10.5 A MODELING INVESTIGATION OF NEAR-CLOUD TURBULENCE

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1. Introduction

Atmospheric turbulence poses a significant risk to the aviation community. Such turbulence has a variety of well known sources, which include thunderstorms, mountain ranges, and jet streams. However, the generation of turbulence by these sources is not particularly well understood. The current study seeks to investigate possible mechanisms which cause turbulence in the clear-air surrounding developing thunderstorms. This study is motivated by a specific turbulence encounter by a commercial jet.

On 10 July 1997 a commercial passenger aircraft encountered severe turbulence near Dickinson, ND, enroute from Seattle to New York. The aircraft was negotiating a number of scattered thunderstorms, yet passed directly over a developing deep convective cloud. While passing over this cloud, the aircraft suffered accelerations of approximately two g's, in a period of about 10 seconds. Subsequently, twenty passengers and two flight attendants suffered minor injuries.

The aircraft was flying at 37000 feet, which on that day, corresponds to about 11 km above ground level (AGL): very close to the height of the tropopause. The encountered convective cell formed between two more mature thunderstorms that were about 100 km apart. The aircraft experienced turbulence while out of cloud and directly above this center convective cell, as it overshot into the relatively undisturbed air at the tropopause.

In an attempt to understand possible processes causing the turbulence encounter, two and three-dimensional cloud-resolving model calculations, are presented. These calculations explicitly resolve both the convection and the turbulence-causing instabilities in the vicinity of the cloud.The cloud-resolving model used in this study was developed by Clark (1977) and Clark and Farley (1984). This model uses the anelastic approximation, and has explicit treatments of cloud processes via a combination of a Kessler (1969) warm rain parameterization and a Koenig-Murray (1976) ice parameterization. The model also features a first-order Smagorinsky (1963)-Lilly (1962) subgrid-scale closure.

The two-dimensional model results are presented in Section 2, the results from the three-dimensional model calculations are presented in Section 3, and some conclusions are presented in Section 4.

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2. Two-dimensional simulations

The two-dimensional model domain is 200 km wide and 36 km high, with a grid spacing of 50 meters in both the horizontal and vertical directions. The uppermost 15 km of the model domain features a Rayleigh-friction absorber to absorb vertically propagating waves with minimal reflection. The model is initialized with wind and thermodynamic data derived from the 0Z 11 July 1997 sounding taken at Bismarck, ND. This sounding was taken approximately two hours after and 200 km to the east of the turbulence encounter. The two-dimensional model wind is derived from the velocity component in the direction of maximum wind in the sounding. Convection is initialized using a localized surface heating. This method produces a mature convective system within about 2 hours of model initialization.

Using two-way interactive grid nesting, a higher resolution domain is included in the region surrounding the cloud top. This domain has 16.67 meter grid spacing in both the horizontal and vertical directions. This domain focuses on the development of the convective updrafts as they overshoot the relatively undisturbed tropopause region. Three representative times during the development of one particular updraft are shown in Fig. 1. Figure 1(a) shows that as this particular updraft overshoots the tropopause, at about 11 km AGL, the flow is initially laminar above the cloud. Within 5 minutes of this overshoot (Fig. 1b), wave-like perturbations in the potential temperature are evident above the cloud, and one phase of these waves has become unstable and broken over the cloud top. This breaking produces turbulent overturning of the clear-air on a horizontal scale less than 1 km. Later in the evolution of the updraft (Fig. 1c), the turbulence region has extended vertically to over 1 km above the cloud top. Also, small turbulent eddies form along the cloud interface. These eddies are formed by a shearing instability, due to the strong deformation of the flow at the cloud interface (see Grabowski and Clark 1991 for further details of this instability).

In addition to the turbulent motion in the first kilometer above the cloud top, turbulence is also generated at higher altitudes. Figure 2 shows the existence of gravity wave breaking later in the cloud's evolution. At 100 minutes into the model calculation, vertically propagating gravity waves generated by the convection become unstable and break in a narrow region above the cloud. These waves are forced by the overshooting updrafts, and the subsequent dry response. The breaking continues in time, and eventually extends vertically to about 14.5 km altitude, spanning approximately 30 kilometers in the horizontal (Fig. 2c). Associated with this wave break-

