P2.21 GRAVITY WAVE BREAKING OVER GREENLAND

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1. INTRODUCTION

The importance of mountain waves for numerical weather prediction is underscored by the numerous studies that document the impact on the atmospheric momentum balance, turbulence generation, and the creation of severe downslope winds. Large-amplitude internal gravity waves are frequently generated as a consequence of stably stratified air that is forced to rise over topography. Amplification of upward propagating gravity waves occurs, in part, due to the decrease in atmospheric density with height and may result in subsequent wave overturning and turbulent breakdown.

The dynamical characteristics of nonlinear gravity wave breaking has been extensively studied. As wave amplification and overturning occurs, momentum transport and turbulent dissipation is significantly enhanced. Many of the numerical studies reported upon in the literature have used two- and three-dimensional models with simple, idealized initial states to examine gravity wave breaking. In spite of the extensive previous work, many questions remain regarding gravity wave breaking in the real atmosphere. Outstanding issues that are potentially important for mesoscale numerical weather prediction include: turbulent mixing and wave overturning processes, mountain wave drag, downstream effects, and predictability of wave breaking. The current limit in our understanding of gravity wave breaking can be partially attributed to lack of observations. During the Fronts and Atlantic Storm-Track Experiment (FASTEX), a large amplitude gravity wave was observed in the lee of Greenland on 29 January 1997 (e.g., see Doyle and Shapiro 1999). Data collected during FASTEX represents a unique opportunity to study topographically forced gravity wave breaking and to assess the ability of high-resolution numerical models to predict the structure and evolution of such phenomena. In the present study, a nonhydrostatic model simulation is validated with continuous research aircraft and dropwindsonde observations from the NOAA G-IV. Real-data and idealized model simulations are used to document the evolution, characteristics and dynamics of the breaking gravity wave event.

2. OBSERVATIONS

Measurements from the NOAA G-IV research aircraft were used to document the evolution and dynamics of the large-amplitude gravity wave event over Greenland, which also provide mesoscale observational validation data for simulations using the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS^{TM}) (Hodur 1997). Vertical cross section analysis of continuous flight-level (~12 km) and dropwindsonde data, with 50-km horizontal spacing, document the

