Numerical Simulation of a Clear Air Turbulence (CAT) event over Northern India using WRF modelling system

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Abstract

Atmospheric turbulence is a primary meteorological hazard to en-route air traffic. The role of Clear Air Turbulence (CAT) for various processes in the atmosphere is still ambiguous. An Air India flight AI462 encountered severe CAT on 19 April 2018. The present study simulates the CAT event and is focused on understanding and investigating favourable conditions for the occurrence of CAT. Weather Research and Forecasting (WRF) Model V4.0.3 has been used to simulate the turbulence. The 6-hourly NCEP FNL Operational Global Analysis data at 0.25° X 0.25° resolution is taken as input to provide the model's initial and lateral boundary conditions. For simulating the atmospheric environments at the time of the event, Yonsei University Scheme, WSM 3-Class Simple Ice Scheme, Kain-Fritsch (New-Eta) Scheme, Rapid Radiative Transfer Model (RRTM) Scheme, and Revised MM5 Monin-Obukhov Scheme are used. This study shows that Vertical Velocity, Geopotential Thickness, Wind Shear and Bulk Richardson Number Shear are correlated with CAT as the model predicted both upward and downward velocity very close to each other between 400 hPa and 550 hPa levels along with strong geopotential thickness gradient and strong wind shear gradient near the accident location. This could lead to CAT. Model simulated variations in CAT Index with change in time and pressure levels. CAT dissipates as we go higher in the atmosphere above 550 hPa.

Keywords: Clear Air Turbulence, vertical wind shear, CAT Index, Ellrod's Index, aviation meteorology, aircraft hazards.

1 Introduction

Turbulence is a primary meteorological hazard to en-route air traffic. At high altitudes, aircraft may encounter turbulence unexpectedly without any significant cloudiness. Clear Air

Turbulence (CAT) occurs when severe turbulence occurs in an environment with no clouds. It creates a ferocious buffeting effect in aircraft. The role of CAT for various processes in the atmosphere and vice versa is still ambiguous. CAT occurs in a statically stable shear layer, typically found amid the high troposphere and low stratosphere. CAT is non-convective turbulence not within the Planetary Boundary Layer (PBL). CAT is "aircraft turbulence that occurs at 5.6 km or higher altitudes, either in cloud-free condition or within stratiform clouds" (Ellrod et al. 2003). According to the Meteorological College office (1997), CAT is horizontally 80-500 km along wind direction and 20-100 km in the across-wind direction having vertical dimensions 500-1000 m. "CAT exists in the atmosphere for about 30 minutes to 24 hrs" (Stefan et al. 2020).

"The physical impact of CAT on crew and passengers varies from discomfort to injuries, loss of flight control, and in some sporadic instances, fatalities have befallen. Repeated turbulence encounters that occur during the lifetime of an aircraft might advance to metal fatigue and, in sporadic cases, structural failure" (Ellrod et al. 2003). Commercial airlines have economic loss also due to meteorological hazards as there is a significant increase in fuel consumption during turbulent flights. So, knowing the unknown about CAT is important for Aviation Safety. Favourable conditions for the occurrence of violent turbulence or CAT, leading to low-level aircraft hazards, are passage of an active cold front; preceding the time of thunderstorm; mountainous terrain; arced parts of jet-stream which might be much more likely to contain turbulence than beeline jet-stream parts; convergence area of polar and subtropical jet-stream; and the presence of vertical wind shear, horizontal shear, convergence, deformation zone, strong thermal wind gradient, and steep lapse rate. From the actual first flight, pilots are acquainted with mid-flight turbulence. In the 1940s, a previously unidentified phenomenon was discovered as fighter aircraft reached the interface between the troposphere and the stratosphere. This phenomenon was termed Clear Air Turbulence (CAT) as antecedent encounters were experienced in cloudless regions. Throughout the latter half of the 20th century, CAT attracted several organized research efforts because the aircraft was designed to fly at significant heights and speeds. As an outcome, our acquaintance with CAT has developed substantially. Between 1967–2010, "the relative contributions of meteorological phenomena to weather-related aircraft accidents shows that turbulence was associated with 66% of the cruise flight accidents and 56% of accidents occurred during descent whereas, CAT accounted for 13% of accidents during cruise flights, and 7% of accidents during descent" (Mazon et al. 2018). Studies concluded that "the frequency of CAT would increase significantly in the next 50 years due to strengthening of jet stream velocities" (Williams and Joshi 2013). "CAT is more frequent in the tropopause region" (Dutton and Panofsky 1970) near the jet stream as "jet stream contains about three times more CAT than the rest of the atmosphere" (Reiter 1963). About 60% of CAT incidents are associated with the jet stream.

