New Approaches to the Parameterization of Gravity-Wave and Flow-Blocking Drag due to Unresolved Mesoscale Orography Guided by Mesoscale Model Predictability Research

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LONG-TERM GOALS

When surface flow impinges on orography with horizontal scales of ~1-500 km, a variety of mesoscale dynamical responses can result, including gravity waves, upstream blocking, flow splitting and lee vortices. These dynamics produce important drag forces on the larger scale atmosphere. Because global numerical weather and climate prediction (NWCP) models under-resolve orography at these scales, all credible NWCP systems must include parameterizations of these missing orographic mesoscale drag (OMD) forces. Recent evidence from mesoscale model simulations clearly indicates that OMD forces cannot be described as a purely deterministic response to upstream forcing, but instead can exhibit a range of values, time histories and states. Our long-term goals are (a) to build these new OMD dynamics delineated from mesoscale models into a new class of OMD parameterizations, (b) to embed those new parameterizations within Navy NWCP systems, and (c) to investigate whether improved time-mean OMD and new explicit OMD variability can improve NCWP skill in Navy global NWCP systems across a range of scales.

OBJECTIVES

The objective of this project is to develop a new class of subgrid-scale parameterizations of gravity-wave and flow-blocking drag due to flow incident upon unresolved mesoscale orography that (a) builds upon the existing OMD parameterization currently implemented in Navy NWCP models (Webster et al. 2003), but (b) modifies it’s behavior in ways that both recognize and explicitly incorporate realistic distributions of possible OMD values that can arise for a given upstream flow environment, as deduced from fully nonlinear mesoscale model ensemble simulations.

APPROACH

Our approach involves a three-tiered research, development and transition (RD&T) strategy based around (a) first-principles mesoscale modeling of the fundamental nature and morphology of OMD dynamics, (b) OMD parameterization based on the results from (a), and (c) objective testing of these new OMD parameterizations in Navy NWCP models.

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For tasks in (a) we leverage results from detailed suites of high-resolution simulations of orographic mesoscale flow dynamics from the Coupled Ocean-Atmosphere Mesoscale Prediction System (COAMPS®), both those from larger research projects at the Naval Research Laboratory (NRL) and a specific subset of companion simulations in this project specifically targeted to our OMD objectives. We analyze these mesoscale model fields to characterize the properties of OMD in various flow and orographic environments (both idealized and realistic). The resulting statistics are compiled as a function of time, mountain height (inverse surface Froude number) and obstacle aspect ratio, using the "regime diagram" approach that currently defines deterministic OMD responses in parameterizations (see Figure 1). This work delineates regions of this regime space that yield reproducible (deterministic) OMD and others that instead yield vacillating or even chaotic OMD. These new results in turn facilitate generalizations of the deterministic regime diagram responses in current OMD parameterizations to new hybrid responses that can vary, from constant deterministic OMD, to periodic/vacillating OMD, to purely stochastic and/or chaotic OMD, depending on their location in the regime space of Figure 1.

Tasks in category (b) focus on modifying the existing deterministic OMD scheme of Webster et al. (2003) in the Navy Global Environmental Model (NAVGEM) to include more realistic OMD properties and variability. Based on the existing literature (e.g., Doyle and Reynolds 2008; Eckermann et al. 2010), there appear to be (at least) two types of temporal OMD variability: (i) periodic vacillations due to cyclical buildup and breakdown of wavebreaking states, and (ii) quasi-chaotic vacillations due to complex internal sensitivities in the nonlinear mesoscale dynamics. We seek initial parameterizations of both types of response using explicitly stochastic methods, in which the range of temporal OMD variability is prescribed but the time history is random, thereby yielding realistic spread and variability in the time mean. For the orographic gravity-wave (OGW) component, we pursue the stochastic approach developed for multi-wave nonorographic gravity-wave drag (NGWD) by Eckermann (2011), and apply it to the orographic problem. Since multiwave methods are required for accurate OGWD parameterization in three-dimensional flows across three-dimensional obstacles (e.g., Shutts 1995), we seek single-wave stochastic analogues for those applications based on the successful NGWD approach of Eckermann (2011). Since the total OMD across the obstacle must also be apportioned into OGW and orographic flow-blocking (OFB) contributions, we also seek stochastic parameterizations for the surface OFB component, based on (a) extending the simple analytical current calculations based on critical Froude numbers that locate the altitude of a dividing streamline, and (b) adapting the Webster et al. (2003) approach of heuristic fits to model-simulated OFB to incorporate realistic ranges of modeled variability within stochastic frameworks.