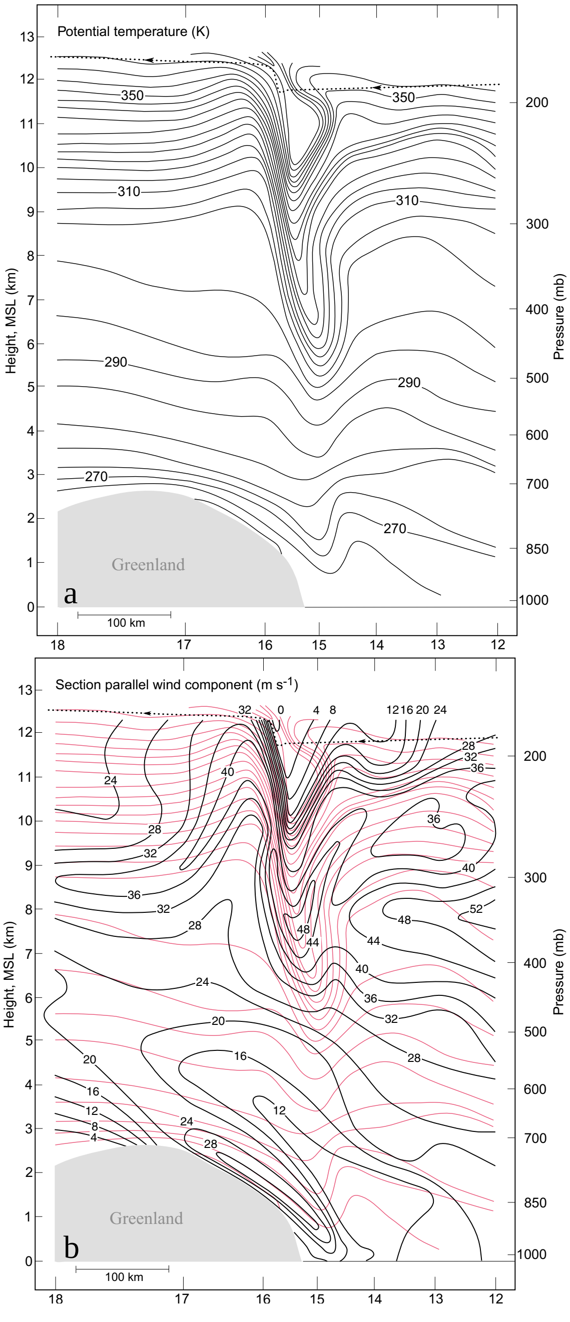

Fig. 1. Vertical cross section analyses based on the NOAA G-IV *in situ* and dropwindsonde observations for (a) potential temperature (K) and (b) section parallel wind speed (m s^{-1}) (black) and isentropes (red) valid at approximately 1200 UTC 29 January 1997.

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presence of a large-amplitude breaking gravity wave extending from above the 180 hPa level to 500 hPa (Fig. 1a). The dropwindsonde data measured deep layers with isentropic overturning and an upshear tilt to the gravity wave. Flight-level data (~180 hPa or 12 km) indicate a horizontal shear of over 10^{-3} s^{-1} across the wave with 25 K potential temperature perturbations. The wind speed downstream of the breaking wave decreased by 30 m s^{-1} resulting in the reduction of the cross-mountain flow to near zero with localized flow reversal areas (Fig. 1b).

3. NUMERICAL SIMULATIONS

The atmospheric component of the Navy's COAMPS (Hodur 1997), which integrates the fully compressible equations of motion, is used in this study. Physical parameterization schemes applied include: explicit mixed-phase cloud microphysics, subgrid-scale convection, short- and long-wave radiation processes, and planetary boundary-layer mixing using an explicit equation for the turbulent kinetic energy. Four grid meshes are used in this study with horizontal grid increments of 45 km, 15 km, 5, and 1.7 km, respectively. The model top is at 22 km with 45 vertical levels. A radiation upper-boundary condition is used to minimize the reflection of vertically propagating gravity waves. An 18-h simulation was performed from the initialization time of 0000 UTC 29 January 1997. The initial fields for the nonhydrostatic model are created from multivariate optimum interpolation analyses of upper-air sounding, surface, aircraft and satellite data that are blended with 12-h COAMPS forecast fields. Coarse-mesh lateral boundary conditions use Navy Operational Global Analysis and Prediction System (NOGAPS) forecast fields.

The COAMPS nonhydrostatic model simulation captures the temporal evolution and three-dimensional structure of the wave. The model results indicate that westerly flow (~10-15 m s^{-1}) in the lowest kilometer above the Greenland ice sheet may have been enhanced by katabatic effects. Vertically propagating gravity waves emanate from near the surface along the steep glacial slopes as the cold-air mass accelerated down the western portion of Greenland. Near-surface wind speeds greater than 40 m s^{-1} were present in the simulation along the steep slopes and documented in the dropwindsonde data. Additionally, onboard scientists observed snow plumes driven by strong surface winds along the glacial slopes.

Figure 2a shows the west-east oriented cross section of potential temperature for the 11.5-h simulation time (1130 UTC 29 January) for the fourth grid mesh (Δx=1.7 km). A large amplitude gravity wave is apparent in the upper troposphere with wave breaking in the stratosphere established in a deep layer between 9 km and 15 km. The wave structure has obvious similarities to the vertical cross section based on dropwindsonde data (Fig. 2), however the model underestimates the vertical amplitude of the wave, particularly in the troposphere. Characteristics of the breaking wave include an upshear vertical tilt, significant superadiabatic layers, and well-mixed near-neutral conditions that extend downstream from the breaking region. A vertical cross section of simulated wind speed for the 11.5-h time (1130 UTC 29 January) is shown in Fig. 2b. Lateral shear of ~10^{-3} s^{-1} is maintained in the vicinity of the breaking wave in the layer between 9 km

