*DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.*

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

Stephen D. Eckermann
Geospace Science & Technology Branch
Code 7631, Space Science Division
Naval Research Laboratory
Washington, DC 20375
Phone: (202) 404-1299 Fax: (202) 404-7997 email: stephen.eckermann@nrl.navy.mil

Award Number: N0001411WX21220
http://www.nrl.navy.mil/ssd/

## 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 as well as gravity-wave drag from unresolved nonorographic sources. 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 a new unified parameterization of orographic and nonorographic gravity-wave and flow-blocking drag within Navy NWCP systems, and (c) to investigate whether improved time-mean drag and new explicit variability can improve NCWP skill in Navy global NWCP systems across a range of scales.

## OBJECTIVES

The objectives of this project were to (1) understand fundamental physical processes relevant to the parameterization of OMD and both orographic and nonorographic gravity-wave drag, (2) develop compact efficient accurate descriptions of these processes amenable to implemetation within existing or new parameterizations, (3) implement these new research results within a new unified gravity-wave drag parameterizations to be transitioned into NAVGEM, and (4) validate the OMD parameterization predictions using independent measurements and modeling results.

## APPROACH

Our original approach is summarized in detail in the original proposal. However our initial research into Objective (1) identified an unanticipated fundamental physical processes that was (a) missing from all existing parameterizations and (b) exerted a first-order influence on the vertical variation of

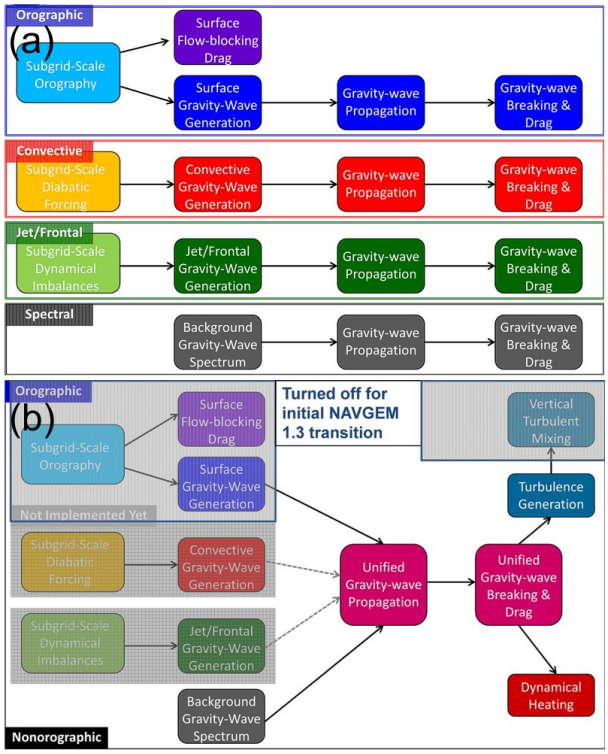


***Figure 1. Diagram depicting our unification of physical mechanisms within inaugural NAVGEM gravity-wave drag parameterization. Panel (a) shows the separate parameterizations of gravity-wave drag due to flow across subgrid-scale orography (blue), deep subgridscale convection (red), jet/frontal instabilities (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. Gray regions were deactivated for initial NAVGEM 1.3 transition. See text for further details.***

gravity-wave amplitude with height, and hence the location and amount of breaking and drag at any given level. This process is the horizontal geometrical spreading of gravity-wave action into progressively larger spatial volumes, which leads in turn, via the principle of wave-action conservation, to corresponding reductions in local wave-action densities and hence the local wave amplitudes that are critical for defining thresholds for the onset of wave breaking and the amount of flux deposition and drag on the atmosphere. This realization motivated us to conduct detailed research into the nature of geometrical spreading across the entire orographic parameter space relevant for OMD parameterization using Fourier-ray numerical simulations. These results, revealing large effects crucially relevant for parameterization, also revealed some surprisingly reproducible features that next motivated a theoretical analysis based on the simplified fluid dynamical equations to see if these findings could be reproduced and parameterized. This work led to a series of entirely new fundamental research results that have generated compact analytical relations ideal for implementation into parameterizations, thereby satisfying Objective (2) and providing a straightforward implementation pathway for Objective (3). Objective (3) was satisfied for nonorographic gravity-wave drag by generalizing the stochastic parameterization approach of Eckermann (2011) to provide a parameterization fast enough for operational use in NAVGEM, then implementing both the orographic and nonorographic within the new unified parameterization approach displayed in Figure 1b, which

used common (unified) parameterizations for wave propagation, breakdown, and resultant drag, dynamical heating and turbulent mixing.

