Gravity wave breaking, secondary wave generation, and mixing above deep convection in a three-dimensional cloud model

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[1] This paper documents the breakdown of gravity waves generated by deep convection in a three-dimensional cloud-resolving model. The convection generates gravity waves that propagate into the lower stratosphere, with horizontal wavelengths between 5 and 10 km. Above-cloud wind shear causes part of the spectrum of these waves to break, inducing overturning. The model grid spacing is small enough (150 m) that the gravity waves are well resolved, and the turbulent cascade induced by the breakdown is partially resolved. Previous model simulations of wave breakdown above deep convection, at this resolution, have only been achieved in two-dimensional models. The wave breakdown generates secondary waves, which have much shorter horizontal wavelengths, and different propagation characteristics compared to the primary waves. Secondary wave generation in the lower stratosphere above deep convection has not been identified in previous studies. The wave breakdown also induces irreversible mixing, which is quantified in terms of the vertical transport of water vapor.


1. Introduction

[2] Deep convective clouds generate atmospheric gravity waves due to the interaction between unstable convective motions and the surrounding stable environment. These waves vary in scale from that of individual convective updrafts to larger scales defined by organized convective complexes. Convectively generated gravity waves can influence the momentum budget of the middle atmosphere [Fritts and Alexander, 2003], can generate turbulence and mixing [Lane et al., 2003], and can interact with the surrounding environment to promote or suppress new convection [Mapes, 1993].

[3] A number of recent studies [e.g., Wang, 2004; Moustaoui et al., 2004; Lane et al., 2003] have highlighted the importance of breaking gravity waves in the lower stratosphere directly above deep convection. Moustaoui et al. [2004] showed that the interactions of gravity waves with a critical level directly above the cloud can cause wave overturning, which generates “mixing layers”, i.e., regions of low or neutral stability that can mix atmospheric constituents, like ozone, vertically. Similar wave overturning and breaking was shown by Wang [2003, 2004] to be responsible for transporting water vapor across the tropopause, and generating lower-stratospheric cirrus clouds. In addition, gravity wave breaking generates turbulence [Lane et al., 2003] and causes a divergence of the wave-induced vertical flux of horizontal momentum [Fritts and Alexander, 2003].

[4] The breakdown of gravity waves in the vicinity of deep convection is of fundamental importance in the generation of small-scale motions that influence aircraft, i.e. “aviation-scale turbulence”. Vertical velocities with horizontal scales from tens of meters to O(1 km) can produce a strong aircraft response. Gravity wave motions are generally too large in scale to influence an aircraft, and an extra mechanism is required to induce a cascade of scales from the gravity-wave scale down to the smaller scales that influence aircraft motion; the breakdown of gravity waves provides such a mechanism.

[5] Using a high-resolution two-dimensional (2D) cloud model Lane et al. [2003] explicitly resolved the breakdown of short horizontal scale (~5–10 km) gravity waves that were generated by deep moist convection. As shown by Lane and Knievel [2005], model grid spacings of O(100 m) are necessary to properly resolve waves of this scale and their eventual breakdown. High resolutions such as these are readily achieved in 2D cloud-resolving models but three-dimensional (3D) modeling remains challenging. Three dimensions are necessary, however, because a 2D model can not provide a realistic representation of the wave breakdown, the turbulent cascade, and the resultant mixing [e.g., Dörnbrack, 1998]. With this in mind, the aim of this study is to examine the details of gravity wave breaking above deep convection, in a similar scenario to the 2D Lane et al. [2003] case, using a high-resolution 3D cloud model.

2. Model Outline

[6] The numerical model used was originally developed by Clark [1977], with subsequent updates and improvements. The model is anelastic, nonhydrostatic, and features finite difference approximations to the governing equations that are second order accurate in time and space. To reduce computational costs, simplified warm rain microphysics are used [Kessler, 1969], and a first-order Smagorinsky parameterization represents the subgrid turbulence. The domain has 674 × 338 grid points in the horizontal, 234 grid points in the vertical, and 150 meter grid spacing in all spatial directions. Therefore, the domain is 101.1 km long (x-direction), 50.7 km wide (y-direction), and 35.1 km deep (z-direction). The uppermost 10 km feature a sponge layer to mitigate reflection of waves off the model lid, and the
lateral boundaries are periodic. Qualitatively similar results were found when a model domain with 250 m horizontal and 200 m vertical grid spacings was used.