Two widely accepted mechanisms supporting CAT formation are Kelvin Helmholtz Instability (KHI) and Mountain Waves. In most cases, KHI triggers CAT as it uses the mechanical energy from the vertical wind shear. Thus, forecasting CAT is challenging without understanding vertical shear (KHI). "Mountain waves are also a source of CAT. There have been several cases where severe CAT was encountered in areas with no significant KHI favourable conditions" (Hopkins 1977). Another CAT production mechanism is Internal Gravity Wave (IGW). The excitation of the IGW also affects the manifestation and strength of CAT from different sources and resonant non-linear relations amongst different IGW modes and among IGW and KHI in turbulent layers. "Low values of Richardson number (i.e., Ri < 1), discontinuity in lapse rate, significant cyclonic horizontal shear, and large vertical velocity (~1m/s) are triggering factors for CAT" (Venkatesh et al. 2014).

Forecasting and predicting CAT is a challenge for Meteorologists, as it is generally a microscale phenomenon having a small temporal and spatial dimension, making it challenging to attain consistent and inclusive observations. In the early 1960s, a basic jet-stream turbulence model was developed in United Airlines by their meteorology department. "Some advances in our knowledge of the global distribution of CAT along heavily traveled airways have been derived from programs to collect PIREPs, like one conducted by ICAO in the mid-1960s. A comprehensive global 'climatology' of large-scale and upper-level conditions favourable for CAT was created using a numerical model to determine the distribution of a globally averaged CAT index equal to the product of horizontal deformation and VWS" (Ellrod et al. 2003). In the United Kingdom in the late 1970s, "turbulence data from 4500 aircraft reports were compared with 11 co-located numerical parameters derived from a coarse-resolution prediction model. It revealed that the best correlation was between CAT and vertical and horizontal wind shears. Similar studies were completed in the United States in the 1980s using higher-resolution numerical model data that showed CAT to be highly correlated with horizontal deformation and scalar wind speed" (Ellrod et al. 2015). "Two models were introduced for CAT prediction, i.e., eddy and wave motions models" (Lester 1993). An ensemble model can be used to create a Global probabilistic turbulence forecast. Most of the indicators used now are derived from the deterministic model. "Using Met Office Global and Regional Ensemble Prediction System (MOGREPS), an ensemble forecast can predict turbulence by the probabilistic indicator of wind shear" (Gill and Buchanan 2013). Today, no warning system can ascertain CAT at archetypal flight altitudes. CAT is a severe security issue for aircraft as there are no land or onboard detection gadgets. Even the onboard weather radars are unsighted to CAT. "Doppler LIDAR has been under research and development for many years to measure wind velocities and CAT detection. Research indicates that moderate CAT could be detected at ranges of 5-8 km and up to 100 s ahead of an aircraft" (ICAO 2005). "WRF Model is also used widely for turbulence prediction and studies related to CAT" (Passner 2008).

It is essential to have an objective and meaningful approach to verify and improve the forecasting of CAT. The aim of this study is mainly to understand the dynamic processes that can trigger CAT events; to simulate a turbulence event of 19 April 2018 using the WRF V4.0.3 Model; to correlate CAT parameters with the WRF Model derived parameters for the selected CAT simulation; and to understand the reliability of turbulence indices, TI1 and TI2, for predicting CAT. Section 2 describes the data, methodology, and model study. Experimental design has been described in section 2.4, whereas results and discussion are explained and analyzed in section 3.

