines (turbulence boundary) and cross-checked with jet stream directions. This means the aircraft is likely to encounter a thunderstorm during the cruise or descent phase. CB clouds are directly linked to hailstorms, turbulence, and wind shear. These conditions match the reported in-flight disturbance of IndiGo 6E2142, which experienced severe turbulence due to a hailstorm. This image strongly supports the claim that severe convective weather played a critical role in the mid-air incident and aligns with radar and satellite data used in earlier analysis.

Conclusion

On May 21, 2025, the weather conditions surrounding IndiGo Flight 6E2142 experienced a sudden increase in convective activity, leading to a hailstorm. Wind speeds varied significantly-initially rising and then falling-indicating strong convective downdrafts. The increasing relative humidity and extensive high cloud cover showed that there was plenty of moisture in the atmosphere and ongoing cloud formation. A noteworthy CAPE value of 1400 J/kg indicated considerable atmospheric instability, which was conducive to the development of severe thunderstorms. Satellite data showed temperatures below -60°C and images from VIS+IR1BT revealed tall cloud tops and thick cloud centres, indicating strong upward growth of the clouds. Furthermore, DMP RGB imagery showcased vivid pink hail cores, providing a strong indication of hail-producing clouds. The established criteria for identifying hail storms such as low OLR, cold cloud tops, and elevated radar reflectivity were distinctly satisfied. Doppler radar data gathered over Srinagar from 09:50 to 11:30 UTC displayed intense storm cells with reflectivity values exceeding 50 dBZ and cloud tops reaching heights of over 12 km. The convective activity was aligned along a southwest-northeast direction, having a notable impact on central Kashmir, particularly in the regions to the north and south of Srinagar. These conditions posed considerable risks to aviation operations, including heightened chances of turbulence, hail, lightning, and decreased visibility. This event highlights the importance of comprehensive weather monitoring, as evidenced by the IMD's utilization of INSAT-3DR satellite data, DWR, and forecasting models to bolster early warning systems and improve aviation safety in India. The upper-level wind and temperature chart for May 21, 2025, at 18 UTC provides crucial details about the weather in the Srinagar region at the time of the IndiGo flight 6E2142 incident. As illustrated in figure 1.11, the temperatures in the mid-atmosphere are low, and there is little wind shear present. When these two things are combined with surface heating and mountainous uplift, they can cause strong convective activity, also the selected SIGWX chart, however figure 1.12 shows a high probability of strong convective activity and clear air turbulence (CAT) in the North Indian air corridor creating an unstable and hazardous flying environment consistent with the reported turbulence and hailstorm. The spatial overlap of deep cumulonimbus clouds with observed CAT near the Delhi–Srinagar route aligns with the hailstorm and turbulence incident faced by IndiGo Flight 6E2142. This supports that the flight onboarding in this route must have encountered an emergency during its descent into Srinagar.

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