The Importance of Convective Stage on Out-of-Cloud Convectively Induced Turbulence from High-Resolution Simulations

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ABSTRACT: Turbulence (clear-air, mountain wave, convectively induced) is an aviation hazard that is a challenge to forecast due to the coarse resolution utilized in operational weather models. Turbulence indices are commonly used to aid pilots in avoiding turbulence, but these indices have been designed and calibrated for midlatitude clear-air turbulence prediction (e.g., the Ellrod index). A significant limitation with current convectively induced turbulence (CIT) prediction is the lack of storm stage dependency. In this study, six high-resolution simulations of tropical oceanic and midlatitude continental convection are performed to characterize the turbulent environment near various convective types during the developing and mature stages. Second-order structure functions, a diagnostic commonly used to identify turbulence in turbulence prediction systems, are used to characterize the probability of turbulence for various convective types. Turbulence likelihood was found to be independent of region (i.e., tropical vs midlatitude) but dependent on convective stage. The probability of turbulence increased near developing convection for the majority of cases. Additional analysis of static stability and vertical wind shear, indicators of turbulence potential, showed that the convective environment near developing convection was more favorable for turbulence production than mature convection. Near developing convection, static stability decreased and vertical wind shear increased. Vertical wind shear near mature and developing convection was found to be weakly correlated to turbulence intensity in both the tropics and the midlatitudes. This study emphasizes the need for turbulence avoidance guidelines for the aviation community that are dependent on convective stage.

KEYWORDS: Turbulence; Thunderstorms; Mesoscale forecasting; Numerical weather prediction/forecasting

1. Introduction

Out-of-cloud convectively induced turbulence (CIT) is an operational challenge to aviation as global flight routes increase and air space becomes more congested (Statista 2020). While numerous forecast guidance systems including real-time avoidance algorithms and preflight forecast systems like the Graphical Turbulence Product (GTG-2; Sharman and Pearson 2017; Pearson and Sharman 2017; Sharman et al. 2006) are in use and are frequently updated to provide pilots with more information, the complexity of CIT is not always depicted by these systems. To address the limitations of prediction systems and reduce the number of aviation encounters with convective hazards, the Federal Aviation Administration (FAA) has thunderstorm avoidance guidelines in place (FAA 2017). The most impactful guideline that influences flight routes and Air Traffic Control is the lateral avoidance of 20 miles (~32 km) from severe convection. While the guidelines are based on empirical research of CIT in the midlatitudes, the same guidelines are also recommended by the FAA to be followed by U.S. airlines along tropical flight routes because of the limited understanding of tropical CIT. However, convective and

environmental properties are known to vary between the midlatitudes and tropics, from the strength, depth, and duration of convection, to the environmental shear and stability profiles (Vant-Hull et al. 2016; Frierson and Davis 2011; Wissmeier and Goler 2009; Frierson 2006; Liu and Zipser 2005; Yuter et al. 2005; Garstang and Fitzjarrald 1999; Chin et al. 1995; Saha and Singh 1972), each of which contribute to and influence the severity of potential aviation hazards.

The hazards to aviation caused by convection are also dependent on the type and stage of convection (Barber et al. 2019; Barber et al. 2018; Lane et al. 2003). However, variations in turbulence probability relative to convective type of stage are not addressed by current FAA guidelines; only the classification “severe convection” is mentioned. In other words, developing convection is a hazard not addressed by the FAA guidelines unless severe in intensity. Developing convection is a concern to aviation because it is generally difficult to forecast, especially timing and location. Therefore, accounting for developing convection results in limited confidence for in-flight planning without nowcasting products. In addition, without real-time observations of convection from satellite and ground-based radar systems, the pilot has to rely on visual cues of developing convection and proper usage of onboard radar.

High-resolution modeling is commonly used to examine small-scale processes that operational forecasting systems cannot resolve. CIT occurs across multiple scales from 10 to 1000 m (Lester 1994) and can impact aviation over 100 km

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FIG. 1. Map of turbulence incidents in the (a) Western and (b) Eastern Hemispheres (red: -C1; orange: -C2; black: C3; green: C4; purple: C5; and pink: C6).

away from the source of convection (Barber et al. 2018; Lane et al. 2012), well past the FAA lateral avoidance distance of 20 miles (~32 km). CIT is generally expressed as an empirical diagnostic or ensemble of diagnostics in operational forecasts (e.g., GTG-2, Ellrod index; Ellrod and Knapp 1992). High-resolution simulations allow for more in-depth analysis of convective processes that, in turn, produce turbulence, which aids in the development of turbulence avoidance procedures (Lane et al. 2012). These small-scale and temporally limited processes include the generation of convective gravity waves, enhancement of deformation zones along cloud boundaries, and enhancement of shear as convection penetrates the tropopause (Lane et al. 2003). An additional benefit of high-resolution simulations is the more representative depiction of turbulence intensity (Barber et al. 2018). While high-resolution simulations of convection allow for further examination of the

characteristics of turbulence and the relationship of convective intensity to turbulence, the majority of these simulations have been designed for midlatitude CIT (Barber et al. 2018; Zovko-Rajak and Lane 2014; Kim and Chun 2012; Lane and Sharman 2008; Lane et al. 2003).

This study examines the influence of near-storm environmental conditions on the distribution of out-of-cloud CIT for tropical and midlatitude convective simulations to determine if the probability of experiencing CIT varies between storm stages and regions. More specifically, this study will investigate if the environmental conditions near various convective types in the midlatitudes and tropics are similar and have comparable turbulence probabilities. Six encounters of moderate to severe CIT in various convective regimes are used as high-resolution simulation case days and compared to observations (Fig. 1). Storm and environmental characteristics that are indicative of turbulence potential are presented.