2 Methodology and Modelling Framework

2.1 Study Area

There are two domains in the ratio 3:1 km resolution, as shown in Fig. 1. Domain 1 (D01) with 6 km horizontal resolution covers the flight route from Amritsar to Delhi that encountered the CAT event. Nested domain 2 (D02) with 2 km horizontal resolution is focused on Amritsar's vicinity where the flight encountered the CAT event. On 19 April 2018, Air India flight AI462 took off at 0923 UTC from Amritsar. While passing from FL80 to FL210, light to moderate turbulence unexpectedly grew severe. The aircraft encountered severe turbulence unexpectedly while climbing out from Amritsar between FL160 and FL190. Once in severe turbulence, while passing through FL180, auto-pilot disengaged at 0929 UTC, and auto-thrust was also disengaged at 0930 UTC. Momentarily, the aircraft climbed almost 600 feet above the cleared level (DGCA Report 2019).

2.2 Data

NCEP FNL Operational Global Analysis Data (NCEP/NWS/NOAA 2015) at 0.25° x 0.25°

resolution with 6-hourly intervals was used as initial and boundary conditions for the model integration for 48 hours from 0000 UTC of 18 April 2018 to 0000 UTC of 20 April 2018. Model is configured as 6 km for Parent Domain (D01) and 2 km for Child Domain (D02). ECMWF ERA-Interim (ECMWF 2011), IMDAA (Rani et al. 2021), and NGFS (Prasad et al. 2016) data sets were also used in this study to analyze the CAT event. The specifications of all the data utilized in this study are stated in Table 1.

2.3 Methodology

The WRF Model Version 4.0.3 is used to simulate the Turbulence or CAT for the given date. The Advanced Research WRF (ARW) dynamic core in the model is used for this project as it is suitable for use in various applications across scales ranging from meters to thousands of kilometers. In this work, GrADS is used as a Post-Processing & Visualization tool. The atmospheric reanalysis datasets can be used to identify the areas in which the onset of hydrodynamics instability in the atmospheric flow occurred and is maintained, resulting in CAT. Several indices exist to predict CAT, such as Ellrod's Index, Brown index, and Dutton index. Ellrod's Indices (TI1 and TI2 given in Eq. (6) and (8), respectively) are calculated to analyze the CAT event in this study as they are popular due to their performance, computational speed, and easy implementation. "Studies indicate that Ellrod's Indices, proposed by Ellrod and Knapp (1992), tend to perform better than others investigated" (McCann 1993; Brown et al. 2000). "The TI1 and TI2 are in operational use at aviation forecasting offices in several countries" (Ellrod and Knox 2010). "For example, TI1 is used at Dutch KNMI (Royal Netherlands Meteorological Institute)" (Overeem 2002), "TI2 is used at Swedish SMHI (Swedish Meteorological and Hydrological Institute)" (Bergman 2001), and "Met Office in U. K. has implemented the indices as well" (Turp and Gill 2008).

2.3.1 Deformation

CAT occurrence chance will increase when deformation in the upper-level frontal zone due to horizontal temperature gradient increases as deformation affects the horizontal temperature gradient. Deformation includes D_{st}, deformation by stretching (s^{-1}), i.e., downwind,

$$D_{st} = \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y} \qquad (1)$$

and D_{sh}, deformation by horizontal shearing (s^{-1}), i.e., crosswind,

$$D_{sh} = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \qquad (2)$$

The Total Deformation (s^{-1}), $DEF = ({D_{st}}^2 + {D_{sh}}^2)^{1/2}$ (3)

where u and v are the wind components (m/s). “The relatively low values of the second Ellrod’s index (TI2) are due to the lower contribution of deformation in areas of horizontally homogeneous and relatively low curvature flow” (Spensberger and Spengler 2014). Turbulence will be more substantial in the more sharply defined deformation zones.

2.3.2 Convergence

The CVG, convergence term (s^{-1}) included in TI2 is shown below (Eq. (4)).

$$CVG = -\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) \qquad (4)$$

The two indices, i.e., TI1 and TI2, show fewer differences in the geographical location of the highest frequency during the summer season. This could be explained by the fact that the jet stream is weaker during summer, although the frequencies of the higher values of TI2 are significantly higher than the same for TI1. The added convergence term in TI2 can explain this. “CVG term is typically much smaller than DEF, but in some cases, it can still contribute significantly to CAT potential” (Kao and Sizoo 1966; Ellrod 1985).

