Final Technical Report

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Continued Research into Characterizing the Preturbulence Environment for Sensor Development, New Hazard Algorithms and Experimental Flight Planning

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Executive Summary

The purpose of the research was to develop and test improved hazard algorithms that could result in the development of sensors that are better able to anticipate potentially severe atmospheric turbulence, which affects aircraft safety. The research focused on employing numerical simulation models to develop improved algorithms for the prediction of aviation turbulence. This involved producing both research simulations and real-time simulations of environments predisposed to moderate and severe aviation turbulence.

The research resulted in the following fundamental advancements toward the aforementioned goal: 1) very high resolution simulations of turbulent environments indicated how predictive hazard indices could be improved resulting in a candidate hazard index that indicated the potential for improvement over existing operational indices, 2) a real-time turbulence hazard numerical modeling system was improved by correcting deficiencies in its simulation of moist convection and 3) the same real-time predictive system was tested by running the code twice daily and the hazard prediction indices updated and improved. Additionally, a simple validation study was undertaken to determine how well a real time hazard predictive index performed when compared to commercial pilot observations of aviation turbulence. Simple statistical analyses were performed in this validation study indicating potential skill in employing the hazard prediction index to predict regions of varying intensities of aviation turbulence. Data sets from a research numerical model where provided to NASA for use in a large eddy simulation numerical model. A NASA contractor report and several refereed journal articles where prepared and submitted for publication during the course of this research.

1. Tasks Performed in Support of the Research Goals

Task 1: (Provide MASS Databases for the Initialization of the TASS LES Model)

Provided NHMASS 500 m horizontal resolution simulated soundings for the initialization of TASS LES simulation experiments for the 13 January 2000 Wilmington FOQA turbulence case study in an effort to better characterize the fine scale environment resulting in aviation turbulence. Soundings generated both behind and ahead of the terrain-induced katafront close to the location of the turbulence accident were generated and e-mailed to the NASA technical contract monitor. Also e-mailed available observational data at the convective scale to the NASA Technical Contract Monitor for comparison to subsequent numerical model simulations.

Task 2: (Produce in depth Analyses of Turbulence Case Studies to Enhance the Characterization of Hazard Generation Mechanisms)

Two low-level convectively-induced turbulence (CIT) events east of the Appalachian Mountains were investigated utilizing observations and numerical simulations. Both events had an inordinate amount of low-level turbulence reported, but one event had more than twice as many severe or greater reports. The events were compared – to include the 72 hours leading up to the turbulence reports – and similarities and differences at the various scales from the synoptic to the meso-•, meso-• and meso-•, and microscale were noted. The case of weaker turbulence featured a meridional wave pattern with ridging over the East Coast and a single upper-level jet closely coupled with the large-scale frontal system. The stronger turbulence case possessed a zonal wave pattern with a vortex over eastern Canada and both a polar jet and subtropical jet. These differences are reflected in the low-level temperature and potential vorticity patterns and affected the hydraulic structures as well – with the stronger turbulence environment more prone to a blocking-type regime. Hydrostatic mountain waves were observed for both events. Stronger cross-mountain flow with a strong low-level leeside inversion resulted in a more vigorous mountain wave with a stronger downstream isentropic upfold (mid-level cold pool) in the stronger turbulence event. This mid-level cold pool was deformed by the large-scale jet resulting in a mid-level cold front (downstream from the surface cold front), surface pressure rises to the lee of the Allegheny mountains, and ultimately a surface cold surge (edgewave) that merges with warm air from the south. The phasing of the mid-level cold pool and the convergence with the northerly cold surge and southerly warm are advection resulted in kata-frontogenesis and cellular convection that transits the observed severe turbulence location in space and time. Convection in the weaker turbulence case was lineal in structure and tied to the large-scale cold anafront. Vorticity, enstrophy, turbulent kinetic energy and Richardson number analyses indicated maxima were lineal in structure and upstream from the convection in the weaker case and arc-like in appearance and downstream from convection in the stronger case. A turbulence index was formulated based on the square of the three-dimensional vorticity (enstrophy), vertical wind shear and static stability.