2. Methodology

In this study, 24–30-h simulations of midlatitude and tropical convection are made using the Advanced Research WRF (ARW) Model, version 3.7 (Skamarock and Klemp 2008). All simulations are initialized with ERA-Interim global dataset (<http://www.ecmwf.int/en/research/climate-reanalysis/era-interim>) at various times (Table 1). One parent and two nested domains are used in these simulations with a horizontal grid spacing of 4.5 km, 1.5 km, and 500 m from the outer to inner domains (Fig. 2). All domains have 100 vertical levels. The vertical grid spacing between 8 and 12 km is approximately 325 m. The number of vertical levels is decreased to 65 (approximately 550 m grid spacing between 8 and 12 km) for 4 June 2018 (C4), due to a numerical instability issue in the simulation, likely influenced by the terrain. A 10-km damping layer is used at the model top that is set to approximately 30 km (10 hPa). This study uses the WDM6 microphysical parameterization and the Mellor–Yamada–Janjić (MYJ) planetary boundary layer scheme (additional parameterization information is provided in Table 2) for all simulations except 10 July 1997 (C2) and 3 August 2009 (C1). These particular cases use the Morrison microphysical scheme as it produces convection that is in better agreement with observed morphology after subjective testing of various microphysical schemes (not shown). Otherwise, the parameterizations were kept consistent for the midlatitude and tropical simulations in order to reduce

TABLE 1. Initialization time, analysis period, and time period of increased temporal resolution for each simulated case. Odd-numbered cases are tropical and even-numbered cases are midlatitude.

Case identifier	Case day	Initialization time	Analysis period	Period of increased temporal resolution
C1	3 Aug 2009	1200 UTC 2 Aug	1800–1800 UTC	1200–1400 UTC 3 Aug
C2	10 Jul 1997	0000 UTC 10 Jul	0600–0600 UTC	1800–2300 UTC 10 Jul
C3	27 Dec 2014	0000 UTC 27 Dec	0600–0600 UTC	0000–0400 UTC 28 Dec
C4	4 Jun 2018	1200 UTC 3 Jun	1800–0600 UTC	1900–2300 UTC 3 Jun
C5	20 Jun 2017	0000 UTC 20 Jun	0600–0600 UTC	1200–1800 UTC 20 Jun
C6	29 Jun 2018	1200 UTC 29 Jun	1800–1800 UTC	1800 UTC 29 Jun–0000 UTC 30 Jun

FIG. 2. Model domain of case studies. Innermost nest (D03) has a horizontal grid spacing of 500 m. The “X” symbol represents the location of the turbulence encounter.

TABLE 2. Parameterizations used in the six simulations.

Model physics	Model setup
Microphysics	WDM6 (Lim and Hong 2010)/Morrison (C1 and C2; Morrison et al. 2009)
Planetary boundary layer	MYJ (Janjić 1994)
Surface layer	Eta similarity (Monin and Obukhov 1954, Janjić 1994, 1996, 2002)
Land surface	Noah (Tewari et al. 2004)
Shortwave radiation	Dudhia (Dudhia 1989)
Longwave radiation	RRTM LW (Mlawer et al. 1997)

uncertainty in the turbulence response due to differences in physics schemes. While a full investigation of the sensitivity to parameterizations is beyond the scope of this study, we are confident that the comparative results presented in this study (e.g., tropical versus midlatitude and developing stage versus mature stage) are robust based on prior simulations of CIT conducted (Barber 2015, Barber et al. 2018, Barber 2019). Simulation output is saved every 10 min during periods of convective activity to examine convective development, maturity, and dissipation of individual convective cells (Table 1).

Turbulence is identified in this study using second-order structure functions following the methodology implemented in Barber et al. (2019). Structure functions are an estimation method for eddy dissipation rate (EDR, ε) in the inertial range (Kolmogorov 1941; Frehlich and Sharman 2004a,b; Sharman et al. 2006) and have had success for turbulence identification in many studies (Barber et al. 2019; Sharman and Pearson 2017; Pearson and Sharman 2017; Frehlich and Sharman 2010). Second-order structure functions (hereafter, SF), are computed as

$$D_{ll}(u) = [u_i(i) - u_i(i + \Delta s)]^2, \quad (1)$$

$$D_{ll}(v) = [v_i(i) - v_i(i + \Delta s)]^2, \quad (2)$$

$$D_{tt}(u) = [u_i(i) - u_i(i + \Delta s)]^2, \quad (3)$$

$$D_{tt}(v) = [v_i(i) - v_i(i + \Delta s)]^2, \quad (4)$$

in both the transverse (tt) and longitudinal (ll) directions. In Eqs. (1)–(4), i is the grid index, $u_{i,l}$ and $v_{i,l}$ are the u -component and v -component of wind along the transverse and longitudinal directions, and s is a separation distance expressed in units of spatial grid steps (dx).

The four $D_{ll,tt}$ components (u -longitudinal, v -longitudinal, u -transverse, and v -transverse) in Eqs. (5) and (6) are averaged together [represented by $\langle D_s \rangle$ in Eq. (7)] after manipulation of Eqs. (5) and (6) to solve for $\varepsilon^{1/3}$ [Eq. (7)]. In other words, $D_{ll,tt}$ from Eqs. (1)–(4) are inserted in Eqs. (5) and (6), and the remaining terms are moved to the left-hand side of the equations, leaving the ε term on the right-hand side. The value on the left-hand side of the manipulated equations for the four components are then averaged together. In this formulation C_k equals 2 (Frehlich and Sharman 2010). A value of 7 is chosen for s because it mirrors the spectral resolution of the model advection scheme particularly well (Muñoz-Esparza et al. 2018; Skamarock 2004):

$$D_{ll} = C_k \varepsilon^{2/3} \Delta s^{2/3}, \quad (5)$$

$$D_{tt} = \frac{4}{3} C_k \varepsilon^{2/3} \Delta s^{2/3}, \quad (6)$$

$$\varepsilon^{1/3} = \langle D_s \rangle^{1/2}. \quad (7)$$

Turbulence intensity is determined from the second-order structure functions using the thresholds provided in Table 3 (values for a medium-sized aircraft). Additional indices such as subgrid-scale eddy dissipation rate computed from turbulent kinetic energy (TKE) and Richardson number were examined for the six cases, but were found to have significant limitations (see Barber 2019).

