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STATUS REPORT ON THE PREDICTABILITY OF MESOSCALE GRAVITY WAVES WITH NUMERICAL WEATHER PREDICTION MODELS

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1. INTRODUCTION

Gravity waves with periods of 0.5 – 4.0 h and wavelengths of 50 – 400 km are commonplace phenomena in current research and operational mesoscale models. The ability of these kinds of waves to produce important effects upon cloudiness and precipitation and to dominate the quasi-geostrophic signals is well-established, but spurious gravity waves also permeate mesoscale models. Consequentially, the credibility of these small-scale phenomena has become an important issue for proper interpretation of numerical guidance. On the one hand, it is well known that imbalances in the initial state of mesoscale models may generate gravity-inertia waves in the first few hours of the forecasts as the model attempts to achieve a certain state of balance. In addition, moist convection in models may excite unrealistic gravity waves, notably in the first few hours of integration as spurious convection is triggered by the initial imbalances (Pokrandt et al. 1996). In other words, gravity waves generated by initial imbalances may trigger spurious convection, which then spawns additional fictitious waves, which may trigger even more erroneous convection, leading to serious model forecast error. Other spurious waves may arise in frontal zones if care is not taken to have compatible vertical and horizontal grid resolutions (Persson and Warner 1991). In addition, the formulation of lateral boundary conditions in limited area models can produce transient gravity-inertia waves (Warner et al. 1997). These spurious waves may complicate the forecast since they may contaminate the interior of the domain within just a few hours.

For all of the above reasons, it is imperative to have a better understanding of the predictability of mesoscale gravity waves. This paper provides an update to the review by Koch et al. (1999) of the ability of limited-area numerical weather prediction models to accurately and reliably predict such waves. Several gravity wave modeling studies have been published in just the last couple of years, thereby providing new information for this study. In addition, investigations of the vertical structure of such waves using active remote sensing systems have recently been completed, making it possible to draw detailed comparisons with the model predictions of wave structures.

2. METHODOLOGY

The approach used here is to consider only gravity wave simulation studies for which detailed observational analyses of the waves have been performed. The simulation studies considered in this report are referred to as follows:

PR93:	Powers and Reed (1993)	“BLIZZARD”
PTH96:	Pokrandt et al. (1996)	“BLIZZARD”
P97:	Powers (1997)	“BLIZZARD”
K98:	Koch et al. (1998)	“PALM SUNDAY”
JK98:	Jin and Koch (1998)	“STORM-FEST”
ZK00:	Zhang and Koch (2000)	“CCOPE 1”
K01:	Koch et al. (2001)	“CCOPE 2”
Z01:	Zhang et al. (2001)	“EAST COAST”

The BLIZZARD and EAST COAST wave events occurred during rapid cyclogenesis events. Gravity waves were generated within a lee cyclone in the STORM-FEST and CCOPE events, whereas waves formed to the north of a slow-moving cold front in the southeastern U.S. in the PALM SUNDAY case. Some of these studies reported on results from use of multiple model configurations; altogether, 6 wave events and 10 numerical simulations are available for this study. Despite the small size of this sample, it is possible to address a number of interesting questions, such as whether there might be a preferred kind of environment in which gravity waves develop, and whether a particular wave vertical structure is typically predicted. Issues related to the predictability of wave characteristics, timing and location are also addressed, as is sensitivity of the waves to model configuration.

3. RESULTS

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3.1 Wave Environment and Corridor

Koch et al. (1999) show that, in general, mesoscale models reliably predict the gravity wave genesis, maturation, and decay regions (the "wave corridor"). The models predict mesoscale gravity waves to be confined to the cold side of surface warm or stationary frontal zones and bounded by a region between such fronts, a ridge in the 300 hPa height field to the northeast, and an inflection axis in the height field to the southwest. Gravity waves are triggered near the inflection axis as a jet streak propagates ahead of the upper-level trough axis, in agreement with the gravity wave conceptual model of Uccellini and Koch (1987). The timing of wave generation is also predicted rather accurately (with the single exception of the PTH96 case). However, as shown below, accurate forecasts of *specific* waves with the correct wavelength, phase velocity, amplitude, and shape have not been obtained in most cases; thus, *deterministic* forecasts of mesoscale gravity waves that could be of use in nowcasting remains a grand challenge.