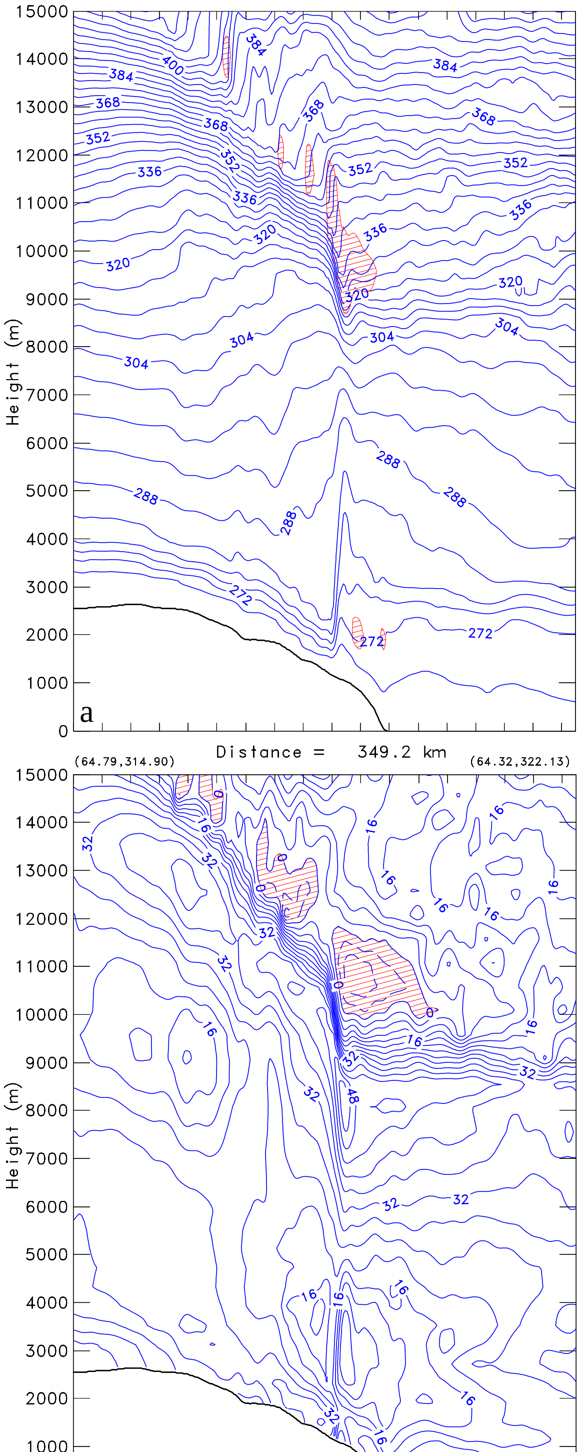

Fig. 2. Vertical cross section analyses based from a COAMPS simulation (Δx=1.7 km) for (a) potential temperature (K) with turbulent kinetic energy greater than 10 m^2 s^{-2} hatched (red), and (b) section parallel wind speed (m s^{-1}) with regions of reversed flow hatched (red) valid at 1130 UTC 29 January 1997 (11.5-h simulation time).

and 11 km. As the result of intense vertical shear (50 m s^{-1} /1000 m) and isentropic steepening associated with the wave amplification, turbulent kinetic energy (TKE) is generated that leads to enhanced momentum flux and dissipation (hatched area in Fig. 2a). The deep breaking layer with a TKE maximum is also apparent in the three-dimensional depiction shown in Fig. 3. This is in agreement with analysis of the dropwindsonde data that indicate a large increase of high frequency structure in the vertical velocity within the wave as opposed to less turbulent conditions upstream.

A series of three-dimensional idealized simulations are conducted to determine the quantitative impact of planetary rotation and the topography shape on upper-level wave breaking. The dependence of the nondimensional mountain slop on the nondimensional drag for a series of simulations with no rotation and with R_o=0.5, where R_o=U/fL, is shown in Fig. 4. The idealized experiments indicate that a critical terrain slope exists beyond which upper-level wave amplitudes are enhanced to a point that turbulent breakdown occurs. Steep terrain upstream enhances blocking and the lee-side wave response such that the effective R_o is increased.