Tasks in category (c) implement the new OMD parameterizations in NAVGEM and assess performance, first in offline single column tests and ultimately in full forecast-assimilation experiments with results benchmarked using objective skill scores.

WORK COMPLETED

The following tasks were performed in this first year of work.

- Transitioned a new "team scheme" code for gravity wave drag parameterization to Navy global models, which includes within it as options both a stochastic parameterization of nonorographic gravity wave drag (Eckermann 2011) as well as the current OMD parameterization of Webster et al. (2003). This team scheme forms the basis for future OMD improvements coming out of this project.

- Port of the latest version of COAMPS to local high-performance computer networks and initial configuration and tuning for experiments focused on inviscid unsheared flow across idealized elliptical obstacles, to provide results comparable with OMD parameterizations.
- Interface of Fourier-ray (FR) diagnostic tools to COAMPS output.
- Tuning of COAMPS numerics and upper boundary conditions via comparison to exact numerical FR gravity-wave solutions to linear three-dimensional OGW problems.
- COAMPS numerical experiments for OMD responses to idealized upstream flow as a function of normalized obstacle height and aspect ratio (Figure 1).
- Systematic study of influence of geometrical spreading on evolution with height of local wave amplitudes and momentum fluxes.

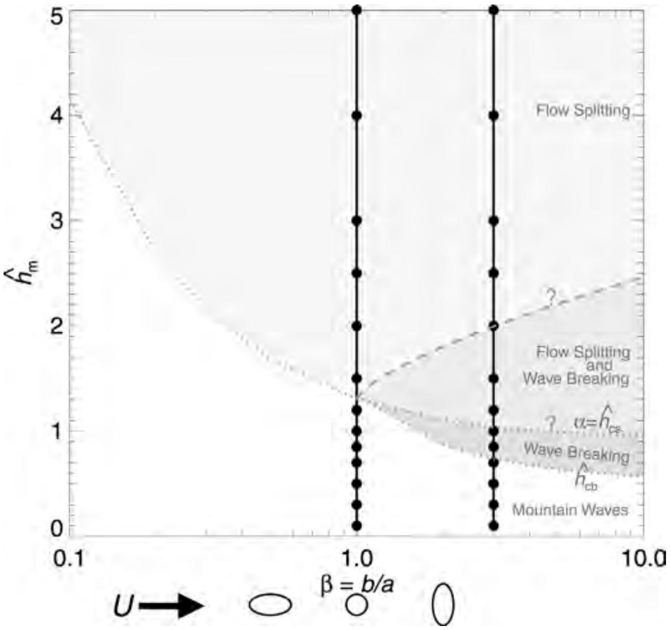

Figure 1. Regime diagram delineating OMD responses to uniform upstream flow of speed U and stability N, as a function of normalized obstacle height $\hat{h}_m = h_m N / U$ ***and obstacle aspect ratio β (after Eckermann et al. 2010).***

RESULTS

Key initial work focused on final development of the first version of a "team scheme" for the parameterization of all gravity-wave drag (GWD) in Navy NWCP models. This was completed in the first half of the year as part of another project focused on implementing and testing a stochastic parameterization of nonorographic GWD (Eckermann 2011). Appendix A of Eckermann (2011) discusses the concepts behind this new "team scheme," in which both orographic and nonorographic GWD are parameterized using the same core physics modules. In particular, the previous standalone Webster et al. (2003) OMD code in the Navy Operational Global Atmospheric Prediction System

(NOGAPS) has been entirely recoded and reimplemented within the team scheme, for future integration into NAVGEM. This new code will now be the focus of all OMD parameterization improvements coming out of this project's research.

