New Constraints on Parameterized Gravity Waves for Climate Model Applications: An International Collaborative Project

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ECHAM / Hines ↔ HIRDLS, SABER

INTRODUCTION

Gravity waves are parameterized in current climate models to control winds and to improve the realism of simulated:

A. Polar winds, temperatures, and ozone chemistry

B. Global winds, Rossby wave propagation, and teleconnection patterns

These processes are known to be important for seasonal, interannual, and regional climate simulation, and for simulation of stratospheric ozone effects on climate. Realism of the parameterizations remains only very loosely tied to observational constraints. New global measures of gravity wave momentum flux are compared here to several well established climate model parameterizations. The results presented here are a sample of preliminary results, with final results due to be completed by March 2011. This work is the result of an international collaboration facilitated by the International Space Science Institute in Bern, Switzerland and SPARC/WCRP. (See http://www.issibern.ch/teams/gravitywave/index.html)

BACKGROUND: Parameterizations

Climate model gravity wave parameterizations start with the specification of "wave stress" or pseudomomentum flux at a source location and source altitude. This source flux is constant with height for conservative wave propagation. Wave propagation is generally assumed to be instantaneous and purely vertical. Decreasing density with height, wind shear, and vertical gradients in static stability can conspire to cause waves to break or dissipate, and pseudomomentum flux is no longer constant. The subsequent divergence of the flux is proportional to the force on the mean flow.

Orographic Waves have their sources specified near the surface, and the source fluxes are tied to the subgridscale topographic variance. Propagation direction is upwind. The frequency and phase speed relative to the ground are zero, so any resulting force on the mean flow is always a drag force, slowing the wind speeds aloft.

Non-Orographic Waves are generally parameterized with a spectrum of phase speeds and frequencies, with source altitudes either in the lower troposphere or near the tropopause (in different models). Direction of propagation for the models below is specified as isotropic in azimuth at the source level. Non-orographic waves can alternately accelerate or decelerate the winds, always dragging the wind toward the phase speeds of the breaking waves.

OBSERVATIONS

Pseudomomentum flux and its vertical gradient provide the measure of wave activity necessary to diagnose the force that dissipating gravity waves exert on the mean flow. Using common assumptions, the Reynold's stress terms, that describe the covariance of horizontal and vertical wind multiplied by background density $\bar{\rho}(\overline{u'w'}, \overline{u'w'})$, provide a suitable estimate of pseudomomentum flux, and are commonly called the "momentum flux". Momentum flux is a vector quantity that requires high temporal and spatial resolution observations of the three-dimensional wind field to properly diagnose. Such observations are rare. Approximate methods using only horizontal winds and/or temperatures have been developed using linear gravity wave theory.

Methods using only temperature provide no directional information. Methods utilizing satellite data provide the needed global coverage, but tend to be low biased because of the unknown propagation direction relative to the line along which the horizontal wavelength is measured.

TABLE 1: Data sets to be used in the comparisons

Data Source	Analysis Method
Vorcore Super-pressure balloon winds	Hertzog et al. [2008]
HIRDLS-Aura Satellite Temperatures	Alexander et al. [2008]
HIRDLS-Aura Satellite Temperatures	Ern et al. [2010]
SABER-TIMED Satellite Temperatures	Ern et al. [2010]
High-Res. Radiosonde Winds & Temperatures	Gong et al. [2008]
AIRS-Aqua Satellite Brightness Temperatures	Alexander et al. [2009]