## WORK COMPLETED

The project culiminated this year and work tasks addressing Objectives (1)-(4) were seen through to completion. The major final Navy deliverable, in addition to peer-reviewed publications cited below, was the first version of a new unified parameterization of OMD and gravity-wave drag that transitioned as part of the most recent NAVGEM 1.3 upgrade (Whitcomb et al. 2015; see Figure 1b).

## RESULTS

Here we summarize the major research deliverables of this project. More details on specific components can be found in the citations to the associated peer-reviewed scientific publication(s) and/or previous yearly research reports for this project.

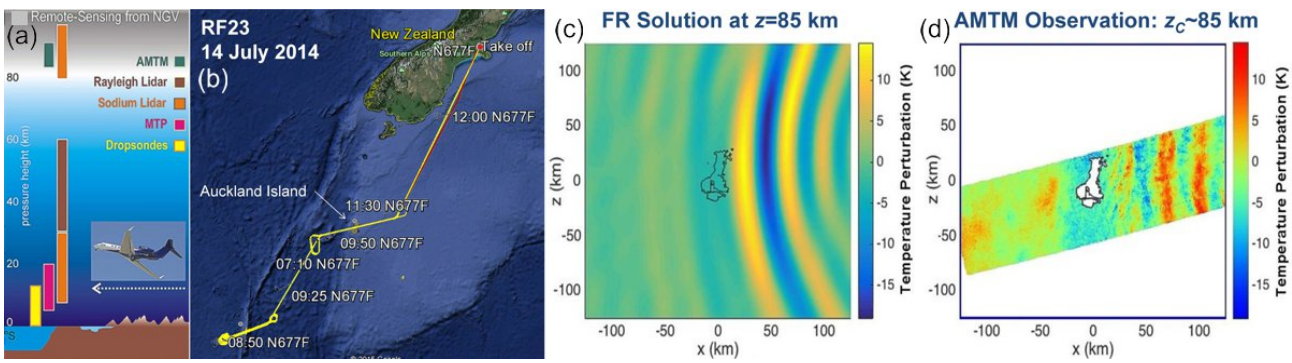


***Figure 2 (a) altitude ranges of NGV instruments, (b) NGV DEEPWAVE flight track for RF23 on 14 July 2014, (c) Fourier-ray simulation of this event as temperature perturbations, using analyzed winds and temperatures for 14 July 2014 at 0600 UTC from NAVGEM, and (d) observations from the AMTM on the NGV. See text for further details.***

- We completed the first ever detailed study of the form, effects and magnitude of horizontal geometrical spreading of three-dimensional (3D) wavefields on the evolution with height of local wavefield amplitudes and the transition to localized wave breaking leading to drag. This work involved a large ensemble of three-dimensional Fourier-ray numerical integrations and a novel Hilbert-transform-based diagnostic technique applied to the output for isolating peak wave amplitudes most prone to break in three-dimensional wavefields. Results were presented across the complete parameter space relevant to OMD parameterization, including functional dependences on upstream wind, stability, obstacle oritentation and obstacle elliptical axial ratios. The high relevance of this process to parameterizations was demonstrated by example (Eckermann et al. 2015a).

- Based on reproducible results emerging from the former study for which no theoretical explanations existed, we performed a follow-on study that tackled the problem from the perspective of simplified solutions to the linearized fluid equations. Using appropriate simplications, we are able to derive for the first time compact analytical solutions for the horizontal

geometrical spreading effects on wave amplitude evolution with height that reproduced many of the salient properties across the parameter space. For example, vertical profiles varied strongly as a function of the elliptical obstacles' 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] and also varied strongly with vertical variations in wind $U(z)$ and buoyancy frequency $N(z)$. Yet these curves collapsed onto common forms when replotted them using a normalized height (phase) variable

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

Our analytical solutions reproduced all these features, and further reinforced the first-order importance of these physical processes for drag parameterizations (Eckermann et al. 2015b).

