IMPROVING CONVECTIVELY INDUCED TURBULENCE FORECAST PARAMETERS THROUGH BULK NUMERICAL SIMULATIONS FOR AVIATION SAFETY

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EXECUTIVE SUMMARY

The number of global flight routes is projected to increase over the next five years, increasing the likelihood of airplanes being influenced by hazards associated with thunderstorms. While turbulence diagnostics are available to pilots and flight dispatchers, many of these predictors have been verified for midlatitude clear-air turbulence only. Current thunderstorm avoidance guidelines do not account for the stage of convection that influences turbulence probability.

For the first time, aviation encounters of convectively induced turbulence in both the midlatitudes and tropics were simulated at high spatial and temporal resolution to identify biases in current turbulence diagnostics and to investigate the influence of storm stage on turbulence probability. This research has found significant disagreement among the turbulence diagnostics for all cases. The probability of turbulence near developing convection was found to be greater than near mature convection, especially in tropical environments, supporting the need for storm stage and region-specific avoidance guidelines.

RESEARCH CHALLENGE

Out-of-cloud convectively induced turbulence (CIT) is a hazard to aviation operations because it can occur vast distances away from convective sources [1] and is nearly impossible to detect using on-board radar systems. CIT is a prediction challenge owing to the spatial (10 to 1000 meters) [2] and temporal scales (seconds to minutes) on which it occurs. Meteorological variables from forecasting systems can be used to calculate large-scale turbulence diagnostics, but generally these modeling systems are too coarse to resolve the numerous CIT generation mechanisms and turbulence propagation. While progress has been made in understanding CIT potential in the midlatitudes through field campaigns, modeling studies, and statistical examinations of pilot reports—all of which have been used to develop avoidance guidelines for aviation [3]—little is known about CIT potential in the tropics. The lack of research on tropical CIT increases the risk of turbulence encounters for tropical flight routes. As new flight routes and air traffic continue to increase, aviation will be more susceptible to convective hazards in both the midlatitudes and tropics.

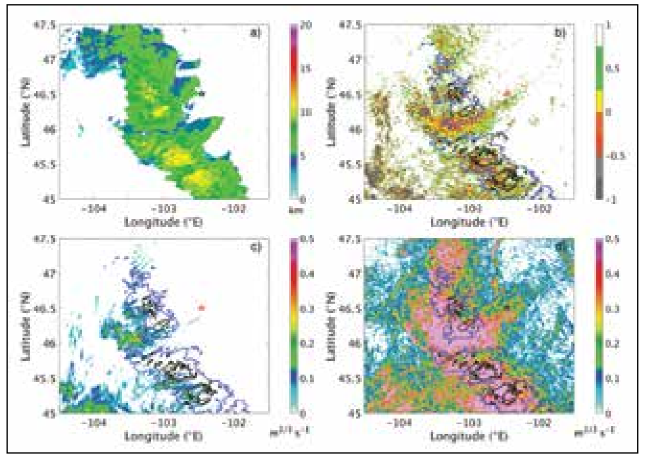

Figure 1: (a) Echo top heights, (b) Richardson number, (c) eddy dissipation rate, and (d) structure functions on June 29, 2018, between 8–12 kilometers (km). Echo tops greater than 8, 10, and 12 km are shown in b–d as blue, black, and magenta contours, and the star represents the location of the aircraft.

High-resolution simulations of convection in the midlatitudes and tropics allow for analysis of turbulence potential for various convective regimes by capturing the majority of turbulence-generation mechanisms. These simulations also help identify the limitations of popular turbulence diagnostics and motivate the development of new diagnostics. Understanding the variation of turbulence potential with convective type, stage, and region allows for the adaptation of thunderstorm guidelines that are more specific and efficient for aviation operations, reducing aviation turbulence incidents.

METHODS & CODES

The Weather Research and Forecasting (WRF) model [4] was used to simulate six cases of CIT on Blue Waters at 500-meter horizontal resolution and 10-minute output. Each case was a real aviation turbulence encounter that caused passenger injuries or structural damage and was associated with convection. Midlatitude turbulence cases were paired with tropical turbulence cases where the convective morphology and cause of turbulence were similar. For example, on June 29, 2018, a commercial aircraft was flying out of cloud in North Dakota in the vicinity of severe convection and encountered severe turbulence. This case was paired with a tropical case that occurred on June 20, 2017, where a commercial aircraft experienced severe turbulence while navigating out of cloud near convection [5]. Turbulence diagnostics including the Richardson number [6], eddy dissipation rate [7], and second-order structure functions [8] were computed in cloud and out of cloud (0.1 g kg^{-1} threshold [9]). Convective stage (*i.e.*, developing and mature) was differentiated by tracking convective objects and their vertical velocities with time [5]. Environmental static stability and vertical wind shear were examined near developing and mature convection and related to turbulence potential.