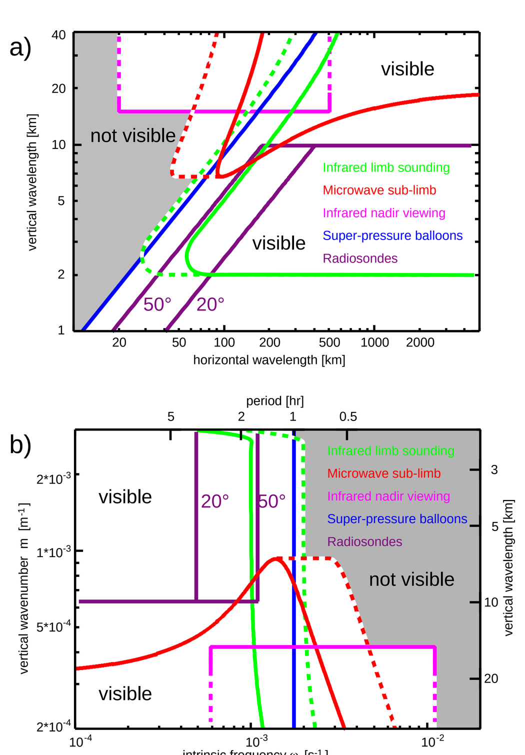

FIGURE 1:

- Each method is also limited by temporal and spatial resolution issues to detecting and quantifying flux from a certain portion of the full gravity wave spectrum.
- Typical visibility limits as function of horizontal and vertical wavenumber (top) and frequency/vertical waveneumber (bottom) for various satellite and balloon measurement techniques.
- Shaded regions are not visible to any current techniques.
- See also Preusse et al. [2008], Alexander et al. [2010].

MODELS

Three atmospheric climate models are included in the intercomparison. Each utilizes a unique set of gravity wave parameterization methods. The models were run with specified sea-surface temperatures based on measurements from the three-year period 2005-2007. Interannual variability associated with sudden stratospheric warmings at high latitudes and the quasibiennial oscillation in the tropics differ among the models. Such changes in the winds affect gravity wave propagation and momentum fluxes. Examination of the three years provides some measure of these differences.

TABLE 2: Climate models to be used in the comparisons

Model/Institution	Published Description	Orographic Param.	Non-Oro. Param.
Model-E/NASA-GISS	Geller et al. [2011]	McFarlane '87	Alexander & Dunkerton '99
ECHAM-5/Max Planck	Manzini et al. [2006]	Lott & Miller '97	Hines et al. '97
HadGEM-3/Met Office	Walters et al. [2011]	Webster et al. '03	Warner & McIntyre '01

Resolved gravity waves in two additional models run at high resolutions are included in the comparisons (Table 3). Absolute momentum fluxes from these models are estimated from the horizontal and vertical kinetic energies $[(u'^2 + v'^2) \cdot w'^2]^{1/2}$.

TABLE 3: High-resolution gravity-wave-resolving climate models.

Model/Institution	Published Description	Resolution	Minimum wavelength
Kanto Model/U Tokyo	Watanabe et al. [2008]	T179	180 km
CAM-5/NCAR	Bacmeister et al. [2011]	0.25°×0.31°	~250 km

GEOGRAPHIC VARIATIONS MOMENTUM FLUX

The lower stratosphere is the best location for comparing momentum fluxes. From an observational standpoint, altitudes above clouds allow infrared satellite measurement. Perturbations observed at these levels can more safely be assumed to be associated with freely propagating waves. From a modeling standpoint, the lower stratosphere is generally below the altitude of direct gravity wave forcing.