Task 3: (Improve the Convective Parameterization Scheme in the Real-Time Turbulence Model (RTTM))

A systematic problem with the simulation of convection with the RTTM was addressed wherein the numerical model's existing Kain-Fritsch cumulus parameterization scheme tended to over predict the converage of moist convection during high CAPE but weak forcing environments. In an effort to address this problem, focusing on the southeastern portion of the United States, due to the number of NASA turbulence research flight missions in this region, four case studies were simulated using multiple different convective parameterization schemes, which were decided upon after an extensive review of the technical literature, i.e., the Kain-Fritsch (e.g., Fritsch and Chappell (1980); Kain and Fritsch (1990); Kain and Fritsch (1992); Fritsch and Kain (1993); Kain and Fritsch (1993); Kain and Fritsch (1998)), Grell (e.g., Grell(1993)) and Kain-Fritsch 2 (e.g., Kain (2004)) cumulus parameterization schemes. Three of the four case studies had weak synoptic forcing with limited sparse precipitation coverage and one case had strong synoptic forcing with concentrated, heavy precipitation coverage. It is usually within the weak synoptic forcing environments that the currently used Kain-Fritsch scheme greatly overestimates the precipitation amounts. Verification of model precipitation against satellite, radar and surface observations was performed in order to statistically assess the impact of the Kain-Fritsch, Grell and Kain-Fritsch 2 schemes for the four cases. This involved dividing the region of validation into fine scale grid boxes and determining if precipitation was predicted and if it was observed, thus categorizing convective precipitation "hits" and "misses" as well as false alarms and nonoccurrences. Then a comparison of the performance of the schemes and an examination of their influence on the local environment was conducted. Statistics that were calculated included: probability of detection, false alarm rate, bias, mean square error, critical success index, total skill score, and skill score. It was found that the Kain-Fritsch 2 scheme more accurately depicted the precipitation coverage in the weak forcing environments due to modifications made to the 1-dimensional cloud model and cloud trigger function, which involved alterations to the CAPE calculation and precipitation efficiency relationship and the inclusion of a minimum environmental entrainment rate and variable cloud radius. By strengthening the cloud model's dependence on deep layer relative humidity the modifications work to reduce the amount of precipitation produced in a weakly-forced environment while having a minimal effect on a strongly-forced environment. This resulted in improved RTTM simulated convection and, hence, convectively-forced turbulence hazard indices.

Task 4: (Develop Improved Turbulence Characterization Hazard Indices)

Research simulations of the two observed turbulence case studies were compared to eight moderate-severe daily RTTM case study simulations of turbulence potential to determine candidates for improved turbulence characterization indices. It was apparent from the RTTM comparisons that the NCSU1 and NCSU2 indices were most useful in case studies of convectively-induced turbulence. These indices tended to maximize downstream from convectively-induced jet streams where upward motions had developed deep cold pools leading to reduced Richardson number (Ri) values in proximity to strong typically streamwise gradients of relative vorticity. In clear air and mountain turbulence case studies they also performed reasonably well. To better determine if these indices could be improved, two research case studies were utilized to test other possible indices than those already in the RTTM, i.e., other than the NCSU1, NCSU2, TKE, Stone and NASA indices. This was done by employing very high resolution (~500 m) simulated fields from the two research case studies to analyze the Richardson number, turbulence kinetic energy, vorticity, entrophy and vorticity tendency. These analyses indicated that TKE maximized primarily upstream of the convection in the single jet case study, i.e., D88 and downstream of the convection in the double jet case study, i.e., J00. Similarly, the majority of Richardson number minima were arc-like in appearance and located downstream from convection in J00 and were elongated and upstream from the surface anafront and convection in D88. Additionally, Ri values were consistently lower for J00 as several contours of Ri<0.25 were observed for J00 and none for D88. A comparison of RI and enstrophy revealed a remarkable correlation – both in orientation and inverse magnitude. Enstrophy maxima were essentially coincident with minima of Richardson number. The ratio of these parameters (enstrophy/RI) should maximize in regions where spin, vortex tube formation, and the ratio of vertical wind shear to static stability are largest, i.e., regions predisposed to turbulence. This ratio, referred to here as riesnstrophy, is offered as a potentially valuable index for identifying turbulence potential and thus is useful to characterize the regions of high turbulence potential. As with the other parameters recently discussed, rienstrophy maxima were elongated, lineal and located upstream of the convection and surface cold front in D88 (although these maxima are much more focused than those provided by any of the previous parameters). Maxima of this ratio for J00 are similarly focused and as with high concentrations of vorticity, enstrophy, vorticity tendency, TKE and Ri minima, are arc-like and located downstream from the convection and surface katafront. Maxima for J00 were two to five times larger than those for D88 despite the fact that the convection was much more intense in D88 as inferred from precipitation rates. The location of the J00 maxima in the vertical occurred in the vicinity of an apparent breaking wave.