In-cloud and out-of-cloud turbulence are differentiated using the mixing ratios of cloud ice and cloud water. A mixing ratio of greater than or equal to 0.1 g kg^{-1} defines in cloud and less than 0.1 g kg^{-1} defines out of cloud (Lane et al. 2003). When SF are computed, the grid point itself and all points considered in the calculation must be out of cloud. An 18-dBZ threshold for simulated radar reflectivity is used to determine the echo-top height, which is used as a proxy for storm height. In this study, individual convective objects (CO) are defined as contiguous regions with echo tops greater than 8 km in height. The COs are followed through time using the object's centroid location. A new object is defined if the centroid location of a previous convective object has changed by more than 10 km (horizontally) in a 10-min period. Vertical velocity is a common convective variable that can be used to describe convective stage (Hamada and Takayabu 2016; Schumacher et al. 2015; Katzwinkel et al. 2014; May and Rajopadhyaya 1999). Additional information on how convective stage has been defined in past studies can be found in Barber et al. (2019). The distinction between developing convection and mature convection in this study follows the methodology of Barber et al. (2019). Developing convection is defined as a convective object in which the simulated maximum vertical velocity for that object is less than the 90th percentile of all maximum vertical

TABLE 3. Turbulence intensity thresholds as determined from the cubed root of eddy dissipation rate (ε ; Sharman and Pearson 2017) for a medium-sized aircraft.

Turbulence intensity	$\varepsilon^{1/3} (\text{m}^{2/3} \text{s}^{-1})$
Light	0.15–0.22
Moderate	0.22–0.34
Severe	≥ 0.34

TABLE 4. Location and time of the aviation turbulence encounters. Odd-numbered cases are tropical and even-numbered cases are midlatitude.

Case identifier	Time of encounter	Location of encounter
C1	0755 UTC	19.73°N, −68.55°E
C2	2141 UTC	46.4°N, −103.6°E
C3	2317 UTC	3.62°S, 109.70°E
C4	0108 UTC	33.4°N, −106.4°E
C5	1651 UTC	21.84°N, −86.16°E
C6	2257 UTC	46.51°N, −102.46°E

velocities of that object's lifespan and less than the maximum vertical velocity of the following time period. The 90th percentile of maximum vertical velocities was chosen based on analysis of vertical velocity distributions for convective objects with time, echo-top heights, and simulated lightning production (not shown). To determine if turbulence is associated with developing convection or mature convection, distance is calculated between the turbulent grid cell and the boundaries of the convective object.

FIG. 3. Observed brightness temperature from (a) *GOES-12* and (b) simulated echo-top heights for C1. Time of analysis provided in the figure.

FIG. 4. Observed radar reflectivity values ($^{\circ}0.5$) from (a) KBIS and (b) simulated maximum radar reflectivity values for C2. Time of analysis provided in the figure.

Static stability and vertical wind shear between 8 and 12 km (representing the typical cruising altitudes of commercial aircraft) are used to characterize the near-storm environment around convection in terms of turbulence potential. Low static stability and/or high vertical wind shear are favorable conditions for growth of instabilities (e.g., Kelvin–Helmholtz waves, gravity waves); this growth can then lead to instability breakdown (e.g., wave breaking) and turbulence production. The computations of static stability (N^2 ; square of Brunt Vaisala frequency) and vertical wind shear (S_v^2) are provided below:

$$N^2 = \frac{g}{\theta} \frac{\partial \theta}{\partial z}, \quad (8)$$

where g is gravity, θ is potential temperature (K), and $\partial \theta / \partial z$ is the change of potential temperature with height.

The vertical wind shear $S_v \sqrt{2}$ is defined as

$$S_v^2 = \left(\left| \frac{\partial u}{\partial z} \right|^2 + \left| \frac{\partial v}{\partial z} \right|^2 \right), \quad (9)$$

where u and v are the horizontal components of velocity (m s^{-1}), and z is height (m).

FIG. 5. Observed brightness temperature from (a) *MTSAT*-2 and (b) simulated echo-top heights for C3. Time of analysis provided in figure. The black line at 4°S is included to illustrate the location biases between the observed and simulated convection.

3. Overview of case days and simulated convection

In this section, details regarding six aviation encounters of convectively induced turbulence are summarized. Table 4 provides a summary of the time and location of the turbulence encounters (see Fig. 1 for geographical locations). Observed convective features compared to simulated convection for each case day are provided in Figs. 3–8. Simulated echo-top heights and second-order structure functions (SF, values for a medium-sized aircraft) for the inner domain of each case day are provided in Figs. 9–14 as depictions of areal coverage and turbulence intensity in the region of interest.

a. 3 August 2009 (C1)

On 3 August 2009, a Boeing 767 encountered severe turbulence while flying to the northeast of the Dominican Republic (19.73°N, −68.55°E) at 0755 UTC. Convection in the

FIG. 6. Observed echo-top heights from (a) *KEPZ* and (b) simulated echo-top heights for C4. Time of analysis provided in the figure.

area was rapidly developing and the aircraft flew through the top of a convective updraft (Monette and Sieglaff 2014; Ahmad and Proctor 2011; NTSB 2011; Vasquez 2009) causing 33 minor injuries. Vertical accelerations experienced by the aircraft ranged from −1 to 2 g between 11 and 11.5 km in altitude for no more than 8 s. While convection was forecasted for this region, turbulence was not predicted along the aircraft's flight path by the deformation-vertical shear index (see Knox et al. 2008 for details pertaining to the deformation-vertical shear index). Although turbulence was not predicted, the captain was aware of convection in the area and had begun safety procedures to limit hazards associated with convection (NTSB 2011). A meteorological overview of this case day was compiled by Vasquez (2009). In short, the area in which the flight experienced turbulence was influenced by the Bermuda high with weak winds aloft, but instability was present in sounding observations between 8 and 12 km. Convection was very isolated, extending past 11 km in very few cells. This convection was likely enhanced by a tropical easterly wave propagating

FIG. 7. (a) Observed cloud-top heights from the Convective Diagnosis Oceanic Algorithm (Kessinger 2017; Kessinger et al. 2008) and (b) simulated echo-top heights for C5. Time of analysis provided in the figure.

through the region or an upper level trough that was also present. Satellite observations later confirmed the aircraft had penetrated a developing convective cell.