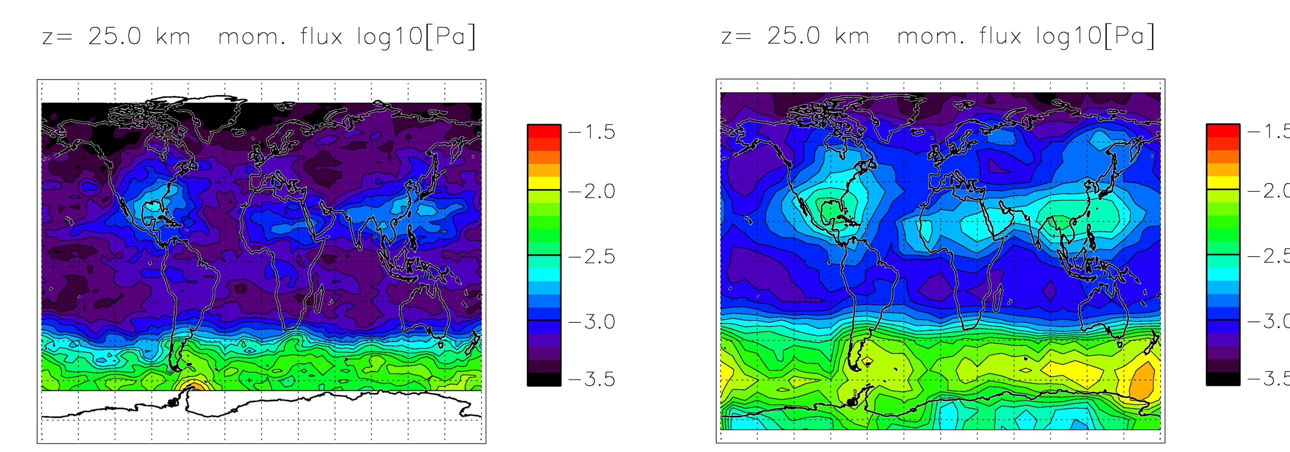

FIGURE 2: Absolute momentum fluxes derived from HIRDLS (left) and SABER (right) at 25 km altitude for July 2006. Units are log(Pa): -3.0=1mPa.

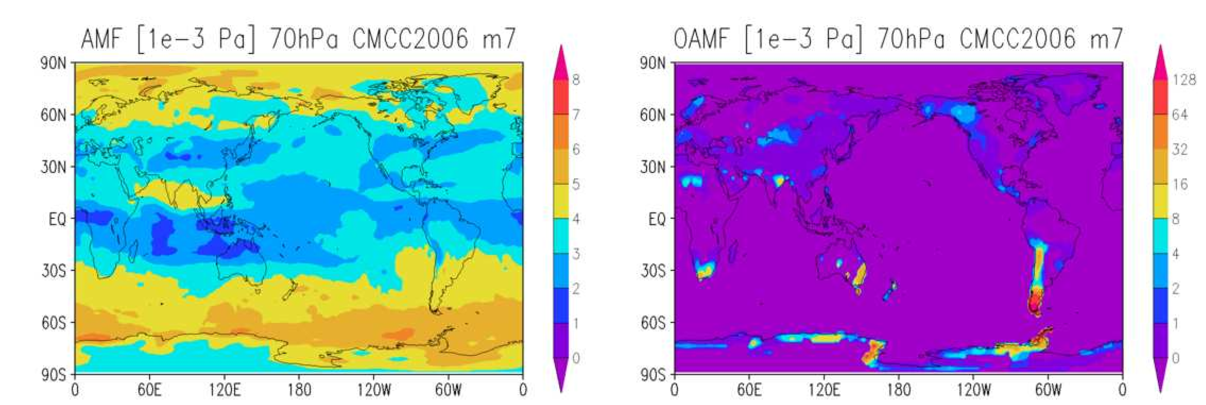

FIGURE 4: Absolute momentum flux for the July 2006 ECHAM simulation at 70 hPa (~20 km). Nonorographic (left) and orographic (right) fluxes in mPa.

