NUMERICAL INVESTIGATIONS OF THE EVOLUTION OF MOUNTAIN-INDUCED TURBULENCE ALONG THE COLORADO ROCKIES ON 9 DECEMBER 1992

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1. INTRODUCTION

On December 9, 1992, a broad area of turbulence associated with orographically forced gravity waves occurred along the Rocky Mountains from Wyoming and Utah south through New Mexico and extended from near the surface into the lower stratosphere. Pilot reports of turbulence were widespread and numerous throughout the day. At 1507 UTC, a DC-8 cargo aircraft encountered extreme turbulence which severed a section of wing and one of its engines while it was attempting to cross the Front Range just west of Denver (Ralph et al. 1997).

2. BACKGROUND AND METHODOLOGY

This case was studied by Clark et al. (2000), who used numerical simulations and observations to analyze the event in the vicinity of the aircraft incident. Clark et al. proposed several possible mechanisms for the turbulence which caused the aircraft accident, including Holmboe instability and jet imbalance.

The present study uses the stratospheric Non-Hydrostatic Mesoscale Analysis Simulation System (NHMASS) Version 6.4 developed by MESO, Inc. Initialization data were obtained from the Global Reanalysis dataset. The model was run at grid lengths of 18 km, 6 km, 2 km, 667 m, 222 m, and 71 m. The model used 90 vertical (sigma) levels with an emphasis on the lower stratosphere. The larger two grid lengths used Kain-Fritsch cumulus parameterization and all runs used a two-dimensional Turbulence Kinetic Energy (TKE) planetary boundary layer (PBL) scheme. Runs from 18 km to 222 m were centered on the aircraft accident location (39.64 N 105.58 W), and the 71 m run was centered slightly west to capture the finer upstream structure.

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3. MODEL RESULTS

Two major synoptic features were present that day which served to set the stage for the extreme turbulence observed. Most prominent was a jet streak propagating into the region from the northwest (Fig. 1) and an upper-level front supporting it. At the larger scale, two major wave modes were found in the vertical velocity and divergence fields along the lee of the Colorado Rockies: a standing hydraulic jump and a downstream propagating wave which was likely associated with the jet-front system. Cross-sections (along AB as denoted in Fig. 1) at grid spacing as coarse as 2 km showed steep isentropes and vertical velocities in the hydraulic jump in excess of 1.5 ms^{-1} (Fig. 2). Energy from the gravity wave associated with the hydraulic jump was shown to penetrate the lower stratosphere. The hydraulic jump was the most obvious of the terrain-induced disturbances, but gravity waves were found to occur on much finer scales as well. Potential vorticity (PV) banners were found to occur on the lee side of the mountains behind the upper-level front (Fig. 3), extending almost completely across the state of Colorado by the end of the period. The maximum wave activity generally occurred in the left exit region of the jet streak entering the area from the northwest and in association with the upper-level front.

At finer scales, gravity waves were found to have been generated both from the terrain and from indirect circulations associated with the jet streak. Model output from runs with grid lengths of 2km and less clearly showed smaller gravity waves which were generated in an unstable layer between the polar and subtropical jets. This layer was characterized by relatively lower Brunt-Väisäla frequency squared ($< 10^{-4}\ s^{-2}$) and Richardson number (< 1), as well as steep isentropes. It is in this layer that we hypothesize the turbulent energy which caused the aircraft accident originated.

4. ANALYSIS

We hypothesize that there was a downward cascade of energy from higher to lower scale vortices which interacted to account for the abundant turbulence and mountain wave activity seen on 9 December 1992. The first feature was the thermally-indirect circulation associated with the exit region of the jet streak and the upper-level front as indicated by the synoptic-scale isentropic gradient. A meso-γ scale flow-aligned frontal boundary was found to exist in the potential temperature fields at finer model resolution. This frontogenesis was caused by the perturbation of the jet streak by the orography in a similar way to that found by Kaplan and Karyampudi (1992). Flow-aligned vortices and gravity waves were found to exist and were likely generated both by terrain and by interactions between finer jet structures. Lastly, cross-flow vortices were found at the smallest grid-length, whose exact structure and energy budgets remain unknown due to limitations in model resolution. Relative vorticity fields at 71 m grid spacing showed both a flow-aligned and a cross-flow structure at the level of the aircraft accident, indicative of these two circulation regimes (Fig. 4).