Isolated cells with simulated radar reflectivity values greater than 35 dBZ at 2 km initiate over the land features of the Dominican Republic and Haiti, due to diurnal heating 3 h into the simulation on 2 August 2009. Oceanic convection initiates 9 h later at 0000 UTC 3 August as weak isolated cells (radar reflectivity values less than 50 dBZ) in the northeast region of the inner domain. Oceanic convection persists north of the Dominican Republic for the next 18 h of simulation and reaches maximum intensity near 1340 UTC as convective cells propagate westward. Simulated echo-top heights over the ocean are less than 8 km until after 1200 UTC when the depth of three convective cells northeast of the Dominican Republic exceed 10 km. The morphology and depth of simulated convection resembles the observed convection (weak, sporadic, isolated cells; Fig. 3), especially to the east and north of Puerto Plata. Convective available potential energy (CAPE) in the domain was greater than 2000 J kg^{-1} and the tropopause was

FIG. 8. Observed echo-top heights from (a) KBIS and (b) simulated echo-top heights. Time of analysis provided in the figure.

near 13.5 km. Compared to radar observations from San Juan, the simulated convection over the ocean initiates approximately 4 h later than observations, but the location of the simulated convective cell that likely influenced the aircraft is within 50 km of observations. The time period of 1200–1400 UTC 3 August will be used to analyze the influence of convective stage on turbulence (section 4) as it compares well against observations, where cells are increasing in depth.

Simulated echo-top heights and maximum second-order structure functions (SF) at 1340 UTC are shown in Fig. 9 between 8 and 12 km, as the turbulence encounter was near 10 km, and observed convection was extending past the altitude of the aircraft. Turbulence intensity predicted by SF is light or null out of cloud mainly to the south of the region of interest. However, SF do indicate moderate or greater turbulence between 8 and 12 km in the simulated convective cell most similar to the observed cell at 1400 UTC. In terms of prediction, SF would have been a beneficial diagnostic to aviation flying near developing convective cells.

TABLE 5. Mean, median, maximum, and minimum static stability (N^2 ; units: s^{-2}) near mature (MCO) and developing (DCO) convection. Odd-numbered cases are tropical and even-numbered cases are midlatitude.

Case identifier	MCO mean (median) N^2	MCO max (min) N^2	DCO mean (median) N^2	DCO max (min) N^2
C1	7.98×10^{-5} (7.88×10^{-5})	1.02×10^{-4} (6.33×10^{-5})	7.70×10^{-5} (7.62×10^{-5})	9.19×10^{-5} (6.87×10^{-5})
C2	1.57×10^{-4} (1.59×10^{-4})	2.66×10^{-4} (3.01×10^{-5})	1.39×10^{-4} (1.42×10^{-4})	2.23×10^{-4} (3.40×10^{-5})
C3	7.41×10^{-5} (7.43×10^{-5})	9.75×10^{-5} (4.58×10^{-5})	7.30×10^{-5} (7.33×10^{-5})	8.47×10^{-5} (6.18×10^{-5})
C4	1.35×10^{-4} (1.31×10^{-4})	3.07×10^{-4} (8.78×10^{-6})	1.23×10^{-4} (1.22×10^{-4})	2.74×10^{-4} (1.56×10^{-5})
C5	7.32×10^{-5} (7.26×10^{-5})	1.08×10^{-4} (4.03×10^{-5})	7.33×10^{-5} (7.25×10^{-5})	9.76×10^{-5} (5.09×10^{-5})
C6	1.86×10^{-4} (1.85×10^{-4})	2.77×10^{-4} (5.16×10^{-5})	1.63×10^{-4} (1.58×10^{-4})	2.46×10^{-4} (7.94×10^{-5})

b. 10 July 1997 (C2)

On 10 July 1997, at approximately 2141 UTC, a Boeing 757 encountered severe turbulence while out of cloud flying southwest of Dickinson, ND (46.4°N, −103.6°E) at 2141 UTC. The aircraft was navigating between numerous convective cells that were extending higher than the altitude of the aircraft (11.2 km) near the time of the incident (NTSB 1997). The aircraft passed over a developing convective cell that was located between two mature convective cells (Fig. 4), causing 22 injuries. As was the case for C1, convection was forecasted in the region, but turbulence was not predicted along the flight path. The pilot had warned the passengers of possible turbulence when convection was in the region, but the “FASTEN SEATBELT” sign was not illuminated. This particular case has been examined with numerical simulations in Lane et al. (2003) in which a brief meteorological overview is provided. Convection was initiated by a frontal system that was associated with a pre-frontal trough. The region was favorable for convective activity as CAPE was greater than 3500 J kg^{-1} . The tropopause was near 11 km.

Simulated convection on 10 July 1997 initiates in the domain at 2000 UTC and develops into two intense convective cells with 2-km simulated radar reflectivity values exceeding 55 dBZ over the next 4 h of simulation time. Three individual simulated convective features (two more intense and one weaker) are present in the domain at 2200 UTC (similar convective morphology as found in Lane et al. 2003). By 2300 UTC, all three simulated cells have increased in strength and echo-top heights exceed 12 km (tropopause is also near 12 km). The convective cell that likely is associated with the turbulence encounter rapidly increases in vertical extent and areal coverage from 2200 to 2300 UTC, less than 1 h after observations indicate (labeled Cell 2 in Fig. 4). CAPE in the model domain is greater than 3000 J kg^{-1} . Figure 4 shows the convective cells

observed from the KBIS radar near 0000 UTC and the simulated cells also at 0000 UTC. Note this time is displayed because it is a time close to the turbulence encounter and the convection has moved into the KBIS radar domain. The northern cell (labeled Cell 1 in Fig. 4) is to the northwest of Dickinson, ND in both the model and observations. The cell closest to Dickinson, ND (labeled Cell 2 in Fig. 4) is much stronger in the simulations than in observations at 0000 UTC (recall this cell strengthens rapidly). Last, the southern cell (labeled Cell 3 in Fig. 4) is farther east in the simulations than in observations. The time period of 1800–2300 UTC 10 July will be used to analyze the influence of convective stage on turbulence (section 4) as the morphology of simulated convection compares well against observations, where the suspect cell is rapidly increasing in vertical depth.

Simulated echo-top heights and maximum SF at 1340 UTC are shown in Fig. 10. Due to the differences in observed and simulated convective height, the turbulence diagnostics are evaluated between 14 and 16 km to be representative of an aircraft flying above a convective cell that is rapidly developing. The height range of 2 km is also applicable to the vertical envelope of turbulence above convection (1–3 km; Lane et al. 2003). SF diagnose severe turbulence before the convective cell reaches a height of 13 km and continues to indicate severe turbulence as the cell increases in height. SF do predict turbulence of appropriate intensity above the convective cell and distance away from convection (within 50 km of convection). SF would have been a beneficial predictor of turbulence intensity and areal coverage for this convective case.

c. 27 December 2014 (C3)

On 27 December 2014, at approximately 2317 UTC, an Airbus A320 flying at 9.75 km went into an unrecoverable aerodynamic stall over the Java Sea (3.62°S, 109.70°E) due to

TABLE 6. Mean, median, maximum, and minimum vertical wind shear (S_v^2 ; units: s^{-2}) near mature (MCO) and developing (DCO) convection. Odd-numbered cases are tropical and even-numbered cases are midlatitude.