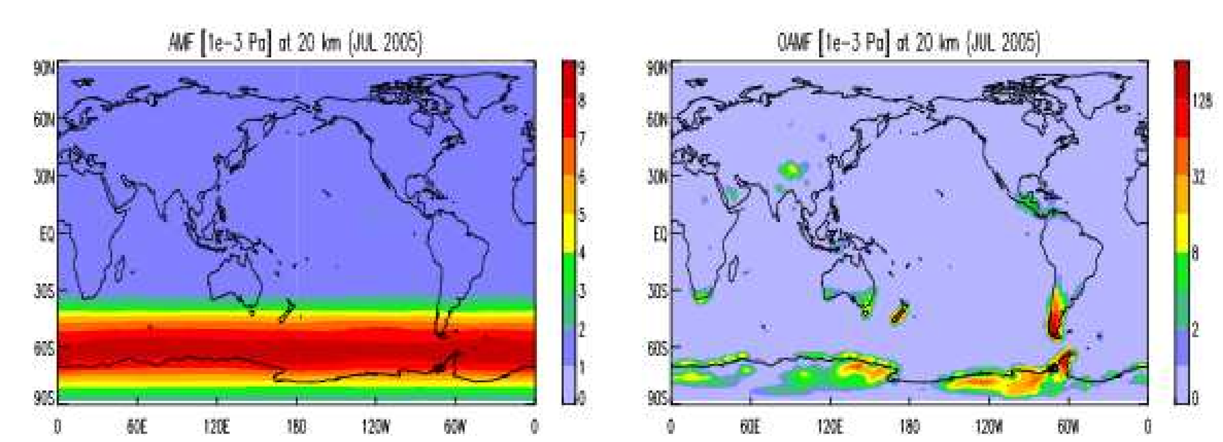

FIGURE 5: Absolute momentum flux for the July 2005 GISS Model-E simulation at 20 km. Nonorographic (left) and orographic (right) fluxes in mPa.

Peak orographic wave fluxes in the models are much larger than observed. However, observations do not yet resolve many of the smaller-scale orographic waves that may carry significant fluxes [Alexander and Teitelbaum, 2011]. Models parameterize larger peak orographic fluxes but over smaller areas than indicated in the observations. Larger-scale gravity waves propagate significant horizontal distances, a process neglected in the parameterizations [Preusse et al., 2002]. This horizontal propagation could explain part of the difference in the localization and peak values seen in the models and observations.

Modelled non-orographic wave fluxes tend to have very simple geographic distributions because of the simplifying assumptions made about sources. Observations cannot easily separate orographic from non-orographic wave fluxes. Island sources can contribute to fluxes over the Southern Ocean [Alexander et al. 2009], while mountain waves can propagate horizontally away from topographic sources [Sato et al., 2011].

ZONAL MEAN MOMENTUM FLUXES and MOMENTUM FLUX VARIATIONS WITH ALTITUDE

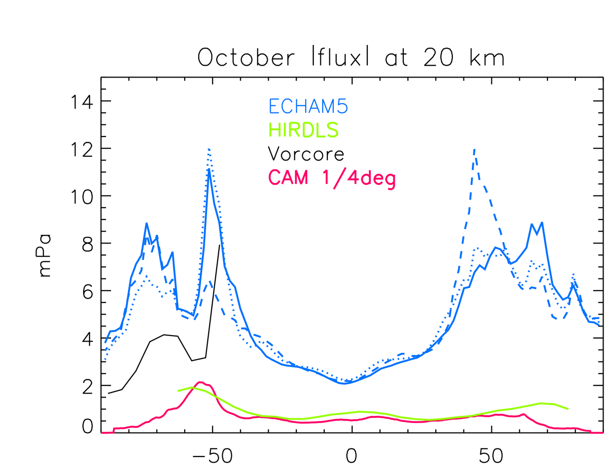

FIGURE 6:
October zonal mean absolute momentum fluxes derived from observations and models. Black: Vorcore balloons 2005. Green: HIRDLS 2005. Red: CAM high-resolution model. Blue: ECHAM 5 orographic plus nonorographic (3 years shown with solid, dashed, and dotted lines to illustrate interannual variability).

