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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

Significant progress in years 1-3 was reported last year, leading to a follow-on proposal that summarized that progress and proposed an additional 2 years of research. The objectives of this follow-on project are to: (a) finalize our parameterizations of horizontal geometrical spreading effects on OMD drag, (b) fully implement these new research results within the new unified gravity-wave drag parameterizations transitioned into NAVGEM (see Figure 1b), (c) quantify the skill impacts of the new scheme in NAVGEM, and (d) validate the OMD parameterization predictions using independent measurements and modeling results from the international DEEPWAVE aircraft experiment to be conducted in and around New Zealand during June-July 2014.

APPROACH

Our approach is summarized as follows (see proposal for additional details): For objective (a) we are conducting additional numerical Fourier-ray experiments and extend our existing analytical theory

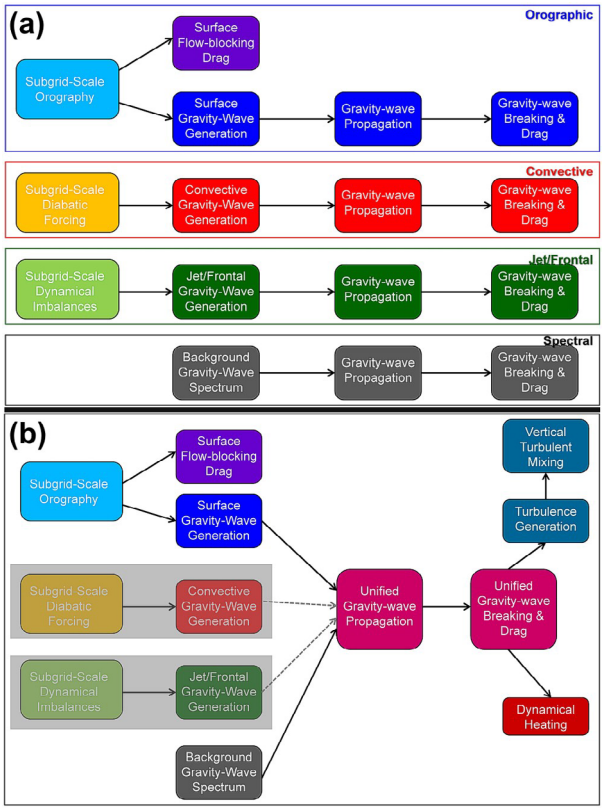

Figure 1. Diagram depicting our unification of physical mechanisms within the inaugural NAVGEM gravity-wave drag code. Panel (a) shows the separate parameterizations of gravity-wave drag due to flow across subgrid-scale orography (blue), deep subgridscale convection (red), jet/frontal instabilities (green), and indistinct wave sources producing a background spectrum of waves (gray), as existed prior to this work. Panel (b) shows the new unified scheme with common modules for wave propagation and breaking. Note also the additional physics of turbulence generation and mixing, and dynamical wave heating. See text for further details.

based on simplifications to the governing exact integral relations, leading to compact schemes for implementation into existing parameterizations to address objective (b). We will run the Navy global models using the new NAVGEM unified gravity-wave drag scheme (see Figure 1b) to assess its performance in Navy models to address objective (c), with some of these runs focused on the DEEPWAVE period of May-July 2014 to address objective (d).

WORK COMPLETED

The following tasks were performed this year:

- We completed an initial study of the effects of horizontal geometrical spreading on wave amplitude evolution with height, new work which led to 3 separate publications submitted to the peer-reviewed scientific literature (Eckermann et al. 2014a 2014b; Knight et al. 2014).
- We continued numerical and theoretical work to extend the results above to elliptical obstacles with principal axes aligned at arbitrary angles to the incident upstream flow.

- We implemented the new unified gravity-wave drag into a Navy global forecast model being developed as a working prototype for a high-altitude seasonal prediction capability, and used it with other model changes to generate for the first time a realistic quasi-biennial oscillation (QBO) of the tropical lower stratosphere, work that led to another peer-reviewed journal publication (McCormack et al. 2014).
- We transitioned the current version of the unified gravity-wave drag parameterization (Figure 1b) into NAVGEM version control and began tuning and sensitivity tests of a preoperational T425L60 configuration.