Case identifier	MCO mean (median) S_v^2	MCO max (min) S_v^2	DCO mean (median) S_v^2	DCO max (min) S_v^2
C1	7.67×10^{-8} (3.29×10^{-8})	1.02×10^{-5} (5.69×10^{-10})	1.05×10^{-7} (8.69×10^{-8})	7.36×10^{-7} (7.39×10^{-9})
C2	1.42×10^{-6} (2.08×10^{-7})	3.13×10^{-4} (7.85×10^{-10})	7.00×10^{-6} (3.91×10^{-6})	2.17×10^{-4} (5.82×10^{-8})
C3	1.14×10^{-7} (7.64×10^{-8})	1.21×10^{-5} (2.21×10^{-9})	2.49×10^{-7} (1.61×10^{-7})	5.01×10^{-6} (8.85×10^{-9})
C4	5.73×10^{-7} (1.06×10^{-7})	2.01×10^{-4} (1.65×10^{-10})	4.02×10^{-6} (1.52×10^{-6})	1.78×10^{-4} (5.71×10^{-9})
C5	1.60×10^{-7} (7.53×10^{-8})	3.74×10^{-5} (1.82×10^{-9})	8.54×10^{-7} (4.86×10^{-7})	1.67×10^{-5} (8.21×10^{-9})
C6	7.82×10^{-7} (1.18×10^{-7})	8.48×10^{-5} (1.96×10^{-10})	4.44×10^{-6} (2.76×10^{-6})	7.84×10^{-5} (8.94×10^{-8})

FIG. 9. (a) Simulated echo-top heights and (b) maximum second-order structure functions at 1340 UTC 3 Aug 2009 (C1) between 8 and 12 km. Echo tops greater than 8 km are shown in (b) as blue contours (and shading) and the black star represents the location of the aircraft at 0755 UTC.

pilot error (KNKT 2015). Convection was present along the flight route and pilots had requested numerous altitude changes in order to avoid convection. The flight path was through a region with active convection and the predetermined flight altitudes were turbulent, suggesting prediction systems were underestimating turbulence intensity and convective hazards. A squall line was present in the region propagating westward and echo-top heights varied between 7.3 and 13.4 km. The convection was likely caused by the migration of the intertropical convergence zone. The proposed flight path intercepted two mature convective cells with echo-top heights greater than 10 km. The tropopause was located above 16 km in altitude.

Simulated convection on 27 December 2014 initiates from a boundary near the land feature of Singapore with intense convective cores that weaken and dissipate by 1200 UTC. After 1200 UTC, a secondary boundary oriented along 5°S latitude propagates northward and initiates a convective line

more than 100 km long over the Java Sea. Convection along the boundary has echo-top heights greater than 15- and 2-km radar reflectivity values greater than 50 dBZ, but dissipates by 2200 UTC. The particular convective feature that likely influenced the aircraft along its flight path is simulated at 0300 UTC 28 December, approximately 4 h after satellite observations indicated (Fig. 5). This simulated convection was linear, extending along 5°S and 4.5°S latitudes with echo-top heights above 14 km. The simulated tropopause height on 27 December 2014 is 15.5 km. The convective features of interest in this particular simulation are approximately 1° too far south and slightly farther east than observed convection (Fig. 5). While a location bias is apparent in this case day, the organization of convection and convective type agrees with observations, giving confidence in accurately representing the convective environment. The time period of 0000–0400 UTC 28 December will be used to analyze the influence of convective stage on turbulence (section 4) as

FIG. 10. (a) Simulated echo-top heights and (b) maximum second-order structure functions at 2210 UTC 10 Jul 1997 (C2) between 14 and 16 km. Echo tops greater than 13 km are shown in (b) as blue contours (and shading) and the black star represents the location of the aircraft at 2141 UTC.

FIG. 11. (a) Simulated echo-top heights and (b) maximum second-order structure functions at 0300 UTC 28 Dec 2014 (C3) between 8 and 12 km. Echo tops greater than 8 (10 and 12) km are shown in (b) as blue (black and dark purple) contours. Blue shading is used to represent the area of echo-top heights greater than 8 km.

the simulated convection is oriented along the flight path with the vertical depths and areal coverage similar to observations.

SF are evaluated between 8 and 12 km (Fig. 11). Of interest is the areal coverage of out-of-cloud turbulence around the convection, as the aircraft was navigating around the observed convection. SF diagnose out-of-cloud turbulence within 30 km of active convection. The most intense turbulence is to the southeast and northwest of the western convective cell. The localized turbulence regions identified by SF are representative of observations as the aircraft navigated around the convection with and without encountering turbulence. SF would have been a beneficial diagnostic for this particular case near the convective boundaries.

d. 4 June 2018 (C4)

On 4 June 2018, near 0100 UTC an aircraft reported severe turbulence at 33.4°N, −106.4°E while flying at 11 km. Convection was forced by an upper level front extending from Colorado to New Mexico and was forecasted to be severe in intensity due to high CAPE (greater than 3000 J kg^{−1}) and bulk shear. Numerous reports of tornadoes and hail occurred in New Mexico and Texas. Echo-top heights ranged from 10 km to over 16 km in the most intense cells and the tropopause on this day was above 12 km.

Simulated convection on 3 June 2018 forms along the east side of the San Andres mountain range and propagates

eastward as the diurnal heating intensifies in a region with CAPE greater than 1900 J kg^{−1}. Simulated radar reflectivity values are greater than 55 dBZ during the initial phase. The convective line begins to form a bowing segment near 0100 UTC as it moves out of the domain. Echo-top heights exceed 12 km after 2200 UTC in four regions along a 200-km convective line. Convection propagates across the region of interest approximately 2 h too early when compared to observations and with slightly lower echo tops than observed (Fig. 6). The simulated cells most representative of the observed convection occur near 2300 UTC at 33.5°N, −106.6°E. The time period of 1900–2300 UTC 3 June will be used to analyze the influence of convective stage on turbulence (section 4) as the simulated convection resembles observed convection in location, strength, and morphology.