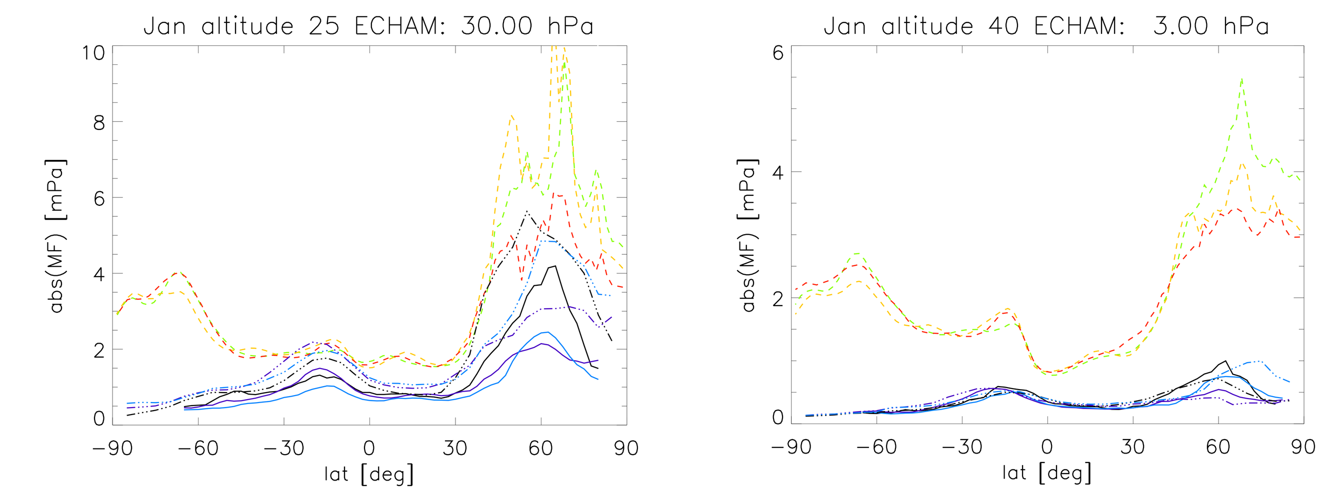

FIGURE 7: Comparisons of HIRDLS, SABER, and parameterized ECHAM momentum fluxes in January at two altitudes: 25 km (left) and 40 km (right). Changes in flux with altitude are loosely related to the gravity wave force on the circulation. Dashed: ECHAM (2005-2007). Dot-dashed: SABER (2006-2008). Solid: HIRDLS (2006-2008).

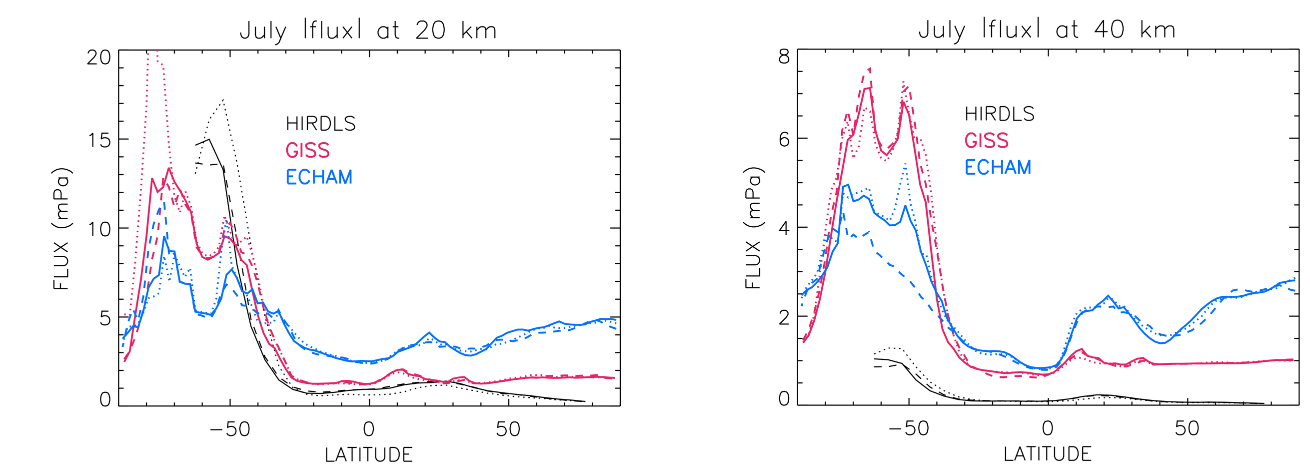

FIGURE 8: Comparisons of HIRDLS and parameterized ECHAM and GISS model momentum fluxes in July at two altitudes: 20 km (left) and 40 km (right). Different line styles show years 2005-2007 to illustrate interannual variability. Blue: ECHAM. Red: GISS. Black: HIRDLS.

CONCLUSIONS

- Some horizontal spreading of mountain wave fluxes is indicated by the observations, however the observations do not yet resolve the smallest-scale waves.
- Non-orographic wave fluxes in the lower stratosphere are surprisingly similar among different models and observations.
- Preliminary examinations of the variation of the flux with altitude suggest the possibility that observations decay more rapidly, however, limitations in the gravity wave horizontal wavelengths that can be observed leave significant uncertainty in the interpretation of these changes.

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