RESULTS

Work this year led to major new results on the heretofore ignored process of horizontal geometrical spreading in orographic gravity-wave drag parameterization. This physical process refers to the horizontal group propagation of three-dimensional gravity waves away from isolated orography into progressively larger spatial volumes. Via conservation of wave action, this process should be accompanied by corresponding decreases in the local wave action density (and hence local wave amplitudes). This important and fundamental physical property of three-dimensional wavefields is entirely absent from current parameterizations of gravity-wave drag, mainly because no one has been able to derive a sufficiently general closed-form analytical theory that quantifies its effects in ways amenable to a computationally cheap parameterization. This year we were able to develop such a theory for the first time and to test it against exact numerical results, work that led to three separate papers submitted to the peer-reviewed scientific lierature.

The first paper (Eckermann et al. 2014a) sets forth a numerical technique for isolating and quantifying this effect, based on the diagnosis of output from numerical Fourier-ray (FR) simulations of flow over three-dimensional elliptical obstacles of aspect ratio $\beta=b/a$, where a and b are lengths of the elliptical obstacle's principal axes parallel and orthogonal to the incident flow. A new Hilbert transform technique applied to the model output yielded local estimates of wavefield amplitudes (with phase removed) at each model gridpoint. Maximum amplitudes at each height were located and stored since these regions of the wavefield are most likely to break and generate drag.

Vertical profiles were studied as a function of both obstacle β and upstream wind speed U and stability N^2, and showed some unexpected and remarkable properties. The curves showed almost no sensitivity to the precise mathematical form (shape) of the three-dimensional obstacle, showing only a strong dependence on β. Furthermore, even though the curves varied with $U(z)$ and $N(z)$, when we replotted them using a normalized height (phase) variable

$$z' = \int_0^z \left[\frac{N(\tilde{z})}{U(\tilde{z})}\right] d\tilde{z} \ , \qquad (1)$$

they all collapsed onto a common curve of universal form for a given atmospheric state parameter.

These features motivated theoretical studies (Eckermann et al. 2014b; Knight et al. 2014) to derive these properties from a first principles analysis of the fluid dynamical equations. We began with exact FR transform equations, then sought relevant simplifications for dominant amplitude responses directly above (or very close to) the mountain. Two separate simplifications each led to analytical solutions: (1) a so-called "small-l" (sl) approximation that assumes cross-flow horizontal wavenumbers l are very much smaller in magnitude than along-flow wavenumbers k, and (2) a "single-k" (sk) approximation

that assumes the wavefield response is dominated by a single along-flow horizontal wavenumber k of the order of the cross-flow width of the obstacle a, such that $k \approx 1/(\gamma a)$ where γ is a constant of order unity. A detailed algebraic derivation outlined in Eckermann et al. (2014b) yields the following small-l and single-k analytical profile solutions for wave-induced vertical displacement oscillations η:

$$a_\eta^{sl}(z') = h_m G_\eta(z') e^{-iz'(1-1/2\beta^2)} \operatorname{erfc}\left[\left(\frac{z'}{\beta^2}\right)^{1/2} \frac{(1+i)}{2}\right], \tag{2}$$

$$a_\eta^{sk}(z') = \frac{h_m G_\eta(z') e^{-iz'}}{\left(\frac{2iz'\gamma^2}{\beta^2}+1\right)^{1/2}}, \tag{3}$$

where $G_\eta(z')$ is the vertical geometrical spreading contribution for η, and erfc is the complementary error function. These solutions revealed excellent agreement with numerical FR results at almost all altitudes and β values and reproduced key properties of these curves, including a universal profile form when regridded to a normalized z' height variable in (1), strong dependence on β but weak dependence on orographic functional form, and an asymptotic $z^{-1/2}$ dependence at large z. Since the relations (2) and (3) can be added into existing OMD parameterizations in a very straightforward way, yet capture for the first time an important and previously missing physical process, we believe these analytical solutions represent a major breakthrough in OMD parameterization coming out of this research.