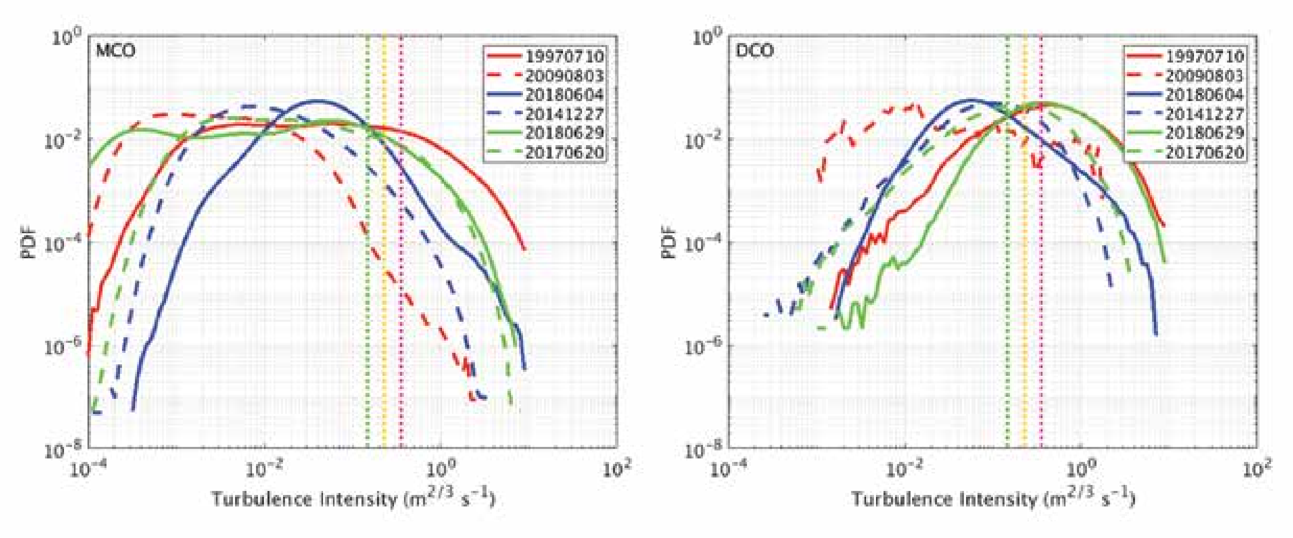

Figure 2: Distribution of out-of-cloud turbulence diagnosed by second-order structure functions between 8–12 kilometers nearest to mature convection (MCO) and developing convection (DCO) for the six simulations. The green (yellow and magenta) vertical line represents the threshold for light (moderate and severe) turbulence.

RESULTS & IMPACT

Six simulations of convection in the midlatitudes and tropics using high spatial and temporal resolution were performed using WRF. Simulated convective properties including morphology, strength, and location compared well against observations. The accuracy of the turbulence diagnostics for intensity and location varied drastically but had the most agreement for the midlatitude cases (Fig. 1). The eddy dissipation rate frequently underpredicted the areal coverage and intensity of out-of-cloud turbulence. Richardson number and structure functions most reproduced accurate turbulence probabilities with similar areal coverages and locations.

The examination of convective stage for the six cases illustrated the variation of turbulence probability for convective type and region (Fig. 2). The greatest probability of turbulence near mature convection occurred in the midlatitudes. Turbulence probability was found to significantly increase near developing convection in both the midlatitudes and tropics, with the greatest increases occurring in the tropics. This result highlights the increased risk for tropical aviation routes where real-time observations are limited.

The environmental static stability and vertical wind shear near developing and mature convection was found to have regional dependencies but not always storm-type dependencies. Static stability near tropical convection was not influenced by convective stage, but near-midlatitude convection was influenced by convective stage. Vertical wind shear was found to be influenced by region, storm type, and storm stage. Vertical wind shear increased significantly around developing convection for both regions and could be an indicator of turbulence potential. For all six cases there was a positive correlation between vertical wind shear and turbulence intensity.

This work motivates the need for more high-resolution simulations of convection to address the shortcomings of turbulence prediction and avoidance for aviation operations. More examination of turbulence diagnostics and turbulence potential in various environments is vitally needed to reduce turbulence encounters.

WHY BLUE WATERS

Blue Waters was necessary for this project because high-resolution (spatial and temporal) simulations of convection require computational resources not available on local systems. Blue Waters allowed for thorough analysis of CIT for large domains and over long temporal periods to capture storm evolution, which required thousands of computing cores. Storage of high-resolution simulations of convection is an additional challenge that was adequately addressed through Blue Waters' resources.

A fourth-year Ph.D. student in atmospheric sciences at the University of North Dakota, Katelyn Barber is working under the direction of Gretchen Mullendore. Wiebke Deierling of the National Center for Atmospheric Research served as a collaborator on this study.