2.3.3 Vertical Wind Shear (VWS)

The measurement of the VWS is often understood as the best indicator for the presence of CAT, as it can occur in areas with strong vertical and horizontal wind shear. “The VWS is a triggering mechanism for KHI, the primary mechanism for CAT formation” (Ellrod and Knapp 1992). The phenomenon occurs when a sufficiently large VWS within a stable layer produces breaking waves that lead to CAT. “Operational meteorologists consider Shear values of at least 6 kt / 1000 ft $\left(\left[\frac{3\ \mathrm{ms}^{-1}}{1000\ \mathrm{ft}}\right]\ or\ 9.7 \times 10^{-3} s^{-1}\right)$ as the threshold for significant (moderate or greater) CAT” (Lee et al. 1984). VWS uses results of the layer difference in u and v wind components from forecast data of the model as calculated in TI.

$$VWS = \sqrt{\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2} \qquad (5)$$

where ∂z is the thickness between the pressure levels. VWS is calculated for a layer amid two pressure levels, not a discrete pressure level. “Low-level cold advection under a ridge tends to increase the VWS, thereby increasing the probability of moderate to severe CAT" (Hopkins 1977). CAT is classified into various categories, as shown in Table 2.

2.3.4 CAT Index (TI1 and TI2)

It was discovered by Mancuso and Endlich (1966) that "VWS and deformation products gave the best correlation with CAT generation". Therefore, the turbulence index TI1 was simplified and defined by Ellrod and Knapp (1992) as Eq. (6) and (7),

$$\text{TI1} = \text{VWS x DEF} \qquad (6)$$

From Eq. (1), (2), (3), and (5),

$$\Longrightarrow \ TI1 = \left(\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2\right)^{1/2} \times \left(\left(\frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right)^2\right)^{1/2} \qquad (7)$$

Ellrod and Knapp (1992) also "defined a second turbulence index (TI2) which included the convergence term", as shown in Eq. (8) and (9),

$$\text{TI2} = \text{VWS x [DEF + CVG]} \qquad (8)$$

From Eq. (1), (2), (3), (4) and (5),

$$\Longrightarrow TI2 = \left(\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2\right)^{1/2} \times \left[\left(\left(\frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right)^2\right)^{1/2} - \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right)\right] \qquad (9)$$

"TI1 is the most skillful and widely used CAT indicator in operational forecasts" (Sharman et al. 2006; Kim et al. 2011; Gill 2012). "It was found that the two indices (TI1 and TI2) give the best performance compared to other indices" (Overeem 2002). Though they do miscalculate CAT areas, the indices are still helpful. WAFC Washington uses TI1 for forecasting shear-induced turbulence, and the AFGWC in Nebraska uses TI2. "For the lower threshold, both TI1 and TI2 perform well on detecting CAT. Both indices overestimate CAT at a lower threshold but cover most turbulence reports. Based on the hits at the lower threshold, TI1 score more hits than TI2. However, based on false alarm rates, TI2 performs slightly better than TI1. For the higher threshold, the indices underestimate CAT occurrences. TI2 values are generally larger than TI1, which is probably the explanation for the higher false alarm rate." (Williams 2017). Onset thresholds for each CAT intensity category are mentioned in Table 3. Values listed in Table 3 may differ from those computed in other studies as thresholds depend on the atmospheric model's grid resolution.

2.3.5 Bulk Richardson Number Shear (BRNSHR)

"Bulk Richardson Number Shear (BRNSHR) is used to quantify the Vertical Wind Shear (VWS)" (Moncrieff and Green 1972), such that,

$$BRNSHR(m^2/s^2) = 0.5(\underline{u}^2 + \underline{v}^2) \qquad (10)$$

where $\underline{u}$ and $\underline{v}$ are "zonal and meridional wind components of the difference between the density-weighted mean winds over the lowest 6000 m (≈ 500 hPa) and the lowest 500 m (≈ 950 hPa) above ground level" (Droegemeier et al. 1993). "Mesomodel output BRNSHR values between 40-100 m^2/s^2 are indicative of a greater likelihood of tornadic supercell thunderstorms" (Stensrud et al. 1997). The threshold value of BRNSHR for supercell thunderstorms development is 40 m^2/s^2.