[7] The conditions used to initialized the model are similar to those used in the Lane et al. [2003] 2D simulations. A horizontally uniform flow is defined by the 0000 UTC 11 July 1997 Bismarck, North Dakota sounding. This sounding possesses convective available potential energy of approximately 3600 J kg\(^{-1}\). The wind profile is unidirectional (along the \(x\)-axis), defined by the 220° component of the observed wind (see Figure 1). Convection is initialized using a localized 3-K perturbation in potential temperature located in the center of the domain, below 2 km. Convection develops rapidly and deepens to the tropopause (\(\sim 11 \text{ km}\)) in about 40 minutes, with maximum vertical velocities exceeding 30 m s\(^{-1}\). At this time, the convection shows little resemblance to the initial warm perturbation, with the cloud updrafts featuring a variety of scales.

3. Model Results

[8] Figure 2 shows the simulated potential temperature at 53 and 75 minutes after model initialization, along with the cloud outline defined by the 1 g kg\(^{-1}\) cloud water mixing ratio contour. (The location of the cloud boundary is insensitive to the choice of this or lower thresholds). At 53 minutes (Figure 2a), the cloud has reached its maximum depth of about 13 km. By 75 minutes (Figure 2b), the modeled convective system is mature, with a relatively broad anvil extending downstream from the leading edge of the cloud. Cloud tops have penetrated into the lower stratosphere, and displace the isentropes vertically. The wave-like perturbations in potential temperature are signatures of vertically-propagating gravity waves. The waves have a variety of scales, including a strong response from waves with horizontal wavelengths between 5 and 10 km.

[9] The largest perturbations in potential temperature in Figure 2 are due to waves propagating in the negative \(x\)-direction, i.e., waves with perturbations that progress towards the negative direction with height. Between 13 and 15 km altitude and 50 < \(x\) < 60 km, the isentropes are steepening and overturning, which is evidence of instability and wave breaking. The first evidence of breaking is at about 53 minutes (Figure 2a) and 14 km altitude. At later times (Figure 2b) and above about 14.5 km, the potential temperature shows a propensity for smaller-scale motions with scales far shorter than the dominant gravity wave scale.

[10] The 3D simulation here is generally similar to those 2D simulations presented by Lane et al. [2003]. (The Lane et al. [2003] simulations used smaller grid spacing (50 m), and more sophisticated microphysics.) While there are differences in the details of the convective evolution, the behavior of the waves and their breakdown are both quantitatively and qualitatively similar to those seen in two dimensions. The horizontal scale of the waves is similar, as is the preference for breakdown of waves propagating in the negative \(x\)-direction. The 3D simulation, however, shows far less mixing in the layer between the cloud top and 15 km. This reduction in mixing could be due...
Lane et al. [2003] showed that waves propagating in the same direction as the above-cloud shear vector (i.e., down-shear) will preferentially break due to an interaction between the waves and a critical level. Spectral analysis of Lane et al.’s simulations showed that waves were generated that propagated at phase speeds of ±10 m s⁻¹ relative to the cloud top wind speed. Therefore, a change in wind speed above the cloud of about 10 m s⁻¹ will induce a critical level for those waves propagating in the same direction as that change (i.e., down-shear). In this wind environment such a critical level occurs at about 15 km for waves propagating in the negative direction relative to the cloud top (see Figure 1), and consistent with these arguments, it is those waves in this 3D simulation that break. See Lane et al. [2003] for a detailed discussion of the mechanisms involved.

3.1. Secondary Wave Generation

The breakdown of the vertically propagating gravity waves shown in Figure 2 initiates a cascade from the relatively long scale of the gravity waves down to the smallest scales resolvable by the model. This cascade generates the small-scale perturbations seen in Figure 2b above the breaking region. In the x-z plane these signals are relatively small amplitude, with little obvious coherence. However, a horizontal cross-section of the vertical velocity at 15 km elevation (Figure 3a) shows that these small-scale signals possess a highly coherent pattern in the vertical velocity in the horizontal plane. The coherent pattern takes the form of a wave train, featuring numerous complete wavelengths propagating in the negative x-direction relative to the moving system. The small scale signals have a horizontal scale of about 2 km, which is about five times smaller than the longer scale waves (wavelength of about 10 km). These signals are secondary waves, generated by the (primary) wave breakdown.