Simulated echo-top heights and SF are evaluated between 8 and 12 km (Fig. 12). The simulated storm depths in this case agree with radar observations in the strength and location. SF identify moderate or greater turbulence in the convective cloud and localized regions of moderate or greater out of cloud. Near the location of the aircraft there is a strong gradient in turbulence intensity, but out of convective cloud the turbulence is light. In-cloud turbulence intensity was well represented by SF and likely underestimated out of cloud.

e. 20 June 2017 (C5)

On 20 June 2017, a Boeing 737 encountered severe turbulence at 11 km in altitude while flying over the Gulf of Mexico (21.84°N, −86.16°E) near 1651 UTC. Convection was present along the flight route as the aircraft traveled from Panama City, Panama to Houston, TX. Additional information regarding the synoptic conditions for this particular case can be found in Barber et al. (2019). Convection was abundant in the flight region with storm depths exceeding 14 km in altitude. The tropopause on this day was above 14.3 km and CAPE was greater than 1500 J kg^{−1}. Satellite observations and flight records indicate the plane was out of cloud at the time of the turbulence encounter, navigating between two regions of developing convection.

Simulated convection on 20 June 2017 initiates from the forcing of a seabreeze north of the Yucatan Peninsula at 1000 UTC as a narrow convective line with 2-km radar reflectivity values greater than 45 dBZ. Simulated convection intensifies and then persists between −87° and −86°E through 1800 UTC. The simulated environment was favorable for intense convection with CAPE values greater than 2500 J kg^{−1}. Echo-top heights exceeded 13 km after 1240 UTC along the convective line and reached 17 km in numerous cells. Simulated convective depth was slightly higher than observations and simulated convection extends much farther north (Fig. 7). However, the horizontal width of the simulated convective line and observed convective line are very similar (approximately 0.5° in longitude). Interestingly, the second prominent convective feature east of −86°E is not simulated in the 500-m domain. However, the aircraft at the time of the turbulence encounter was closer to the western line and therefore is more important to accurately represent the

FIG. 12. (a) Simulated echo top-heights and (b) maximum second-order structure functions at 2300 UTC 3 Jun 2018 (C4) between 8 and 12 km. Echo tops greater than 8 (10 and 12) km are shown in (b) as blue (black and dark purple) contours. Blue shading is used to represent the area of echo-top heights greater than 8 km. The black star represents the location of the aircraft at 0108 UTC 4 Jun.

western line. The time period of 1200–1800 UTC 20 June will be used to analyze the influence of convective stage on turbulence probability (section 4).

Simulated echo-top heights and SF at 1650 UTC are shown in Fig. 13. SF indicate moderate or greater turbulence in cloud along the convective line and light to moderate or greater turbulence along the cloud boundaries. Approximately 50 km to the east and west of the convective line, a broad area of increased turbulence severity is present. Near the location of the aircraft, turbulence was identified as light with large gradients in turbulence intensity. SF accurately represented in-

cloud turbulence intensity but likely under predicted out-of-cloud areal coverage.

f. 29 June 2018 (C6)

On 29 June 2018, at 2257 UTC an Airbus A320 experienced severe turbulence while flying at an altitude of 11 km near Dickinson, ND (46.51°N, −102.46°E). The aircraft descended more than 600 m and decreased in speed by 50 kt (1 kt $\approx$ 0.51 ms^{-1}) at the time of the encounter. Convection was present along the flight path, with composite radar reflectivity values exceeding 45 dBZ in isolated cells west of Bismarck,

FIG. 13. (a) Echo-top heights and (b) maximum second-order structure functions at 1650 UTC 20 Jun 2017 (C5) between 8 and 12 km. Echo tops greater than 8 (10 and 12) km are shown in (b) as blue (black and dark purple) contours. Blue shading is used to represent the area of echo-top heights greater than 8 km. The black star represents the location of the aircraft at 1651 UTC.

FIG. 14. (a) Echo-top heights and (b) maximum second-order structure functions at 2250 UTC 29 Jun 2018 (C6) between 8 and 12 km. Echo tops greater than 8 (10 and 12) km are shown in (b) as blue (black and dark purple) contours. Blue shading is used to represent the area of echo-top heights greater than 8 km. The black star represents the location of the aircraft at 2257 UTC.

North Dakota, and more intense cells exceeding radar reflectivity values of 55 dBZ in northwest South Dakota. It is important to note that the flight path was along a region of Montana, North Dakota, and South Dakota where there is a void in radar coverage. Convection was severe in western South Dakota where numerous storm reports were recorded including tornadoes, large hail, and severe winds within the hour of the turbulence encounter. CAPE exceeded 3000 J kg^{-1} and echo-top heights were greater than 14.7 km.

Simulated convection at 1900 UTC 29 June 2018 initiates near the western South Dakota–North Dakota border. Isolated cells intensify in two distinct regions with simulated 2-km radar reflectivity values greater than 50 dBZ. The cells propagate eastward and weaken by 0000 UTC 30 June (Fig. 8). The strongest observed and simulated convection near 2300 UTC is to the southwest of Lemmon, South Dakota. A simulated and observed cell is also weakening southwest of Dickinson, South Dakota, near 2300 UTC. Echo-top heights exceed 10 km throughout the period of interest with the deepest storms to the south. The time period of 1800–0000 UTC 29–30 June will be used to analyze the influence of convective stage on turbulence probability (section 4).

Simulated echo-top heights and SF at 2250 UTC are shown in Fig. 14. SF diagnose a large region of moderate or greater turbulence both in cloud and out of cloud near convection. Near the location of the aircraft, there is a localized area of enhanced turbulence out of cloud. SF would have been a beneficial diagnostic for this convective day to identify turbulence in cloud and out of cloud.