2.4 Experimental Design

This study can be classified as a climatological analysis and a regional study of a CAT event in India. WRF Model V 4.0.3 is used for all simulations and configured with 6 km and 2 km grid space domains. WRF model was integrated for two days, from 0000 UTC of 18 April 2018 to 0000 UTC of 20 April 2018. The model was set to a time step of 36 seconds with 1 hour (60 minutes) history intervals for the 1st domain (D01) and 15 minutes history intervals for the 2nd domain (D02). The 1st domain (D01) had 110 x 110 grid points, and the 2nd domain (D02) had 109 x 109 grid points in the west-east and north-south directions. Both the domains were set with 33 vertical levels. Various literature on WRF modelling and simulation of CAT were studied at the beginning of this project (Wasson 2021). Thus, considering results and suggestions from those works of literature, the physics parameterization schemes were given weightage, and accordingly, each scheme used in this study was selected. Model physics parameterization schemes used in this study to simulate turbulence are given in Table 4. The most important scheme for the simulation of CAT is the Planetary Boundary Layer (PBL) Scheme. When grid size is more than or equal to 1 km, we rely on PBL schemes to handle the upper air turbulence or CAT to its vertical diffusion. So, different PBL schemes may give different results because they handle vertical diffusion in different ways. In this study, Yonsei University Scheme is used as a PBL scheme.

3 Results and Discussion

This section discusses the results obtained from the simulations and their comparison with the corresponding observations. The weather incident occurred on 19 April 2018 during 0900 UTC to 1200 UTC, and the model has been integrated for 48 hours, from 0000 UTC of 18 April 2018 to 0000 UTC of 20 April 2018. The model-designed parameters are Vertical

Velocity, Horizontal Velocity, Geopotential Thickness, Vertical Wind Shear, Clear Air Turbulence (CAT) Index, and Bulk Richardson Number Shear (BRNSHR).

3.1 Vertical Velocity

Vertical Velocity is an essential parameter for the occurrence of turbulence. Fig. 2 and 3 illustrate the time series of Vertical Velocity (m/s). Longitude varies from 73.4° E to 75.6° E as the turbulence was encountered for a small region. Vertical Velocity is plotted for latitude 31.3149° N at 450 hPa level in Fig. 2 and different pressure levels (from 400 hPa to 550 hPa with intervals of 50 hPa) in Fig. 3 at 1000 UTC on 19 April 2018. The blue and red color region indicates downward (-2 m/s) and upward (6-8 m/s) velocity, respectively, at 450 hPa level (Fig. 2 and 3(c)). So, this is a severe to extreme turbulence case (refer to Table 2). In reality, turbulence was encountered between 0900 UTC and 1000 UTC. The model simulated strong Vertical Velocity at 1000 UTC at 74.97° E (Fig. 2 and 3), closer to reality.

Fig. 4 illustrates the spatial distribution of Vertical Velocity where the aircraft encountered turbulence. Plots (A) to (D) in (D01) Parent Domain (6 km) and plots (a) to (d) in (D02) Child Domain (2 km) represent Vertical Velocity at different levels (from 400 hPa to 550 hPa with 50 hPa interval), respectively, at 1000 UTC on 19 April 2018 as simulated by the model. It shows substantial and strong Vertical Velocity near the ‘X’ mark (i.e., 74.97° E and 31.3149° N). The negative values indicate accelerating updraft, and the positive values indicate descending downdraft. At 450 hPa ((B) and (b)), both upward (6-8 m/s) and downward (-2 m/s) velocities are seen very close to each other. From Fig. 1, it is clear that the location near ‘X’ is where CAT was encountered. The dashed circle marks this area.

Fig. 5 illustrates the vertical profile of Vertical Velocity over the accident location with a longitude of 74.97° E and latitude of 31.3149° N at 1000 UTC on 19 April 2018. Vertical Velocity varies with changes in pressure level (altitude). Dash patches represent the region between 400 hPa and 550 hPa where the model simulated strong Vertical Velocity (6-8 m/s). The left side of the straight line drawn on zero represents the downward velocity, and the right side represents the upward velocity. There is a sudden increase in Vertical Velocity by at least 4-5 m/s, and the speed is rising to 7 m/s or more (from Fig. 3, 4, and 5).