A possible mechanism for the turbulent energy which led to the aircraft incident is examined. At 222 m and 71 m, the model generated areas of near-zero N^2 coinciding with those of $Ri<.25$ at roughly 200 hPa (Fig. 5), both values traditionally associated with static and shear instabilities (Lin 2007). Here the isentropic deformation from both the larger-scale circulation and the terrain-induced meso-front coincided, leading to flow-aligned gravity waves. The flow circulation was structured such that wave energy from this unstable layer could have been reflected downward and advected downstream, toward the location of the aircraft incident (at approximately 278 hPa in the 222 m simulation). An examination of vertical flux of horizontal momentum $(\overline{u'w'})$ showed flux convergence in the vicinity of and near the time of the aircraft accident. In addition, a wave-induced critical level may have developed in the unstable layer, as indicated by isentrope overturning, which could have served to overreflect wave energy propagating upward from the surface terrain, a process described by Smyth and Peltier (1989). These overturned isentropes indicate possible wave-breaking. Anticyclonic flow-parallel vorticity found in this area may have been indicative of vortex tube formation which could have also been driven downward toward the accident location by the flow-aligned gravity wave circulations.

5. CONCLUSIONS

Numerical simulations of this mountain wave case indicated that turbulence can be generated through the interaction between an approaching jet streak and gravity waves generated by rough topography. When the juxtaposition of these features is optimized, the resultant gravity waves and wave-breaking can create extreme turbulence of a magnitude capable of causing structural damage or failure to an aircraft as happened on 9 December 1992.

6. ACKNOWLEDGEMENTS

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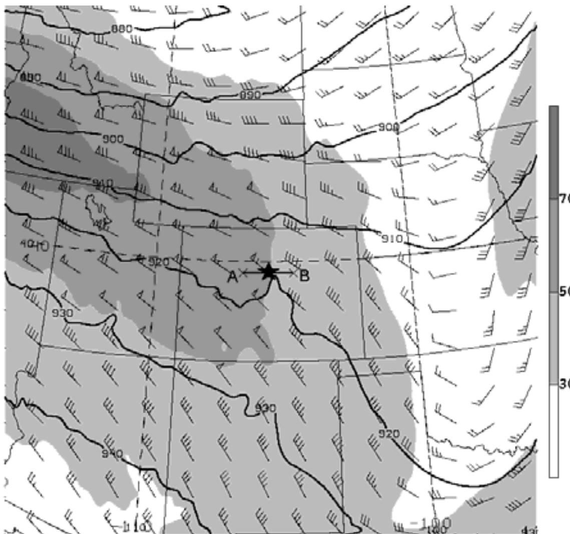

Figure 1: Wind speed (ms^{-1}) and heights (dam) over the Rocky Mountains at 1500 UTC 9 December 1992, from 18 km NHMASS model output. Aircraft accident location denoted by star.

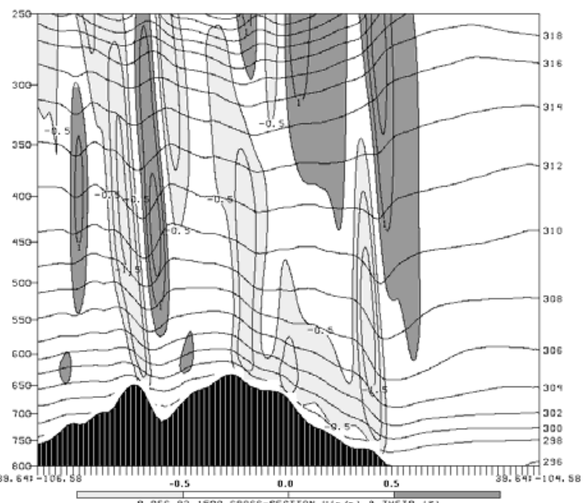

Figure 2: Vertical cross-section of vertical velocity (ms^{-1}) and potential temperature (K) through the accident location at 1500 UTC 9 December 1992 from 2 km NHMASS model output. Vertical scale is pressure in hPa. The cross-section is denoted as AB in Fig. 1.