Examination of the temporal evolution of the vertical velocity at different heights from the model (not shown) reveals that the 2 km wavelength waves are highly confined in the vertical. Although there are many small-scale signals at heights of 13 and 14 km, they do not show any coherent wave-like patterns like those at 15 km. The secondary waves have the strongest signatures at 15 km, i.e., at least 2 km above the cloud top, and as time progresses these signatures extend upwards to about 17 km, but with smaller amplitudes.

A space-time cross-section of the vertical velocity (Figure 3b) shows that the secondary waves are first identified at 15 km at around 55 minutes and x ≈ 55 km, i.e., shortly after and just above the wave breaking seen in Figure 2a. The secondary waves appear as shorter horizontal scale motions (~2 km) in the vertical velocity, modulating the larger scale (~10 km) waves. Also shown in Figure 3b, is the contour that surrounds the regions at 14 km with Richardson number (Ri) less than one, which highlights the regions of wave breaking just below 15 km. The regions of low Ri also illustrate that the onset of wave breaking at 14 km shortly precedes the appearance of the secondary waves at 15 km. Moreover, short-scale secondary waves appear to be generated at later times also; small-scale signals in the vertical velocity are present just to the left of the wave breaking regions until about 70 minutes.

Figure 3b can be used to infer the phase speed of the waves, and illustrates the differences in propagation characteristics between the (longer-scale) primary waves and the (shorter-scale) secondary waves. The longer wavelength (~10 km) waves (x > 55 km) have phase speeds between about 15 and 30 m s⁻¹ (in the positive direction), while the shorter-scale secondary waves (x < 55 km) propagate in both the positive and negative directions at about ±3 m s⁻¹ (see Figure 3b). These estimates of phase speed and wavelength imply that the period of the secondary waves is about 10 minutes. Simple wave theory shows that relatively short period, short wavelength waves, such as these, are readily filtered by wind shear through critical level dissipation or evanescence [Lane and Clark, 2002]. This filtering confines the secondary waves to a narrow vertical layer, and they do not extend above about 17 km.

Vadas et al. [2003] and Fritts et al. [2006] illustrate that secondary waves can be generated when wave breaking induces a localized “body force”, with the details of the body force defining the character of the secondary waves.
Secondary waves have also been identified in the context of the breakdown of convectively generated gravity waves by both Holton and Alexander [1999] and Snively and Pasko [2003], who showed the important role of secondary wave generation in defining the wave spectrum surrounding the wave breaking region. These two studies, however, examined 2D wave breakdown in the mesosphere, rather than in the lower stratosphere in three dimensions as is considered here.

3.2. Mixing

Previous studies [e.g., Moustaoui et al., 2004] have identified that breaking gravity waves above convection can modify the vertical distribution of atmospheric constituents like ozone or water vapor. In the absence of diabatic processes like condensation, small amplitude gravity waves have a reversible influence, i.e., they do not mix irreversibly. However, large amplitude nonlinear waves, or breaking gravity waves can induce irreversible vertical transport or mixing of trace species.

In regions devoid of condensation or evaporation, water vapor mixing ratio is a passive tracer. In the cloud model there is no condensation or evaporation above about 13 km. The perturbations in water vapor mixing ratio and potential temperature at 15 km are shown in Figure 4 at 40 mins and 75 mins after model initialization. At 40 mins (Figure 4a), the water vapor and the potential temperature perturbations are in-phase. At 15 km, the background profiles of potential temperature and water vapor mixing ratio both increase with height (the background water vapor is a minimum at about 14 km), and the in-phase perturbations at this time represent simple vertical advection. This vertical advection is reversible and does not result in (irreversible) cross-isentropic transport of water vapor. At the later time (Figure 4b), the water vapor mixing ratio and potential temperature perturbations remain in-phase, except in the region 50 < x < 60 km, i.e. the wave breaking region.