3.2 Horizontal Velocity

Fig. 6 illustrates a comparison between the Horizontal Velocity (m/s) vertical profile over the accident location as simulated by the (a) Model at 1000 UTC, (b) ERA-Interim data at

1200 UTC, (c) IMDAA data at 0900 UTC, and (d) NGFS data at 1200 UTC. Horizontal Velocity varies with changes in pressure levels (altitude). The dash patches represent the region between 100 hPa and 350 hPa where the model and other data sets simulated strong horizontal velocity (60-65 m/s). There is a sudden increase in Horizontal Velocity by at least 40-50 m/s, and speed is rising to 62 m/s or more. It could lead to the formation of CAT.

3.3 Geopotential Thickness

Fig. 7 illustrates a comparison between the Geopotential Thickness (m) on 19 April 2018 between 400 hPa and 650 hPa, as simulated by the ((A) and (a)) Model at 1000 UTC and ((B) and (b)) ERA-Interim data at 1200 UTC. Plots (A) and (B) represent Geopotential Thickness in (D01) Parent Domain (6 km), whereas plots (a) and (b) represent Geopotential Thickness in (D02) Child Domain (2 km). Here, 'X' indicates the position where the model predicted strong Vertical Velocity near the accident location (Fig. 4). The area enclosed by the dashed circle is where the model and ERA-Interim data sets simulated a strong Geopotential Thickness (more than 36.5 km). This could lead to CAT. Patches in the model simulation are not visible in ERA-Interim data simulation, as CAT is generally a microscale phenomenon. Thus, the Geopotential Thickness gradient is visible in the plot (a) of (D02) Child Domain.

3.4 Vertical Wind Shear (VWS)

Fig. 8 illustrates a comparison between the Vertical Wind Shear (m/s per 1000 ft) between 200 hPa and 850 hPa for both the domains (D01 and D02) on 19 April 2018 as simulated by the ((A) and (a)) Model at 1000 UTC, ((B) and (b)) ERA-Interim data at 1200 UTC, ((C) and (c)) IMDAA data at 0900 UTC and ((D) and (d)) NGFS data at 1200 UTC. Plots (A), (B), (C), and (D) represent VWS between 200 hPa and 850 hPa in (D01) Parent Domain (6 km), whereas plots (a), (b), (c), and (d) are representing VWS between 200 hPa and 850 hPa in (D02) Child Domain (2 km).

Here, 'X' indicates the position where the model predicted strong vertical velocity (Fig. 4) and strong geopotential thickness gradient (Fig. 7) near the accident location. The area enclosed by the dashed circle is where the model and other data sets simulated a strong Wind Shear gradient (more than 5.5 m/s per 1000 ft). So, this is a severe turbulence case (refer to Table 2). The patches in the model simulation are not visible in other data simulations as CAT is generally a microscale phenomenon that is harder to predict and requires high-resolution data sets. Thus, the Wind Shear gradient is more clearly visible in plot (a) of (D02) Child Domain (2 km). It could lead to CAT.

3.5 Clear Air Turbulence (CAT) Index

The CAT Index indicates the most probable region of CAT. Fig. 9 illustrates a comparison between CAT Index TI1 (s^{-2}) and CAT Index TI2 (s^{-2}) at different pressure levels (from 300 hPa to 550 hPa with 50 hPa interval) in (D02) Child Domain (2 km) at 1000 UTC on 19 April 2018, as simulated by the model. Plots (A) to (F) represent CAT Index TI1 (s^{-2}) whereas plots (a) to (f) represent CAT Index TI2 (s^{-2}). Here, 'X' indicates the position where the model predicted strong vertical velocity (Fig. 4), strong geopotential thickness gradient (Fig. 7), and strong wind shear gradient (Fig. 8) near the accident location. The area enclosed by the dashed circle is where the model simulated strong CAT Index intensities at 1000 UTC for TI1 (480.404×10^{-9} s^{-2}) and TI2 (503.783×10^{-9} s^{-2}) at 450 hPa level ((D) and (d), respectively). Model simulated variations in CAT Index with change in different pressure levels. The dissipation of the CAT is visible as we go higher in the atmosphere above 550 hPa. In Fig. 9, the white-colored region represents the region with No CAT intensity, the blue-colored region represents the region with Light CAT intensity, the green-colored region represents the region with Light to Moderate CAT intensity, the yellow-colored region represents the region with Moderate CAT intensity, the orange-colored region represents the region with Moderate to Severe CAT intensity, and the red-colored region represents the region with Severe CAT intensity (refer to Table 3).