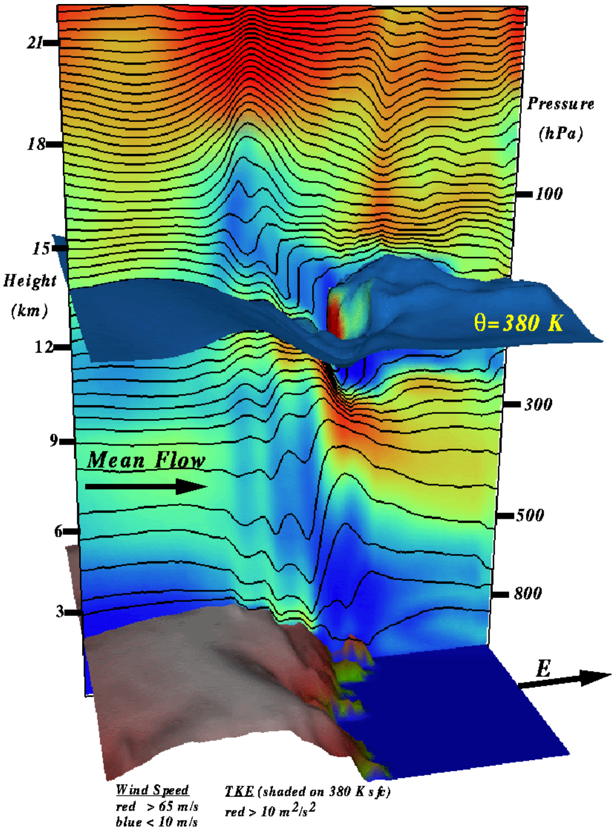

Fig. 3. Three-dimensional depiction of a COAMPS simulation (Δx=5 km) valid at 1300 UTC 29 January 1997 (13-h simulation time). The 380 K isentropic surface is displayed in a 3-D perspective with the color shading representing the turbulent kinetic energy (red represents values greater than 10 $m^2 s^{-2}$). A west-east oriented vertical cross section of potential temperature (black contours) and the cross-mountain wind speed component (color shading with red greater than 65 m s^{-1} and blue less than 10 m s^{-1}) is also shown.

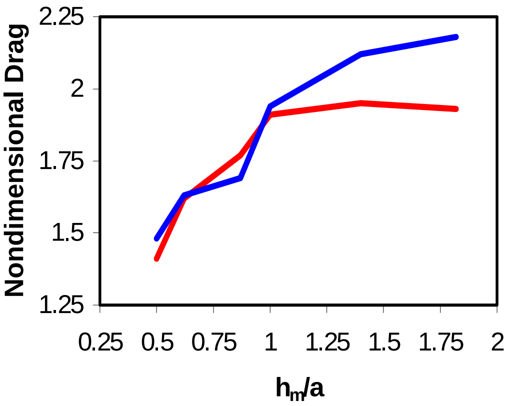

Fig. 4. The dependence of the nondimensional slope (h_m/a), where h_m is the mountain height and a is the half-width, on the nondimensional drag. The drag is normalized by the linear drag. Two series of simulations are performed with R_o=0.5 (blue) and no rotation (red).

4. SUMMARY

This study documents a real-data numerical simulation of a breaking gravity wave event that occurred in the lee of Greenland on 29 January 1997 using NRL's nonhydrostatic mesoscale modeling system. The simulation successfully captures the development of the large amplitude gravity wave and the results compare favorably with research aircraft and dropwindsonde observations obtained during FASTEX. Wave overturning and turbulent breakdown in the stratosphere (~12 km) occurs in the lee of Greenland above the steepest topographic slopes. Simulations performed with idealized elliptical topography suggest the steep lee-side terrain slope of Greenland enhances that upper-level gravity wave breaking substantially and acts to increase the effective R_o. The results of this study suggest that the simulation and prediction of fine-scale structures associated with breaking gravity wave events may be routinely possible in both research and operational applications using sophisticated nonhydrostatic modeling systems. Predictive capability of events, such as documented in this study, is necessary to improve our understanding of topographically forced gravity waves.

ACKNOWLEDGEMENTS

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