The region of the wave breaking induces irreversible cross-isentropic transport of water vapor, resulting in a local reduction in water vapor. This transport is highly localized in space and in time.

To further quantify the irreversible transport induced by the breaking gravity waves, the water vapor field was interpolated onto the 400 K isentropic surface. This surface is located just above 15 km when undisturbed. At 75 minutes into the simulation, the 400 K surface showed a net reduction in water vapor mixing ratio of approximately 0.05%, averaged over the entire 101.1 km x 50.7 km domain. As mentioned above, the mixing is relatively localized, mostly occurring directly above the cloud. A net reduction in a tracer that increases with height would be expected at the top of a mixed layer, i.e., consistent with the wave breaking produced in the simulations.

The mixing induced by wave breaking is a diabatic process. However, in the model equations, the only diabatic process at this height is induced by parameterized turbulent mixing via an eddy mixing coefficient defined using the Smagorinsky closure. This implementation of the Smagorinsky closure uses the same eddy mixing coefficient for all variables (i.e., the Prandtl number is unity). The equations for potential temperature and water vapor mixing ratio use the same eddy mixing coefficient, and the same numerical formulation, and therefore the deviation of the two variables arise because of their different background vertical profiles. Nevertheless, quantitative estimates of mixing and transport from models like this possess large uncertainty because the amount of mixing is controlled entirely by the sub-grid scale turbulence closure scheme. Such closure schemes possess significant uncertainty, especially in the stable stratosphere where they have not been constrained or calibrated by observations. While model simulations like this one are qualitatively useful, detailed observations of turbulence and the resultant transport are essential to obtain robust quantitative estimates of mixing.

4. Discussion

This paper has documented the breakdown of gravity waves generated by deep convection in a 3D cloud resolving model. The model is configured at a resolution that is high enough so that the generated waves are well resolved, and that turbulent processes generated by the breakdown are, at least, partially resolved. Gravity waves with horizontal wavelengths of about 5–10 km break in the lower stratosphere, below about 15 km. The wave breakdown is shown to occur in a similar location to comparable 2D model simulations. There is a preference for the breakdown of waves propagating in the same direction as the above-cloud shear vector, due to critical level interactions.

The wave breakdown was shown to generate a coherent train of waves with horizontal wavelengths of about 2 km. These waves appear to be the result of “secondary wave generation”. The short horizontal scale of the secondary waves, their short period, and their slow phase speed cause them to be confined to a shallow layer about 2 km deep. Yet, the secondary waves extend horizontally for about 10–20 km, i.e., through a number of upward and downward phases of the larger scale gravity waves. To our knowledge, this is the first modeling study
that documents secondary wave generation in the lower stratosphere directly above deep convection.

[23] Previous research [e.g., Lane et al., 2003] has identified that turbulence due to the breakdown of gravity waves above convection is a major concern for aviation. However, the presence of the coherent secondary waves is an additional concern. The secondary waves do not possess the highly localized and spatially-variable patterns characteristic of turbulence, but because of their small spatial scale, may still induce a strong aircraft response.

[24] The breakdown of the gravity waves was shown to cause cross-isentropic mixing of water vapor in the breaking region. This result can be generalized to other constituent species that possess non-zero vertical gradients in the lower stratosphere, such as ozone. However, previous studies have shown that breaking gravity waves are inefficient mixers [e.g., Dörnbrack, 1998], because the vertical displacement caused by such gravity waves are small (see the discussion by McIntyre [1989, and references therein]). This seems to be true for the thunderstorm case, as the maximum vertical displacements induced by the gravity waves in the simulations presented herein are only about 200 m. Nonetheless, thunderstorms occur frequently around the globe, especially in the tropics, and therefore the net effect of all thunderstorms in causing the vertical redistribution of atmospheric constituents in the lower stratosphere may be important.

[25] This paper has documented a single case of wave breakdown, secondary wave generation, and mixing in the lower stratosphere above deep convection. Further model simulations are underway to determine the sensitivity of these results to background flow conditions and increased numerical resolution; these results will be presented in a future paper.

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