Fig. 10 illustrates the comparison of Time-Series between CAT Index TI1 (s^{-2}) and TI2 (s^{-2}) for 24 hrs, i.e., from 0000 UTC on 19 April 2018 to 0000 UTC on 20 April 2018, at 450 hPa near the accident location as simulated by the model. Here, the red-colored plot with 'o' markings represents the time-series of CAT Index TI2 (s^{-2}) and the blue-colored plot with 'x' markings represents the time-series of CAT Index TI2 (s^{-2}). Model simulated variations in CAT Index with change in time. Model simulations show that CAT evolved or generated at approximately 0900 UTC near 'X' and reached the peak intensity at 1000 UTC; after that, it started dissipating at around 1200 UTC. The time-series of the CAT Index shows that at 1000 UTC, the CAT index is high, implying more chances of encountering CAT. In Fig. 10, it is visible that the model simulated strong CAT Index intensities at 1000 UTC for both TI1 (480.404×10^{-9} s^{-2}) and TI2 (503.783×10^{-9} s^{-2}) at 450 hPa level. So, this is a severe CAT case (refer to Table 3) that can lead to dangerous conditions.

It is observed that TI1 tends to overpredict, but the model simulation for TI2 is very similar to TI1. TI1 and TI2 perform similarly, but TI1 performs slightly better than TI2. Thus, (from Fig. 9, 10, and Table 3) for the lower threshold, both TI1 and TI2 perform satisfactorily for CAT detection. It is observed that both TI1 and TI2 sometimes overestimate CAT at a lower threshold, due to which they might have a high rate of false alarm; however, this might cover the maximum region of turbulence. For the higher threshold, it is observed that both TI1 and TI2 might underestimate CAT occurrences. The TI2 value is more than the TI1 value, explaining the high rate of false alarms.

3.6 Bulk Richardson Number Shear (BRNSHR)

"Bulk Richardson number shear (BRNSHR) is used to quantify the VWS" (Moncrieff and Green 1972). Fig. 11 illustrates BRNSHR (m^2/s^2) on 19 April 2018, showing variations with time (from 0900 UTC to 1200 UTC with 1 hour time interval), as simulated by the model. Plots (A) to (D) and plots (a) to (d) represent BRNSHR variations with time in (D01) Parent Domain (6 km) and (D02) Child Domain (2 km), respectively. Here, 'X' indicates the position where the model predicted strong vertical velocity (Fig. 4), strong geopotential thickness gradient (Fig. 7), strong wind shear gradient (Fig. 8), and strong CAT Index intensity (Fig. 9) near the accident location. The area enclosed by the dashed circle is the area where the WRF model simulated strong BRNSHR ($235.047\ m^2/s^2$). High values of BRNSHR ($235.047\ m^2/s^2$) are simulated for the accident day around 1000 UTC at 450 hPa level ((B) and (b)), indicating sheared environment. So, this could show the probability of encountering turbulence that can lead to dangerous conditions.

Fig. 12 illustrates the Time-Series of BRNSHR (m^2/s^2) for 12 hours, i.e., from 0600 UTC to 1800 UTC on 19 April 2018, near the accident location as simulated by the model. Model simulated variations in BRNSHR with change in time. The model simulations show that BRNSHR evolved or generated at approximately 0900 UTC near 'X' and reached the peak intensity at 1000 UTC; after that, it started dissipating at around 1200 UTC. The time series of BRNSHR shows that at 1000 UTC, BRNSHR is high, which implies more chances of encountering turbulence. So, this could be a severe turbulence case that can lead to dangerous conditions. Most of the BRNSHR values are more than the threshold value (40 m^2/s^2) for the development of supercell thunderstorms. The highest value of the BRNSHR simulated by the model is approximately $235.047\ m^2/s^2$ which is usually large enough to generate spinning storms.