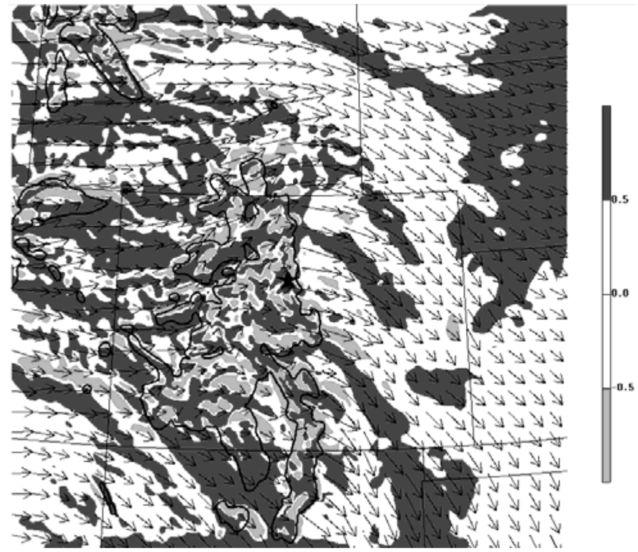

Figure 3: 700 hPa potential vorticity (in PVU, or 10^{-6} $Km^2s^{-1}kg^{-1}$), horizontal wind vectors (length proportional to speed in ms^{-1}), and 2500 m terrain contour for 1500 UTC 9 December 1992, from 6 km NHMASS model output. Aircraft accident location denoted by star.

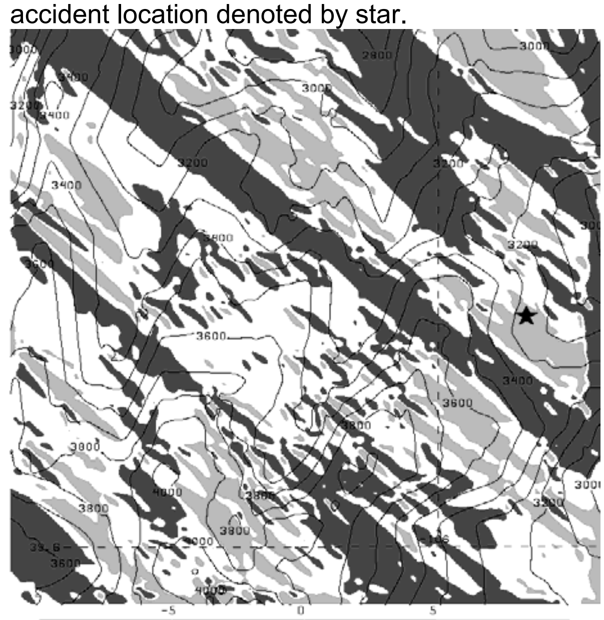

Figure 4: 275 hPa relative vorticity ($\times10^{-4}$ s^{-1}) and terrain contours (100 m interval) for 1507 UTC 9 December 1992 from 71 m NHMASS model output. Aircraft accident location denoted by star.

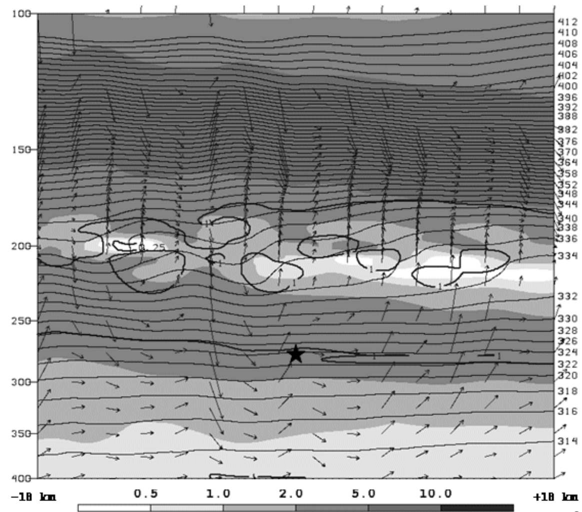

Figure 5: Vertical east-west cross-section of N^2 ($\times 10^{-4}$ s^{-2}, shading), Richardson number, x-P circulation (ms^{-1}), and potential temperature (K) at 1507 UTC 9 December 1992 from 222 m NHMASS model output. Vertical scale is pressure in hPa. Accident location is denoted by star.