Task 5: (Provide Real-Time Support of NASA B-757 Flights by Running the RTTM)

During the period of the grant the RTTM model was run twice daily at North Carolina State University in support of the NASA Turbulence Prediction, Analysis and Warning System Program B-757 research flights. The turbulence characterization indices, convective forecast parameters and soundings were posted on the following web site: http://www.shear.meas.ncsu.edu/. Forecasters supporting the NASA B-757 flights employed these products as part of their mission planning. Occasionally, real-time case studies were archived for further study as directed by the NASA Technical Contract Officer.

Task 6: (Develop a RTTM Index Validation Program)

Code was written to validate the RTTM turbulence characterization hazard indices. This involved collecting approximately two years of commercial aircraft pilot report (PIREP) data from NASA. Then software was written to employ a statistical validation code, which was originally designed to validate the various convective precipitation schemes in Task 3, above, and then subsequently modified for use in the predicted locations of turbulence in several categories of turbulence intensity. This involved turbulence “hits” versus “misses” analogous to convective precipitation “hits” versus “misses” in multiple grid squares for the NCSU1 index values archived from the RTTM simulations over a two-year period. Similar statistical parameters/tests of skill were calculated for turbulence as was done for convective precipitation described in Task 3, above. Preliminary results of the validation indicated that the index did have intrinsic skill in predicting different categories/intensities of turbulence in many different geographical locations. This indicated its potential utility in hazard characterization.

Task 7: (Documenting the Results of the Research)

During the period of this grant several dissertations, publications and presentations on this and the preceding grant’s research were prepared, submitted, accepted, completed and published. These included:

1. Dissertations:

a) S. W. Slusser, 2003, “An Evaluation of the Influence of Several Convective Parameterization Schemes on a Real-Time Turbulence Model (RTTM) in Weakly-Forced Environments”. M.S. Dissertation, Department of Marine, Earth and Atmospheric Sciences, North Carolina State University, Raleigh, NC, 163 pp.

b) J. D. Cetola, 2003, “The Role of Terrain and Convection on Microfront Formation Leading to Severe Low-level Turbulence”. PhD. Dissertation, Department of Marine, Earth and Atmospheric Sciences, North Carolina State University, Raleigh, NC, 323 pp.

2. NASA Contractor Reports:

a) M. L. Kaplan, A. W. Huffman, K. M. Lux, J. D. Cetola, J. J. Charney, A. J. Riordan, Y.-L. Lin and K. T. Waight III, 2003: “Characterizing the Severe Turbulence Environments Associated with Commercial Aviation Accidents. Part II: Hydrostatic Mesobeta Scale Numerical Simulations of Supergradient Wind Flow and Streamwise Ageostrophic Frontogenesis”. NASA/CR-2003-212138, NASA Langley Research Center, Hampton, VA, 37 pp.

b) M. L. Kaplan, K. M. Lux, J. D. Cetola, A. W. Huffman, A. J. Riordan, S. W. Slusser Y.-L. Lin, J. J. Charney and K. T. Waight III, 2004: “Characterizing the Severe Turbulence Environments Associated with Commercial Aviation Accidents. A Real-Time Turbulence Model (RTTM) Designed for the Operational Prediction of Hazardous Aviation Turbulence Environments”. NASA/CR-2004-213025, NASA Langley Research Center, Hampton, VA, 49 pp.

3. Journal Publications:

a) M. L. Kaplan, A. W. Huffman, K. M. Lux, J. J. Charney, A.J. Riordan and Y.-L. Lin, 2005: "Characterizing the Severe Turbulence Environments Associated with Commercial Aviation Accidents. A 44 Case Study Synoptic Observational Analyses". In press, Meteorology and Atmos. Phys.

b) M. L. Kaplan, A. W. Huffman, K. M. Lux, J. D. Cetola, J. J. Charney, A. J. Riordan, Y.-L. Lin and K. T. Waight III, 2005: "Characterizing the Severe Turbulence Environments Associated with Commercial Aviation Accidents. Hydrostatic Mesoscale Numerical Simulations of Supergradient Wind Flow and Ageostrophic Along-Stream Frontogenesis". In press, Meteorology and Atmos. Phys.

c) M. L. Kaplan, K. M. Lux, J. D. Cetola, A. W. Huffman, A. J. Riordan, S. W. Slusser, Y.-L. Lin, J. J. Charney and K. T. Waight III, 2005: "Characterizing the Severe Turbulence Environments Associated with Commercial Aviation Accidents. A Real-Time Turbulence Model (RTTM) Designed for the Operational Prediction of Hazardous Aviation Turbulence Environments". In review, Meteorology and Atmos. Phys.

4. Presentations:

M. L. Kaplan, 2003: "Employing the RTTM to Characterize Turbulence Hazards to Aviation". NASA-FAA-Industry ATDS Workshop, NASA Langley Research Center, Hampton, VA, 2 December 2003.

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