3.1 Phase Speed, Wavelength, Amplitude

Gravity wave characteristics predicted by mesoscale models were compared to those analyzed from the detailed observations. Phase speeds (horizontal trace velocities) appear to be predictable with fair accuracy and no clear evidence of bias (Fig. 1). The quality of the predictions does not seem to depend upon model grid resolution, as those simulations that utilize grid meshes coarser than 15 km seem to do just as well as those that use the finer resolutions. On the other hand, the predicted phase speeds appear to depend to a certain degree upon the grid mesh size (Fig. 2). A possible reason for this, according to P97, is that higher frequency waves appear in the higher-resolution simulations as the result of an expansion in the predicted wave spectrum relative to that in the coarse mesh simulations. High frequency waves display higher vertical wavenumbers m and should propagate more slowly according to the wave dispersion equation $C = N\left(m^2 + k^2\right)^{-1/2}$.

Wave amplitudes are underpredicted in many cases (Fig. 3). There also is a suggestion that wave amplitudes are more *poorly* predicted as model resolution *improves*. P97 noted that a nearly perfect prediction of the wave amplitude in the BLIZZARD case was achieved when using a 10-km grid, but a severe underforecast resulted with use of a 3.3-km grid mesh. Higher frequency (shorter wavelength) waves in the model simulations tend to be weaker (and largely unverifiable in surface data). In fact, these short waves appear to permeate model fields rather than organizing a few precipitation bands into stronger, more coherent structures. In other words, they are more of a nuisance than a help.

Horizontal wavelengths are predicted with about the same accuracy as gravity wave phase speeds, which is to say that considerable scatter exists in the accuracy of these predictions. However, it is interesting to find a strong dependence of the predicted wavelengths on grid mesh resolution. Figure 4 shows that the predicted wavelengths vary

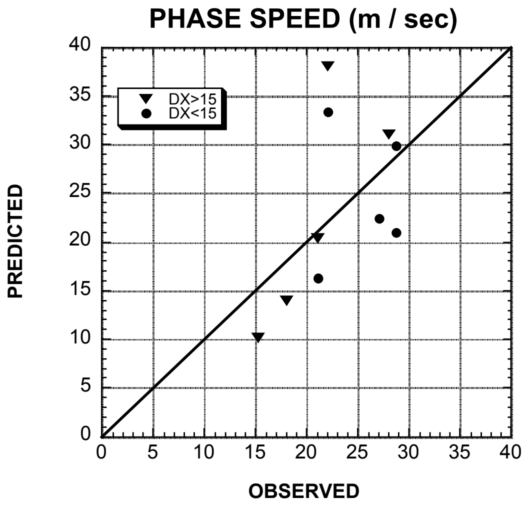

Fig. 1. Comparison of predicted wave phase speeds to those observed (m s^{-1}) in the 10 model simulations.

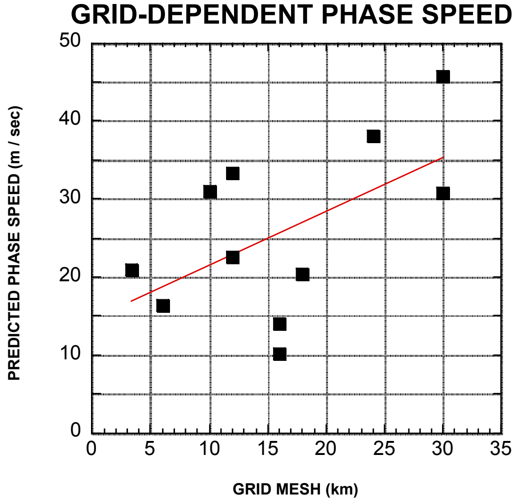

Fig. 2. Relationship of predicted wave phase speeds to model grid mesh size. Line of regression is shown.

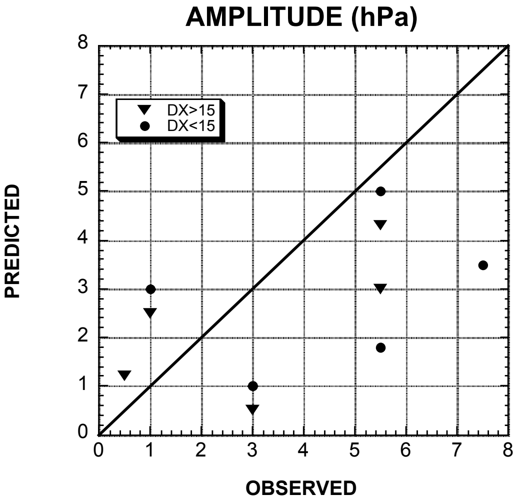

Fig. 3. Comparison of predicted wave surface pressure amplitudes to those observed (hPa).