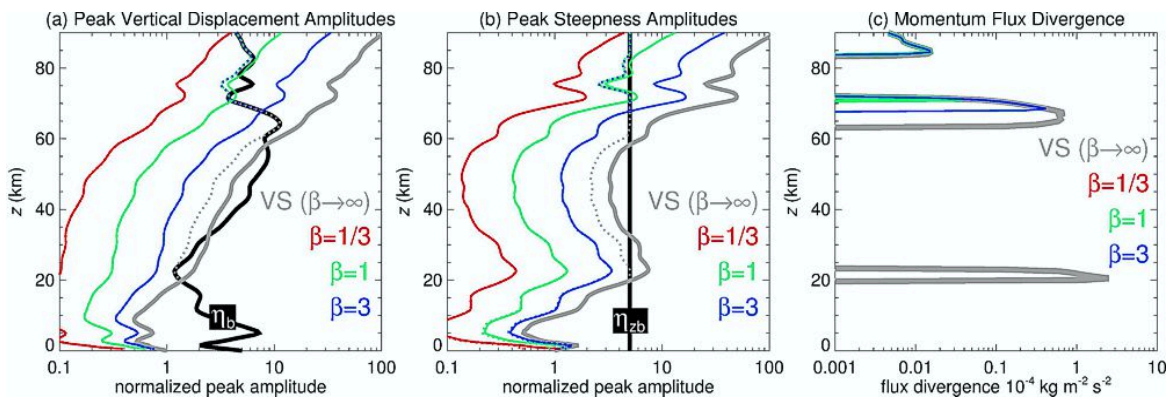

Figure 2. Profiles of (a) normalized vertical displacement amplitudes and (b) normalized steepness amplitudes for β=1/3 (red), β=1 (green), β=3 (blue), and β→∞ (gray). Black curve shows nominal wavebreaking amplitude and dotted curves show amplitude profiles after imposition of wavebreaking via linear saturation. Resulting drag profiles due to breaking are plotted in (c). See Eckermann et al. (2014b) for more information.

Figure 2, taken from Eckermann et al. (2014b), shows the impacts for parameterization. The left two panels show wave-induced vertical displacement and steepness amplitudes from geophysical $U(z)$ and $N^2(z)$ profiles from 0-90 km altitude taken from a Navy analysis. The black curve shows a nominal maximum amplitude above which wavebreaking occurs. The gray curves for β→∞ are the results without geometrical spreading that are included in all current parameterizations, while the red, green and blue curves show the actual vertical variations of wave amplitude that occur with horizontal geometrical spreading included for flow over obstacles of β=1/3 (red), β=1 (green), and β=3 (blue). Note the huge resulting differences in predicted drag in Figure 2c, with the unspread (gray) solution showing a large spurious burst of drag at z=20 km that is absent from the corrected solutions that

incorporate spreading. Indeed, many current parameterizations artificially reduce drag in the lower stratosphere to reduce model errors caused by excessive parameterized lower stratospheric gravity-wave drag, which our results suggest is an ad hoc fix for the missing physics of horizontal geometrical spreading.

QBO Generation in a Navy Global Model for Seasonal Prediction

The unified gravity-wave drag parameterization (Figure 1b) has now been implemented in Navy models and we have begun to use it to see if we can generate key circulations critical to providing seasonal prediction capabilities to these models, a task related to the concurrent ONR Seasonal Prediction DRI. As a step towards NAVGEM, we began tests in an antecedent high-altitude version of the NOGAPS global model known as NOGAPS-ALPHA to see what changes were needed to generate and maintain a quasi-biennial oscillation (QBO) in the tropical lower stratosphere. The major changes needed to generate a QBO involved adding a new tropical wave spectrum to the parameterization and tuning the model to be less numerically diffusive. Figure 3 shows that for the first time we can generate and maintain a realistic QBO in Navy models thanks to the implementation of the new unified gravity-wave drag parameterization developed under this project. This QBO modeling and prediction work has been written up and submitted for publication to the peer-reviewed scientific literature (McCormack et al. 2014).