4. Impacts of convective stage

Figure 15 provides the distribution of out-of-cloud turbulence for each case day for grid points closest to mature convective objects and grid points closest to developing convective objects between 8 and 12 km. Near mature convection (Fig. 15a), the midlatitudes (solid lines) have a higher probability of turbulence than the tropics (dashed lines). But the probability of strong turbulence is greater for both tropical and midlatitude cases near developing convective objects

(Fig. 15b) by nearly an order of magnitude when compared to probabilities near mature convective objects (with the exception of C1). This finding highlights the hazards associated with developing convection in regards to aviation operations. The greatest increase in turbulence probability from the mature subset to the developing subset occurs for the midlatitude cases. While the developing convection signal shown here is weaker for the tropics, the methodology of computing out-of-cloud turbulence is possibly overly conservative for regions close to convection, which has a stronger impact on tropical results (i.e., must be at least $7\Delta x$ or 3.5 km away from a cloudy grid point).

5. Characteristics of the environment near convection

In this section, comparisons of the simulated environment around mature and developing convection for the six cases will be made and related to the likelihood of turbulence. Mean out-of-cloud static stability and vertical wind shear are examined between 8 and 12 km (representing the typical cruising altitudes for commercial aircraft) for all grid points closest to mature convective objects and all grid points closest to developing convective objects, at a frequency of 10 min during the periods shown in Table 1. The objective of this analysis is to determine if the average near-storm environmental conditions near various convective types in the midlatitudes and tropics are similar. Specifically, are the midlatitude and tropical static stability and vertical wind shear distributions the same during similar convective periods, and is the turbulence response the same? Additionally, near-storm environmental conditions are analyzed for both developing and mature convective stages. Importantly, a given storm environment will vary depending on both the background environment and influence of the storm on that environment, and this environment can vary on meso- to microscales; this study does not differentiate between these two factors. Instead, we are investigating the variability in environmental (near-storm and background) factors in different regions and storm stages and how that might relate to turbulence production. Note, median, minimum,

FIG. 15. Distribution of out-of-cloud turbulence diagnosed by second-order structure functions ($\text{m}^{2/3} \text{s}^{-1}$) between 8 and 12 km nearest to (a) mature convection (MCO) and (b) developing convection (DCO) for the six simulations. Dashed lines are tropical cases and solid lines are midlatitude cases. The green (yellow and magenta) vertical line represents the threshold for light (moderate and severe) turbulence; see Table 3 for threshold values.

and maximum static stability and vertical wind shear values are also provided in Tables 5 and 6 to illustrate the statistical variability of the environment.

The distributions of mean static stability (N^2) for the six cases are shown in Fig. 16. Near mature convective objects (Fig. 16a), the mean static stability is lower for the tropical cases than the midlatitude cases (Table 5), which is expected (Saha and Singh 1972; Garstang and Fitzjarrald 1999; Frierson 2006; Frierson and Davis 2011). Near developing convection (Fig. 16b), again the tropical cases have a lower mean static stability than the midlatitude cases, and subtle variation between the cases themselves. Interestingly, the midlatitude distributions are more similar near developing convection (Fig. 16b, solid lines) than mature convection (Fig. 16a, solid lines), suggesting that static stability is not influenced by storm

type during the developing stage. Importantly, for five of the six cases, static stability is lower (by $0.2 \times 10^{-5} \text{s}^{-2}$ in the tropics and by $0.2 \times 10^{-4} \text{s}^{-2}$ in the midlatitudes) near developing convection compared to mature convection (Table 5). These results indicate that environmental stability processes influence turbulence in the midlatitudes and tropics near developing convection more than during the mature stage.

The out-of-cloud vertical shear (S_v^2) distributions between 8 and 12 km (Fig. 16c) near mature convection have large variability (in breadth and mean and median values) between the six cases, likely as a result of convective type. The largest mean vertical wind shear is associated with the midlatitude cases (Table 6), which again is expected when nominal vertical wind shear values are compared to the tropics (Wissmeier and Goler 2009). The breadth of vertical wind shear is also the greatest for the midlatitudes. Near developing convection (Fig. 16d), S_v^2 distributions shift toward higher shear values for all six of the cases (Table 6). In the tropics, during the developing stage (Fig. 16d) the distributions of S_v^2 vary significantly by storm type. On the other hand, in the midlatitudes near developing convection (Fig. 16c), the extreme S_v^2 values for C2 and C4 are very similar to one another (less influenced by storm type). The larger S_v^2 near developing convection is hypothesized to be caused by deformation at the cloud boundary and increases the probability of turbulence through shear producing mechanisms.

6. Distributions of environment variables subset by turbulence intensity

The distributions of N^2 and S_v^2 are subset by turbulence intensity (i.e., turbulence that is light only or turbulence that is moderate or greater only) to discern if turbulence intensity is influenced by the environment (Fig. 17, note that only the environment near mature convection is shown). Specifically, is the environment (near-storm and background) significantly different for all cases where there is only light (LGT) turbulence and only moderate or greater (MOG) turbulence? When N^2 is examined as a subset of turbulence intensity, N^2 in the midlatitudes is very similar for LGT and MOG turbulence (Fig. 17a). The turbulence intensity of the tropical cases is also not dependent on static stability (Fig. 17b). These results are consistent for developing convection (not shown). In relationship to aviation operations, the environmental N^2 in the tropics and midlatitudes is not significantly different for MOG turbulence versus LGT turbulence near convective objects. These results suggest that N^2 distributions would not provide enough information to discern between the likelihood of no turbulence (NULL) or LGT or MOG turbulence.

The distributions of S_v^2 between the 8- and 12-km subset by turbulence intensity for the midlatitude cases are shifted toward higher S_v^2 values, indicating that turbulence with greater intensity is occurring more frequently in regions of increased shear (Fig. 17c). The mean S_v^2 for the midlatitude cases (Fig. 17c) has increased by nearly half an order of magnitude from the LGT turbulence to the MOG turbulence. In the tropics S_v^2 slightly increases for MOG turbulence for C3 and C5 (Fig. 17d). In relationship to aviation operations, the environmental S_v^2 in the midlatitudes is significantly different for

FIG. 16. (a),(b) Distribution of mean out-of-cloud static stability (s^{-2}) and (c),(d) mean vertical wind shear (s^{-2}) between 8 and 12 km nearest to (a),(c) mature convection (MCO) and (b),(d) developing convection (DCO) for the six simulations. Dashed lines are tropical cases and solid lines are midlatitude cases. Typical ranges of static stability are shaded (cyan: tropics; pale yellow: midlatitudes).

turbulent regions than null regions near convection. The shift toward higher values of S_v^2 could be an indicator of increased turbulence potential. The distinction in distributions between the mature convective environment and the developing convective environment (not shown) look similar, meaning the same shift in distribution could be used for turbulence prediction near mature and developing convection. Because at least some of the shear magnitude is likely due to storm outflow, an additional investigation to determine the probability of turbulence specifically near convective outflow regions with respect to storm stage would be of considerable value (future work).