- This analytical study produced a range of new analytical tools and results that led to a series of additional research spinoffs. One new result was a previously unappreciated singularity in standard three-dimensional mountain wave solutions near the ground for steepness, which is the vertical derivative of vertical wave-induced displacement and the key variable for determining when and where waves break and how strongly. We studied this singularity and identified it as a side effect of the Hilbert-transform-based approach to diagnosing peak wave amplitudes, and derived asympotic analytical solutions for the form of this singularity as $z \rightarrow 0$ which closely matched numerical results (Knight et al. 2015a).

- Another unanticipated spinoff from this work was some fundamental new insights into so-called stationary (or WKB) approximations to the three-dimensional wavefields coming out of the full numerical transform solutions to the problem. This work was motivated by local amplitude maxima in wavefields generated by winds incident at oblique angles to the major axes of an elliptical obstacle, identified in our earlier Fourier-ray numerical work. While the standard stationary phase method reproduces one of these local amplitude maxima that migrates downwind with increasing altitude, another type stays close to the vertical axis over the mountain peak where the standard stationary-phase solution is formally invalid. We derived a new generalized stationary phase solution to describe this additional local amplitude maximum, accommodating both vertical variations in wind and stability (Knight et al. 2015b).

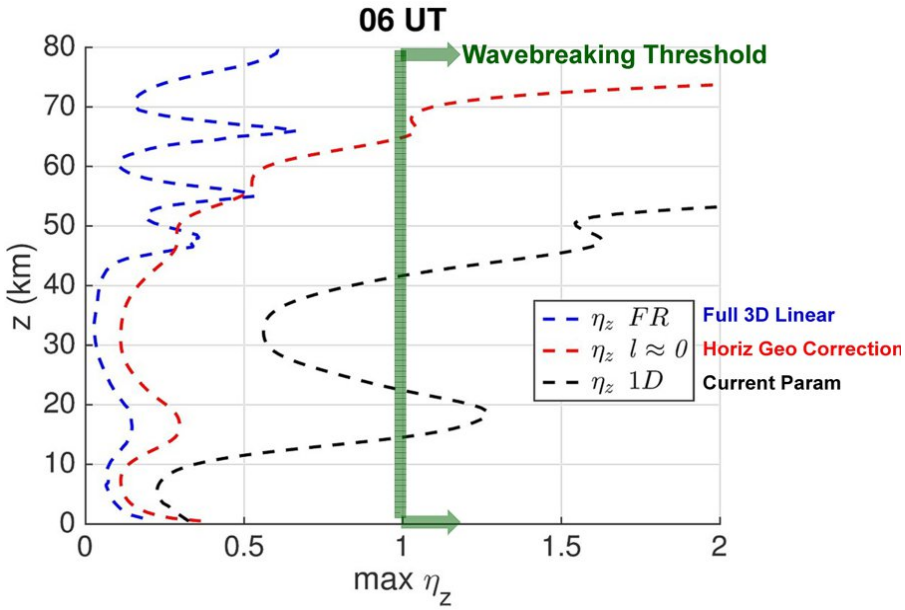


***Figure 3 OMD parameterization predictions for peak steepness amplitudes as function of height for wave event in Figure 2. Results are shown for current OMD parameterizations without geometrical spreading (black dashed), new OMD scheme with horizontal geometrical spreading included (red dashed) and full 3D integral solution (blue dashed). Green curve shows steepness breaking threshold (unity). See text for further details.***