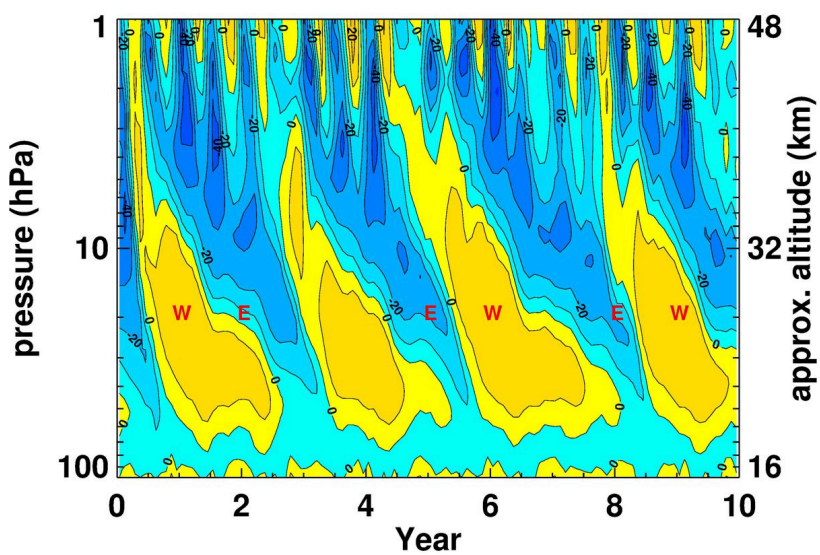

Figure 3. Monthly zonal mean zonal winds (m s^{-1}) over the equator as a function of height (pressure) and time (years) from a 10-year free-running Navy global model simulation using the unified gravity-wave drag parameterization, revealing a realistic model-generated QBO (see McCormack et al. 2014 for details).

IMPACT/APPLICATIONS

The new unified gravity-wave drag parameterization has transitioned to NAVGEM (see below) and is providing key new prediction capabilities for Navy global models (see Figure 3). McCormack et al. (2014) show that the new QBO prediction capability in Figure 3 yields additional realistic teleconnections among the tropical stratosphere and Arctic winter stratosphere and troposphere that are

critical to long-term seasonal predictions of key Arctic parameters, such as sea ice, thereby directly impacting the Navy's need for accurate future seasonal prediction systems.

TRANSITIONS

The new unified gravity-wave drag parameterization code has transitioned into the NAVGEM development branch, and is now fully available for use by all NRL researchers and developers of the NAVGEM code. Pre-operational testing of the scheme for future FNMOC transitions are planned in FY15 using a new NAVGEM T425L60 configuration.

RELATED PROJECTS

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Eckermann, S. D., et al., Capturing the Stratosphere's Influence on Seasonal and Intraseasonal Predictability in a State-of-the-Art Navy Global Environmental Model (NAVGEM), ONR DRI on Predictability of Seasonal and Intraseasonal Oscillations, Award No. N0001412WX21321, 1 October 2011-30 September 2014.

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Knight, H., D. Broutman, and S. D. Eckermann (2014), Integral expressions for mountain wave steepness, Wave Motion, in review.

McCormack, J. P., S. D. Eckermann, and T. F. Hogan (2014), Generation of a quasi-biennial oscillation in an NWP model using a stochastic gravity wave drag parameterization, Mon. Wea. Rev., in review.

HONORS/AWARDS/PRIZES

1. Stephen Eckermann was awarded the 2013 Sigma-Xi Award for Applied Science from the NRL Edison Chapter for foundational contributions to the Navy's high-altitude forecasting and analysis capabilities

2. Stephen Eckermann was awarded the 2013 American Meteorological Society's Editor's Award of the Journal of the Atmospheric Sciences for "thorough and detailed reviews with well-informed, well-posed and carefully argued questions for authors": see http://www.ametsoc.org/awards/2013awardrecipients.pdf

3. Stephen Eckermann was one of ten NRL awardees of the Navy Acquisition Excellence Award for Technology Transition, for the Navy Global Environmental Model (NAVGEM): see http://www.nrl.navy.mil/media/news-releases/2013/nrl-receives-navy-acquisition-excellence-award-for-global-weather-prediction-model