4 Summary and Conclusion

At high altitudes, aircraft may encounter turbulence unexpectedly without any significant cloudiness. We have already discussed how difficult is the prediction of CAT. The role of CAT for various processes in the atmosphere is still ambiguous. To know the unknown about CAT, modification of tools is essential for simulating turbulence. This study is focused on understanding and investigating favourable conditions for the occurrence of CAT. The results show that the WRF model simulated the CAT incident between Amritsar and Delhi, as reported by the Air India flight AI462 on 19 April 2018. Although limitations exist as a model cannot predict exact atmospheric conditions, it can predict close to the case; this work has proven that WRF Model V 4.0.3 used for this study is sensitive to simulate turbulence. NCEP FNL Operational Global Analysis Data at 0.25° x 0.25° resolution with 6-hourly intervals was used as initial and boundary conditions for the model integration for 48 hours from 0000 UTC of 18 April 2018 to 0000 UTC of 20 April 2018. This study also shows that the Rapid Radiative Transfer Model (RRTM) Scheme, Yonsei University Scheme, WSM 3-Class Simple Ice Scheme, Kain-Fritsch (New Eta) Scheme, and Revised MM5 Monin-Obukhov Scheme can be used for simulating the atmospheric conditions during a CAT event and predicting the turbulence over a region. This study shows that Vertical Velocity, Geopotential Thickness gradient, Wind Shear gradient, and BRNSHR are correlated with CAT. The TI1 and TI2 are based on deformation and might not consider additional mechanisms that might produce CAT, e.g., mountain waves. Some more studies must be done to capture the climatology of other mechanisms. The main conclusions of this study are:

- This is a severe CAT case, and the results show that the WRF model reasonably predicts turbulence. The most important scheme for the simulation of CAT is the PBL Scheme. In this study, Yonsei University Scheme is used as a PBL scheme.
- Model simulated both upward (6-8 m/s) and downward (-2 m/s) velocity, very close to each other between 400 hPa and 550 hPa levels at 1000 UTC near the accident location. So, this is a severe to extreme turbulence case (refer to Table 2).
- Model and other data sets simulated strong horizontal velocity (60-65 m/s) at the same region between 100 hPa and 350 hPa levels near the accident location.
- Model and other data set simulated strong Geopotential Thickness (more than 36.5 km) and strong Wind Shear gradient (more than 5.5 m/s per 1000 ft) near the 'X' location at 1000 UTC. So, this is a severe turbulence case (refer to Table 2).

- Model simulated variations in CAT Index with change in time and pressure levels. CAT dissipates as we go higher in the atmosphere above 550 hPa.
- Model simulations show that CAT evolved or generated at approximately 0900 UTC near 'X' location and reached the peak intensity at 1000 UTC; after that, it started dissipating at around 1200 UTC.
- The model simulated strong CAT Index intensities for TI1 ($480.404 \times 10^{-9}\ \mathrm{s}^{-2}$) and TI2 ($503.783 \times 10^{-9}\ \mathrm{s}^{-2}$) at 450 hPa level at 1000 UTC (from Fig. 9, 10, and Table 3), at the exact location where the model predicted strong vertical velocity (Fig. 4), strong geopotential thickness gradient (Fig. 7), and strong wind shear gradient (Fig. 8) near 'X' location, closer to reality. So, this is a severe CAT case (refer to Table 3) that can lead to dangerous conditions.
- TI1 and TI2 perform similarly, but TI1 performs slightly better than TI2.
- The model also simulated variations in BRNSHR with changes in time. Model simulations show that BRNSHR evolved or generated at approximately 0900 UTC near 'X' and reached the peak intensity at 1000 UTC; after that, it started dissipating at around 1200 UTC. High values of BRNSHR ($235.047\ \mathrm{m}^2/\mathrm{s}^2$) are simulated at around 1000 UTC for the accident day at 450 hPa level (Fig. 11 and 12), indicating sheared environment. Thus, this could show the probability of encountering turbulence as the high intensity of BRNSHR indicates more chances of encountering turbulence.

Even though there are differences in reality and model prediction, the model can still predict turbulence. We should also know how significantly other schemes can predict turbulence by finding different parameterization scheme combinations to predict turbulence more accurately. Only one case is discussed in this study, but many other cases are being reported worldwide, and only after studying a more significant number of cases can we tell the exact behaviour of CAT. These all will do in the future as a continuation of this work.

Statements and Declarations

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