- We developed an initial parameterization of these geometrical spreading effects based on the results of Eckermann et al. (2015b) and Knight et al. (2015b), then validated its predictions against observations of a deep mountain-wave event over Auckland Island during the NSF/NCAR/NRL Deep-Propagating Gravity-Wave Experiment (DEEPWAVE: Fritts et al. 2015). The instrument suite on the NSF/NCAR Gulfstream V (NGV) is illustrated in Figure 2a, and the flight track over Auckland Island during Research Flight #23 (RF23) on 14 July 2014 is illustrated in Figure 2b. Imagery from the Advanced Mesospheric Temperature Mapper (AMTM) instrument on the NGV (depicted in green in Figure 2a) is plotted in Figure 2d, and shows a large amplitude mountain wave immediately downstream of the island. Figure 2c shows a Fourier-ray simulation of this wave event using analysis winds and temperature from a high-altitude NAVGEM reanalysis run. These simulations and the observations reveal that this wave propagated largely unattentuated into the mesosphere and thus did not break until it reach an altitude of ~70-80 km, given the similarity to the AMTM observations from the NGV at ~80km in Figure 2d. We used these observations to test OMD parameterization predictions for this event, with results shown in Figure 3. The standard critierion for onset of wave breaking is shown as the green line, so wherever amplitudes exceed this threshold, wavebreaking is predicted to occur. Existing OMD parameterizations that omit horizontal geometrical spreading (black line) predict that this wave would break at ~20 km, in complete disagreement with these observations. Our new OMD parameterization that incorporates our new parameterization of horizontal geometrical spreading effects (red line) predicts wave breaking at 70 km. While this is still a little too low compared to observations and full 3D model simulations (blue curve), this is a substantial improvement over current parameterization predictions (Broutman et al. 2015).

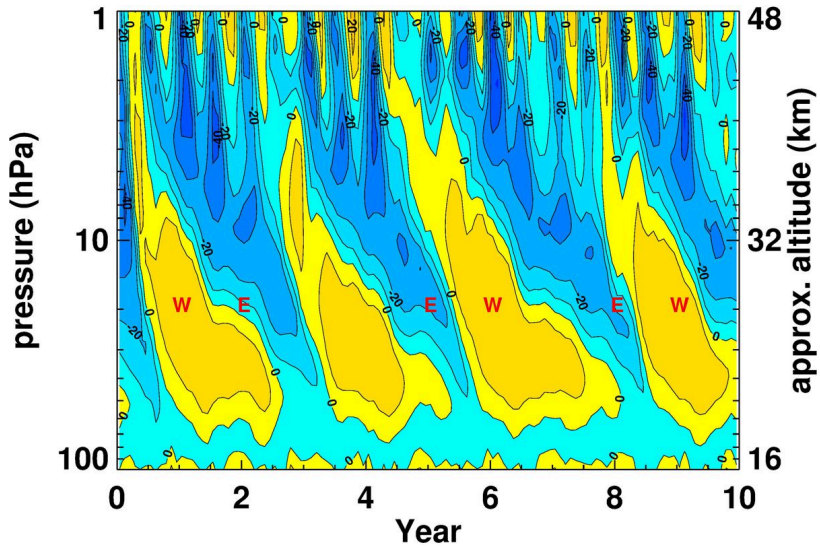


***Figure 4 Monthly zonal mean zonal winds (m s$^{-1}$) over the equator as a function of height (pressure) and time (years) from a 10-year free-running Navy global model simulation using the unified gravity-wave drag parameterization, revealing a realistic model-generated QBO (see McCormack et al. 2015 for details).***

- The nonorographic gravity-wave component was optimized using the fast stochastic parameterization methodology set out by Eckermann (2011). Both the new nonorographic and orographic components were then combined into a new unified gravity-wave drag parameterization, depicted in Figure 1b, in which common physics modules are shared for efficiency. The first version of this unified scheme was implemented into NAVGEM for the first time as part of the NAVGEM 1.3 operational transition, as documented in section 2.13 of the Validation Test Report of Whitcomb et al. (2015). For this initial transition the new OMD component was deacivated until detailed tests against the current standalome OMD parameterization can be performed to assess its suitability for use in future NAVGEM operational transitions. Nonetheless the unified infrastructure is now a part of NAVGEM and can be successively augmented in future transitions as needed.

- As an example, work with this new unified scheme focused on changes to the parameterized spectrum of tropical gravity waves, leading for the first time to a self-generated realistic quasi-biennial oscillation (QBO) in a Navy global forecast model, as shown in Figure 4. The ability to generate and sustain a realistic QBO is due to the new physics provided by the unified gravity-wave-drag parameterization in Figure 1b (McCormack et al. 2015).