Correlations between N^2 and S_v^2 and turbulence intensity are examined to determine if turbulence intensity can be estimated by the parameters near convection (Figs. 18 and 19). Figure 18 shows the correlation of N^2 and turbulence for all cases subset by mature and developing convection. For the tropical cases (Figs. 18b,d,f), there is no correlation between N^2 and turbulence intensity for the environment near mature or developing convection. For the midlatitude cases C2 and C6 (Figs. 18a,e), there is a weak negative correlation between N^2 and turbulence intensity for developing and mature convection (stronger correlation for developing convection). Figure 19 shows the

correlation of S_v^2 and turbulence intensity for all cases subset by mature and developing convection. For all six cases there is a weak positive correlation between S_v^2 and turbulence intensity. The correlations are generally slightly stronger for developing convection in the midlatitude cases (Figs. 19a,c,e). These results suggest that S_v^2 may be a promising variable to use to diagnose turbulence intensity potential in the midlatitudes. Overall, however, the correlations are not that impressive for both N^2 and S_v^2 , motivating the need for more cases to build up robust statistics.

7. Discussion and conclusions

Convectively induced turbulence (CIT) is a forecasting challenge for aviation operations. Convective properties including storm height and environmental conditions such as stability and vertical wind shear can influence turbulence production significantly, all of which must be predicted correctly in model simulations to offer aviation operations assistance in turbulence avoidance. Past CIT research has focused on convection over the continental United States aiding in the creation of the Federal Aviation Administration Thunderstorm Avoidance guidelines. The lack of tropical CIT

FIG. 17. (a),(b) Distribution of mean out-of-cloud static stability (s^{-2}) and (c),(d) mean vertical wind shear (s^{-2}) between 8 and 12 km nearest to mature convection (MCO) for the six simulations [(a) and (c) are midlatitude cases; (b) and (d) are tropical cases] subset by turbulence intensity (LGT: dashed lines; MOG: solid lines).

investigations limits the improvement of tropical CIT avoidance. Six cases of CIT were simulated at high vertical and horizontal resolution ($\Delta x, \Delta y = 500$ m, $\Delta z \approx 350$ m). These simulations were used to investigate the variability of turbulence diagnosed by second-order structure functions in tropical and midlatitude regions, in order to determine the variability in diagnostics when implemented globally. In addition, these simulations were used to determine if the convective environment, defined as the out of cloud area within 30 km of convection, varies for storm stage and region (tropical and midlatitude), and if the variation in convective environment influences turbulence intensity. Simulated convection compared well to observational datasets from ground-based radar and satellite in morphology and strength for the majority of the cases, while timing for the tropical simulations generally had a lag of up to 4 h.

Turbulence intensity and probability were examined for the six cases and subset by convective stage (mature or developing) by tracking convective objects in 10-min intervals. The probability of turbulence near convection was found to vary significantly by region and convective stage. Turbulence probability was found to be greatest in the midlatitudes and increased near developing convection. Turbulence probability in the tropics varied by convective stage and also increased

near developing convection (Fig. 15). The increased probability of turbulence near developing convection in the midlatitudes and the tropics is of concern for aviation operations because generally pilots avoid flying near mature convection (especially when following the turbulence avoidance guidelines) and presumably will fly closer to developing convection. In addition, there are limited real-time observational datasets available to pilots in tropical regions to aid in flight diversions.

Static stability and vertical wind shear were used to characterize the out of cloud convective environment for the six simulations in this study. The environmental conditions out of cloud near convection in the midlatitudes and tropics varied significantly as was expected. Static stability was less for the tropical environment on average than in the midlatitudes and was greater around mature convection than developing convection, but was not found to directly influence turbulence potential. Vertical wind shear was less for the tropical environment than in the midlatitudes and increased around developing convection in both the midlatitudes and tropics. When turbulence was subset by intensity, static stability was not significantly different. However, average vertical wind shear increased for turbulent locations with MOG turbulence intensity in the midlatitudes. In terms of turbulence prediction,

FIG. 18. Correlation of mean out-of-cloud static stability (s^{-2}) and turbulence intensity between 8 and 12 km nearest to mature convection (MCO; red) and developing convection (DCO; blue) for the six simulations: (a),(c),(e) midlatitude cases and (b),(d),(f) tropical cases. The correlation coefficients for the data subset by convective object type are provided (r_{mature} and r_{dev}).

increased vertical wind shear could be indicative of increased turbulence intensity especially near developing convection.

Aviation operations in the United States currently do not have federally mandated thunderstorm avoidance guidelines that are region or convective stage specific. The overall objective of this study was to determine if region-specific and convective stage specific guidelines are needed to decrease the probability of an aviation turbulence encounter. This study found that turbulence intensity only subtly varies by region

(with greater probability near mature midlatitude convection), and therefore guidelines that are not region specific are adequate for midlatitudes and tropical turbulence avoidance. However, as was found for a single case in Barber et al. (2019), storm stage does have an important impact on turbulence potential, with proximity to developing convection increasing the turbulence probability for all intensities. When convection is subset by stage, regionality does cause a substantial difference in turbulence potential. In the midlatitudes and tropics,

FIG. 19. Correlation of mean out-of-cloud vertical wind shear (s^{-2}) and turbulence intensity between 8 and 12 km nearest to mature convection (MCO-red) and developing convection (DCO-blue) for the six simulations: (a),(c),(e) midlatitude cases and (b),(d),(f) tropical cases. The correlation coefficients for the data subset by convective object type are provided (r_{mature} and r_{dev}).

turbulence probability can increase by more than one order of magnitude near developing convection. The increase could be due to the increase in shear around the developing convection. With smaller background shear levels in the tropics, the local impacts on shear may be more important for turbulence production. This study found important differences in turbulence potential in the six cases and motivates the need for more simulations of CIT at high resolution to understand turbulence mechanisms in both tropical and midlatitude regions. More research will further increase understanding of CIT on aviation

operations and eventually lead to needed adaptations to the current avoidance guidelines.

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