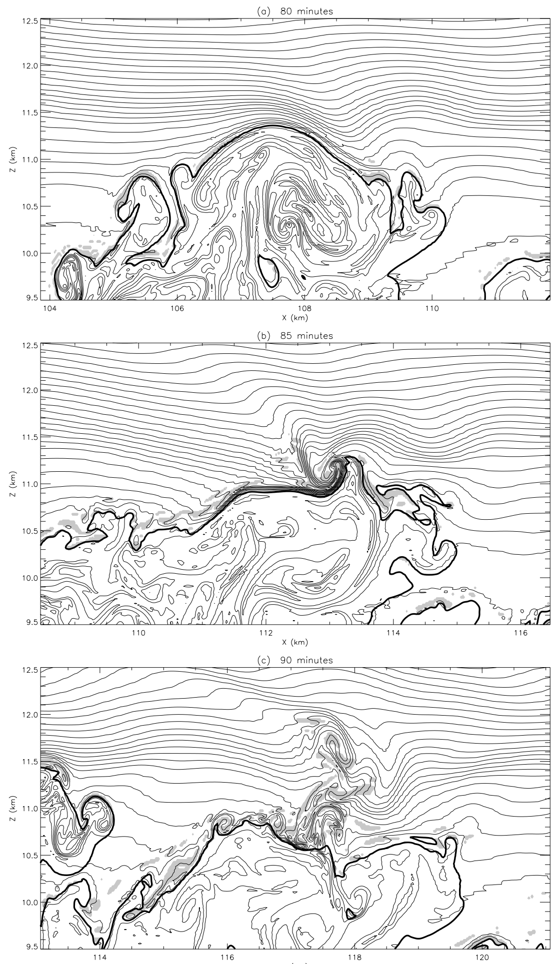

FIG. 1: Three representative times during the two-dimensional model calculation illustrating the overshoot of a single convective updraft. Contours of potential temperature (1 K intervals), and the (0.05 $g\ kg^{-1}$) total cloud loading outline (thick). Shading denotes regions of convective instability outside cloud. Z is height AGL, and the background wind is from the left.

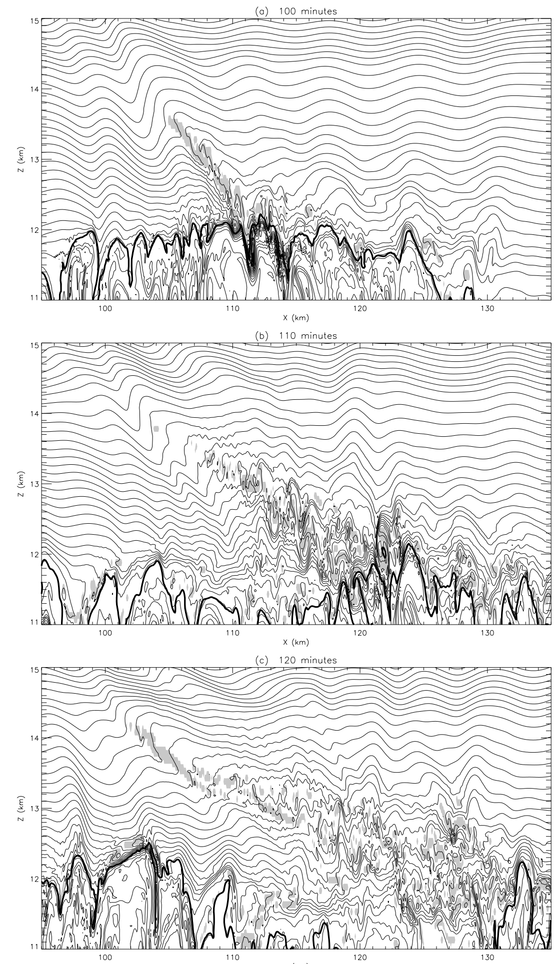

FIG. 2: Three representative times during the two-dimensional model calculation illustrating the breaking of waves above the convection. Contours are the same as Fig. 1, except the potential temperature has 2 K intervals.

ing is turbulent mixing down to the smallest resolvable scale in the model. This breaking is due to the interaction of these vertically propagating waves with a critical level, where the flow speed equals the propagation speed of the waves.

3. Three-dimensional simulations

This section examines the results from a more realistic model calculation in three spatial dimensions. In order to examine the development and initiation of convection in a more realistic environment, the cloud model is coupled to a large scale forecast model, MM5. An MM5 calculation begins 24 hours prior to the turbulence encounter, and is used as initial and boundary conditions for the cloud model. MM5 makes a reasonable representation of the conditions surrounding the event. It produces convection in approximately the correct area, but about an hour early and about 100 km to the west. Nonetheless, the convection develops in a similar configuration to that observed, with a cell developing in the center of two larger more mature cells. It is this center cell that was encountered by the aircraft, and is the focus of the three-dimensional modeling. Within the cloud model domain, six levels of grid nesting are used, with the finest scale grid having 55 meter horizontal and 33 meter vertical grid spacing.