## IMPACT/APPLICATIONS

The new unified gravity-wave drag parameterization has transitioned into NAVGEM as part of the recent NAVGEM 1.3 operational update (Whitcomb et al. 2015) and is providing key new prediction capabilities for Navy global models (see Figures 3 and 4). For example McCormack et al. (2015) show that the new QBO prediction capability in Figure 4 yields additional new 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 as part of the Earth System Prediction Capability initiative.

## TRANSITIONS

The new unified gravity-wave drag parameterization code has transitioned into the NAVGEM as part of the operation NAVGEM 1.3 update, as documented in Whitcomb et al. (2015).

## RELATED PROJECTS

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

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.

## REFERENCES/PUBLICATIONS


Broutman, D., and S. D. Eckermann (2012), Analysis of a ray-tracing model for gravity waves generated by tropospheric convection, J. Geophys. Res., 117, D05132, doi:10.1029/2011JD016975.

Broutman, D., J. Ma, and S. D. Eckermann (2015), The Fourier modeling of mountain waves generated by Auckland Island during the Deep-Propagating Gravity-Wave Experiment (DEEPWAVE). J. Atmos. Sci., in preparation.

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

Eckermann, S. D., J. Ma and D. Broutman (2015a), Effects of horizontal geometrical spreading on the parameterization of orographic gravity-wave drag. Part 1: Numerical transform solutions, J. Atmos. Sci., 72, 2330-2347, doi:10.1175/JAS-D-14-0147.1.

Eckermann, S. D., D. Broutman and H. Knight (2015b), Effects of horizontal geometrical spreading on the parameterization of orographic gravity-wave drag. Part 2: Analytical solutions, J. Atmos. Sci., 72, 2348-2365, doi:10.1175/JAS-D-14-0148.1.

Fritts, D. C., R. B. Smith, M. J. Taylor, J. D. Doyle, S. D. Eckermann, A. Dörnbrack, M. Rapp, B. P. Williams, P.-D. Pautet, K. Bossert, N. R. Criddle, C. A. Reynolds, P. A. Reinecke, M. Uddstrom, M. J. Revell, R. Turner, B. Kaifler, J. S. Wagner, T. Mixa, C. G. Kruse, A. D. Nugent, C. D. Watson, S. Gisinger, S. M. Smith, J. J. Moore, W. O. Brown, J. A. Haggerty, A. Rockwell, G. J. Stossmeister, S. F. Williams, G. Hernandez, D. J. Murphy, A. R. Klekociuk, I. M. Reid, and J. Ma (2015), The Deep Propagating Gravity Wave Experiment (DEEPWAVE): An airborne and ground-based exploration of gravity wave propagation and effects from their sources throughout the lower and middle atmosphere, Bull. Am. Meteorol. Soc., doi:10.1175/BAMS-D-14-00269.1, in press.

Knight, H., D. Broutman, and S. D. Eckermann (2015a), Integral expressions for mountain wave steepness, Wave Motion, 56, 1-13, doi:10.1016/j.wavemoti.2015.01.003.

Knight, H., D. Broutman, and S. D. Eckermann (2015b), Generalized stationary phase approximations for mountain waves, Phys. Fluids, submitted.

McCormack, J. P., S. D. Eckermann, and T. F. Hogan (2015), Generation of a quasi-biennial oscillation in an NWP model using a stochastic gravity wave drag parameterization, Mon. Wea. Rev., 43, 2121-2147, doi:10.1175/MWR-D-14-00208.1.

Whitcomb, T., W. Clune, T. Hogan, R. Pauley, B. Ruston, C. Skupniewicz, S. Eckermann, T. Maurer, J. McCormack, E. J. Metzger, J. Moskaitis, G. Poe, J. Ridout, P. Shen, S. Swadley, K. Viner, and A. Ulina (2015), Validation Test Report for the Navy Global Environmental Model (NAVGEM) 1.3 System, Navy Atmospheric Models Oversight Panel, 65 pp, 3 March 2015.

**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