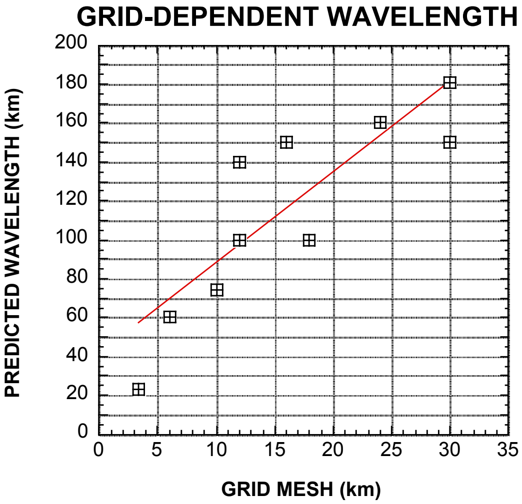

Fig. 4. Relationship of predicted wavelength (km) to grid mesh size (km). Line of regression is shown.

almost linearly with the grid size – the predicted waves tend to have wavelengths of ~6-8 ∆x no matter what the model resolution. This is clearly a matter of some concern, since such waves are only marginally well resolved; thus, there is some doubt that the wave generation mechanism is realistic.

3.2 Wave Vertical Structure

Koch et al. (1999) showed that model predicted gravity wave phase speeds agree quite well with those predicted from wave ducting theory. In fact, “ducted wave-CISK modes” seem to adequately describe the vertical structure of nearly all simulated mesoscale gravity waves. The models produce waves that are primarily confined to a stably stratified duct layer beneath a wave critical level, but with a sudden phase shift in the vertical motions at the critical level, such that updrafts become coincident with lens-shaped perturbations in the isentropes. This behavior implies that moist convection travels with the wave, as in wave-CISK theory. Yet, the “convection” is most often in the form of resolved precipitation produced by the model’s explicit precipitation scheme. In essence, these elements are the model’s attempt to represent elevated convection explicitly.

Do remote sensing observations show this kind of prevalent structure? Ramamurthy et al. (1993) used profiler and Doppler radar VAD data to compare the structure of two gravity waves. In one case, their analysis suggested a structure consistent with a solitary wave, and in the other case, the wave appeared more like “a wave atop an inversion” or a bore. Ralph et al. (1993) used profiler and sodar data to infer the existence of a ducted gravity wave, but the strong phase shift aloft and in-phase relationship between the updraft and isentropes typically seen in mesoscale models did not appear in the observations. Koch et al. (1993) used thermodynamic retrieval techniques applied to multiple Doppler radar analysis. They showed that the structure of a gravity wave was consistent with the vertical normal mode of a free wave from linear theory, but an MM5 model simulation of this event by K01 predicted a ducted wave-CISK structure. Bores generated by downslope flow over the lee slopes of the Rocky Mountains encountering a warm frontal inversion were suggested in separate observational studies of mesoscale gravity waves by Karyampudi et al. (1995) and Rauber et al. (2001). In summary, it does not appear that “ducted wave-CISK modes” are all that prevalent in the limited set of profiler and Doppler radar analyses that are available for comparison with the model predictions. An example of profiler analysis of gravity waves observed in the STORM-FEST case is provided in Fig. 5. The single wave of depression B- seen at Havilland (Fig. 5a) was characterized by strong downward motion at low levels in association with the period of most rapid surface pressure falls. The wind profiler also detected weaker wave A+, though it was barely evident in the microbarographs at that time. A more classical ducted-wave CISK type of appearance has developed 2 h later at Hillsboro (Fig. 5b). The subsidence feature has developed an appearance of a rear inflow to the line of strong convection that has developed aloft.