Three representative times during the center cloud's evolution are shown in Figure 3. As the updraft overshoots the tropopause region, the isentropes are strongly compressed forming very high stratification at the cloud boundary (Fig. 3a). Later in the evolution (Fig. 3b), the updraft has completely overshot the tropopause and a net downward buoyancy force is exerted on the top of the cloud. These isentropes at the cloud top are forced downwards (Fig. 3c). During this downward response, however, a turbulent mixed layer forms at the cloud top. The result is a turbulent layer about 1 km deep, and about 2 km wide.

This three-dimensional turbulence generation is sim-

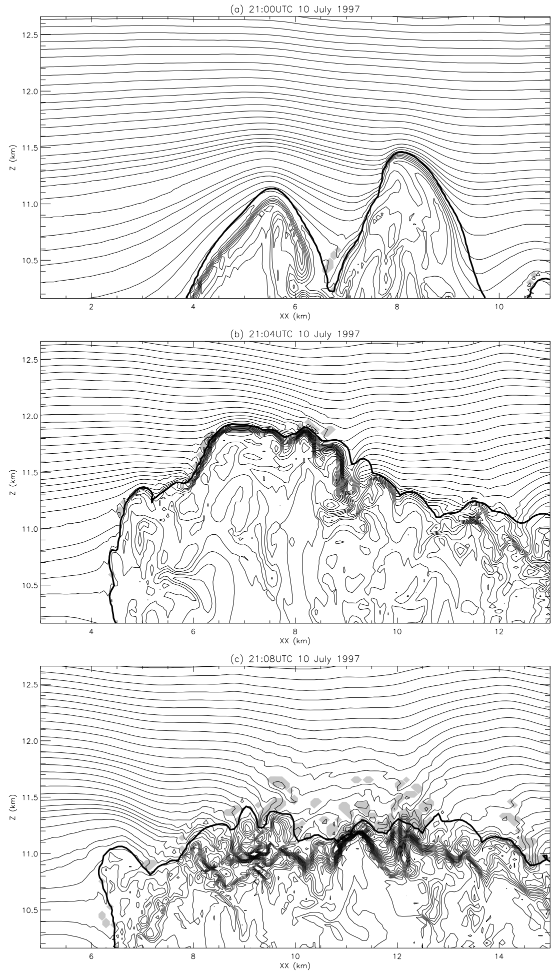

FIG. 3: Three representative times during the three-dimensional model calculation illustrating the overshoot of a single cloud. Contours are the same as Fig. 1. The horizontal axis is aligned with the mean shear vector at the tropopause.

ilar to that seen in the two-dimensional case. In particular, during the updraft reversal, which is a response to the overshoot, regions of turbulence are generated above the penetrating updraft. The mechanism causing this turbulence generation may be a combination of a gravity wave response (as suggested by Fig. 1), or a more complicated response to vorticity generation by the strong buoyancy gradients at the boundary of the overshooting updraft. Understanding this mechanism is a topic for future research.

The three-dimensional case, however, does not show the coherent wave breaking above the cloud as was seen in the two-dimensional case (Fig. 2). The reason for this is probably a combination of three-dimensional effects and the reduced wind shear; the MM5 failed to reproduce the strength of the wind shear observed in the Bismarck sounding. Subsequently, the three-dimensional calculation possessed about one half of the wind shear of the two-dimensional calculation. This reduced wind shear removed the critical level that caused the gravity wave breaking in Fig. 2.

4. Conclusions

This study has examined the generation of turbulence in the clear-air above deep convection. Using a number of high resolution cloud-resolving model calculations, it was shown that local instabilities generated turbulence in a layer 1 to 2 km deep above the cloud top. Also, in a case where the wind shear was sufficiently strong, gravity waves became unstable and broke up to 4 km above cloud top, generating a turbulent layer about 30 km long. In all cases, however, the turbulence appears highly localized, being surrounded by relatively laminar flow.

This study was motivated by a specific turbulence encounter, where a commercial aircraft encountered turbulence very close to the top of a developing cloud. These results provide some insight into some possible mechanisms which may have led to this turbulence encounter. Also, case studies such as this can be used to evaluate and improve strategies for turbulence avoidance by aircraft. Further case studies are planned for the future.

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