Our initial COAMPS and FR experiments delineated an important and as-yet unparameterized influence of geometrical spreading of three-dimensional OGW fields into progressively larger volumes in controlling the amplitude evolution of these waves with height and their subsequent transition to instability and wave breaking. We focused our initial research on these properties, since no current OMD parameterizations incorporates any description of this geometrical spreading effect, implicitly assuming that such effects are secondary, relative to amplitude changes due influences of the background environment, in controlling the evolution of wave amplitudes with height.

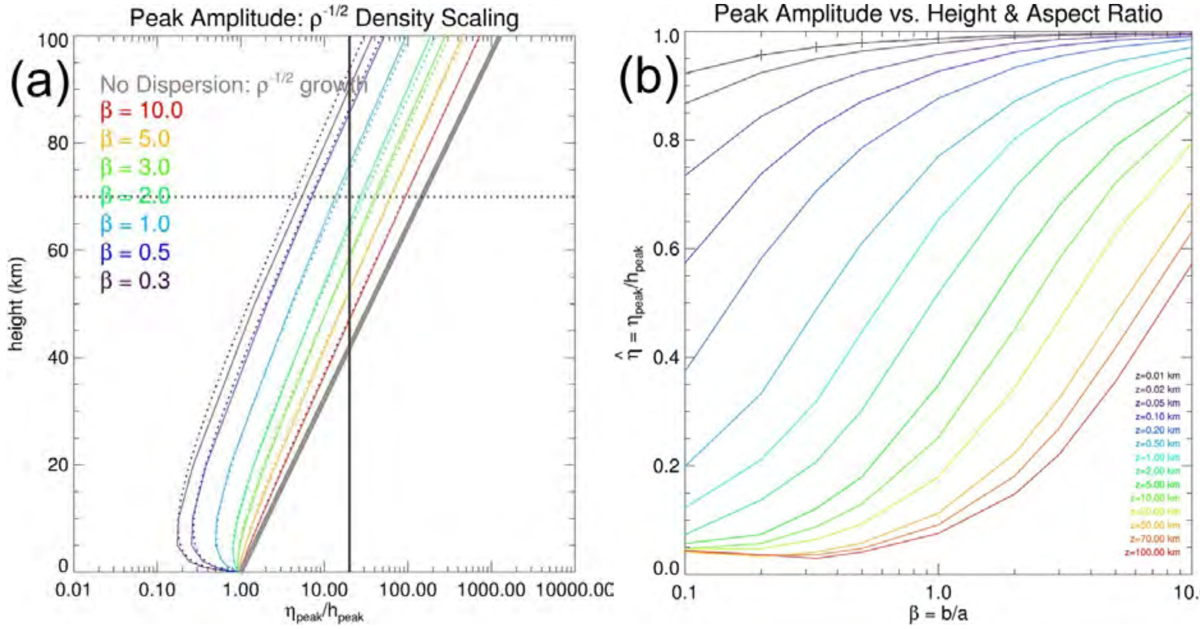

Figure 2. (a) amplitude variation versus height of FR OGW solutions for flow over idealized elliptical obstacles of various β based on regime diagram in Figure 1. Solution without geometrical spreading is shown as thick solid gray curve. (b) Normalized peak amplitude versus β for OGW solutions at various altitudes. The solution without geometrical spreading has a normalized amplitude of unity (top y-axis value).

Our experiments reveal this not to be the case in general: indeed, geometrical spreading often has large influences on OGW amplitude evolution. To illustrate this, Figure 2a plots vertical variations of the peak vertical displacement amplitudes of the three-dimensional OGW fields in our FR solutions for uniform unsheared inviscid flow over three-dimensional elliptical obstacles with different elliptical aspect ratios β. The thick gray curve shows the standard solution without geometrical spreading, which is the uniform solution used in all current OMD parameterizations. The other colored curves show results from the FR solutions using different β values, and reveal that geometrical spreading yields a substantially slower growth in peak wave amplitudes with height. The black vertical line in Figure 2a shows a nominal threshold amplitude for wave breaking, revealing that the standard solution without geometrical spreading would predict that the waves break and generate OMD at ~40 km altitude, whereas the solutions with geometrical spreading included break at substantially higher altitudes. The differences (errors) in breaking height between solutions with geometrical spreading included and excluded can be up to 40-50 km. Figure 2b plots normalized amplitudes of the various FR solutions at different heights, illustrating again the large influence that geometrical spreading has on the amplitude evolution with height (the standard solution without geometrical spreading has a uniform normalized amplitude of unity). These results have been cross-checked and confirmed using first principles COAMPS numerical simulations of selected cases (not shown).