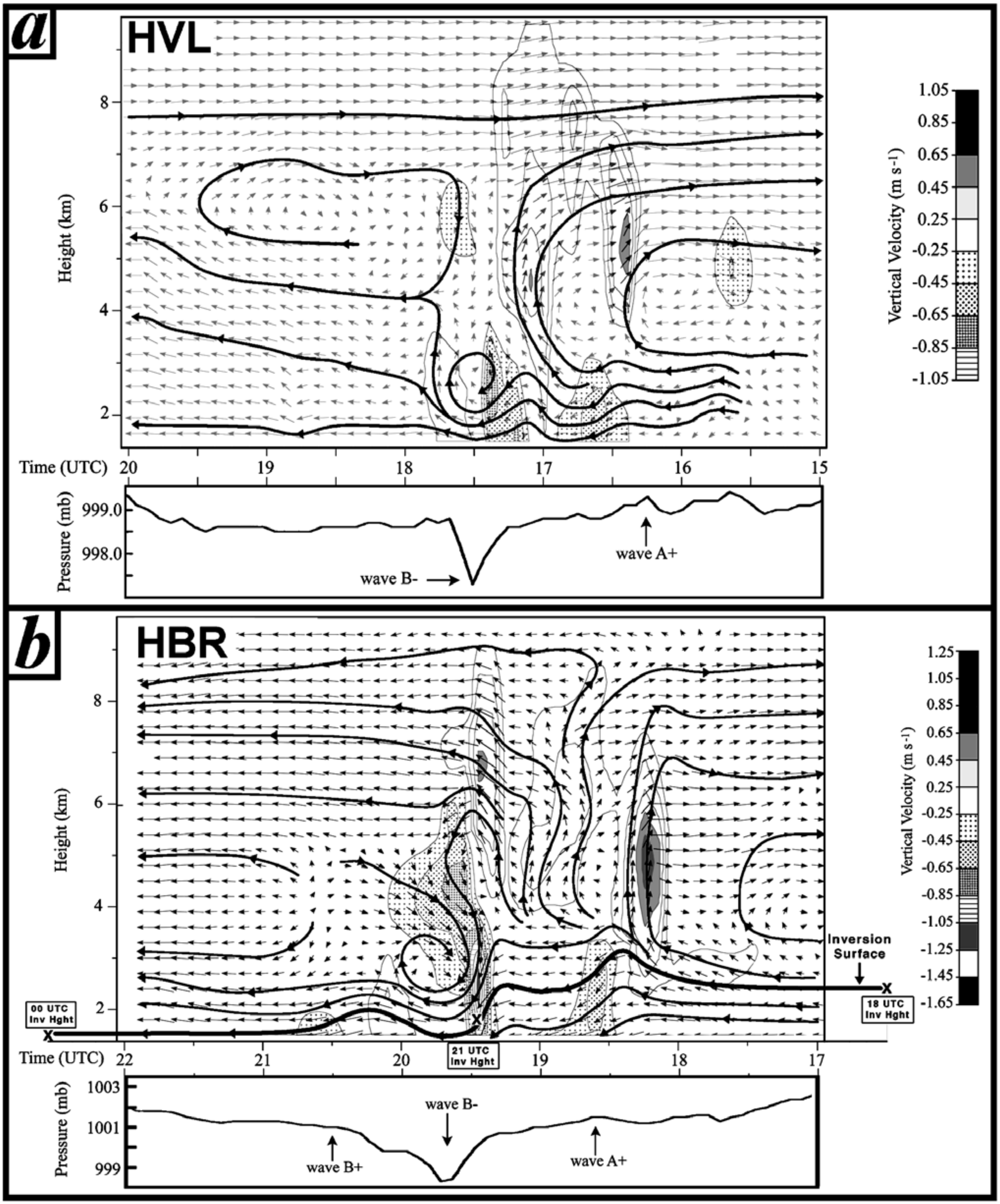

Fig. 5. Time height cross sections of vectors and streamlines of vertical velocity and wave-relative horizontal wind in the direction of wave propagation for a) Havilland and b) Hillsboro wind profiler sites. Vertical velocities are shaded and representative surface microbarograph traces are included for each profiler site. Heavy solid line in (b) indicates evolving depth of a low-level inversion depicted as a streamline. The three X marks denote the observed inversion height from STORM-FEST rawinsonde data. See Trexler and Koch (2000) for additional details.

4. CONCLUSIONS

Mesoscale models have not achieved the goal of being able to predict gravity wave characteristics with sufficient accuracy to be very useful in nowcasting the weather. However, the general wave corridor and timing seem to be fairly predictable. The region in which mesoscale gravity waves typically occur fits the synoptic-scale pattern first proposed by Uccellini and Koch (1987). Ducted wave-CISK modes dominate the kinds of gravity waves predicted by the models, but this kind of structure is not as prevalent in wind profiler and Doppler radar analyses of such waves. Another concern is that predicted wavelengths are all $< 8\Delta x$. Also, shorter waves predicted as model resolution increases cannot be verified easily with operational data. Subtle changes in the model physics, such as handling of the background vertical diffusion and precipitation physics, not only affect the wave characteristics, but may even prevent gravity waves from occurring at all (Jin and Koch 1998). Also, the timing and horizontal scale of the wave disturbances are often determined by the initial location and scale of model grid-resolved "convection."

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