Given the first-order nature of this effect, we have begun exploring ways in which the geometrical spreading effect on OGW amplitudes can be built into current OMD parameterizations (Webster et al. 2003). Geometrical spreading is a complex dispersion effect that manifests indirectly in the wave-action continuity relation governing wave amplitudes, and its effect on wave amplitudes is sensitive to details in both the Fourier content of the source orography and the ways in which the background atmosphere refracts emergent OGW components as they propagate away from their parent orography. For uniform unsheared inviscid flow over idealized obstacles, we have derived solutions with asymptotic range-dependent limits for geometrical spreading that vary as $z^{-1/2}$ for some problems and z^{-1} for others, where z is height above the mountain. For the specific problems whose results are summarized in Figure 2, fitting reveals an asymptotic $z^{-1/2}$-like behavior in the far-field solutions. We have begun studying how a uniform wind shear with height affects this behavior, and are now formulating more generalized numerical approaches to researching this effect within more real-world situations relevant to parameterization, using ray methods and COAMPS simulations. The goal is to find parameterizable aspects of these effects that are simple enough for inclusion in OMD parameterizations yet accurate enough to capture the first-order effects of geometrical spreading (i.e. solutions superior to the current approximation of zero geometrical spreading) for most practical applications. Using our COAMPS and FR solutions together, we have also begun looking at the ways in which spatially localized wave momentum fluxes of these solutions vary with height due to spreading effects, since this too is needed for OMD parameterization. We are investigating this using our Hilbert transform-based diagnostic FR algorithm for computing spatially resolved wave momentum fluxes from three-dimensional OGW solutions, as described in Eckermann et al. (2010).

IMPACT/APPLICATIONS

This project focused on new classes of OMD parameterization for weather and climate models generally, and for NAVGEM specifically. The parameterization of unresolved OMD is one of the more important parameterizations in weather and climate models, required for credible and accurate reproductions of mean sea-level pressure distributions in the Arctic, closure of lower stratospheric wind jets, and reversals of winds above the extratropical winter stratopause. The improved parameterizations of OMD from this work should therefore result ultimately in improved prediction capabilities of weather and climate prediction models that incorporate the new schemes.

TRANSITIONS

We transitioned the “team scheme” GWD code of Eckermann (2011) into the NOGAPS R&D prototype with Advanced-Level Physics and High-Altitude (ALPHA). The team scheme includes an option for generating the parameterized OMD of Webster et al. (2003), which replaces the previous standalone Webster et al. code in NOGAPS. This GWD team scheme will form the basis for future improved OMD features for integration into NAVGEM that come out of this project’s research.

RELATED PROJECTS

Doyle, J. D., and S. D. Eckermann, *The Boundary Paradox*, NRL 6.1 Accelerated Research Initiative, 1 October 2010-30 September 2015.

REFERENCES

Doyle, J. D. and C. A. Reynolds (2008), Implications of regime transitions for mountain-wave-breaking predictability. Mon. Wea. Rev., 136, 5211–5223.

Eckermann, S. D. (2011), Explicitly stochastic parameterization of nonorographic gravity-wave drag, J. Atmos. Sci., 68, 1749-1765.

Eckermann, S. D., J. Lindeman, D. Broutman, J. Ma and Z. Boybeyi (2010), Momentum fluxes of gravity waves generated by variable Froude number flow over three-dimensional obstacles, J. Atmos. Sci., 67, 2260-2278.

Shutts, G.J. (1995), Gravity-wave drag parametrization over complex terrain: The effect of critical-level absorption in directional wind-shear. Quart. J. Roy. Meteor. Soc., 121, 1005-1021.

Webster, S., A. R. Brown, D. R. Cameron, and C. P. Jones (2003), Improvements to the representation of orography in the Met Office Unified Model. Quart. J. Roy. Meteor. Soc., 129, 1989–2010.

PUBLICATIONS

Eckermann, S. D. (2011), Explicitly stochastic parameterization of nonorographic gravity-wave drag, J. Atmos. Sci., 68, 1749-1765.