The Gravity Wave Project

A Proposed International Team for Merging Space- and Ground-based Observational Constraints for Gravity Wave Parameterizations in Climate Models

Abstract:

Gravity waves, sometimes called buoyancy waves, have dramatic effects on the circulation in planetary atmospheres through the wave drag and diffusion they induce.[1–6] Because they have small scales compared to the resolution in global models, these effects are parameterized. The importance of including parameterized wave drag has long been recognized as critical to weather prediction,[7,8] and now researchers are demonstrating new sensitivities to gravity wave drag in simulations of Earth's climate that incorporate trends in greenhouse gases and ozone-depleting chemicals.[9–11] Modelers using the parameterizations must set numerous poorly constrained parameters that describe wave propagation properties and amplitudes. Key to accurate parameterization of the wave drag is knowledge of the spectrum of wave momentum flux as a function of wave phase speeds and wavenumbers.[12–14]

Global constraints on wave momentum flux are needed that can only come from satellite observations. Gravity wave scales are small compared to typical satellite measurement footprints, yet in the last 15 years detection of atmospheric gravity waves in satellite data are becoming more common.[15,16] Determination of wave momentum flux from these observations places special demands on the measurements that have only been met with some of the more recent data using innovative analysis techniques.[17–19] The waves must not only be detected but fully resolved, and their three-dimensional structure must be characterized. Satellite measurements and analysis methods now exist to characterize a large fraction of the spectrum of wave momentum flux. However, to realize the goal of defining global constraints sufficient for climate modeling requires merging of a collection of measurements from different techniques on different satellites with full characterization of the limitations of each technique[20] as well as the uncertainties.[21] Uncertainties in momentum flux using satellite measurements alone remain large (Figure 1), but cross-calibration among the various techniques along with ground-based balloon measurements can provide the constraints that will lead to dramatic changes in the way gravity wave parameterizations are used in global models. Instead of conducting poorly constrained and laborious tuning excercises, modelers will have a set of well-defined parameter ranges from which to choose.

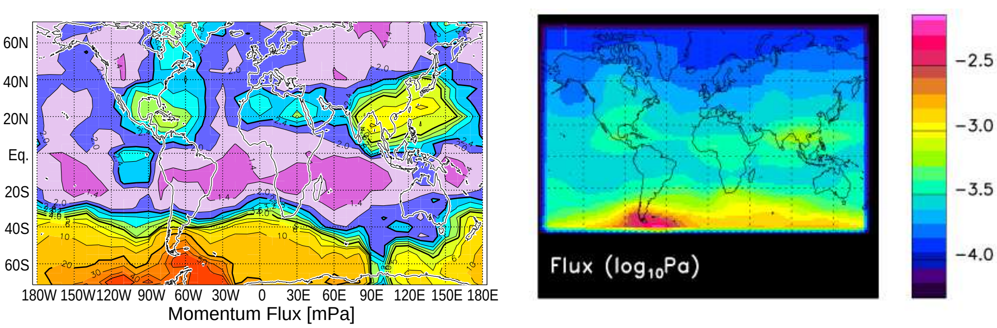

Figure 1. *Global maps of momentum flux estimated from satellite data during southern hemisphere winter season.*

Scientific Rationale:

- *The goal of our team's work will be to create a self-consistent global dataset of atmospheric gravity wave momentum fluxes and propagation properties for climate and weather forecasting applications.*

This will be accomplished with cross-calibration along with careful consideration of the limits and uncertainties involved in each of the relevant satellite and ground-based data sets. Our team includes the leading experts on the use of each of the relevant data sets for gravity wave studies. A collection of different gravity wave parameterizations are in use at different international modeling centers, and this means each parameterization requires specification of a slightly different set of input parameters.[22–24] Our team includes key members of the global modeling community who will ensure that the dataset we create will be in a readily useable form for modeling work.

Figure 1 above shows two example maps of momentum flux estimated from satellite data. Fluxes in the left panel are derived from CRISTA (Cryogenic Infrared Spectrometers and Telescopes of the Atmosphere)[18] with contours in 10^{-3}Pa. The right panel was derived from HIRDLS data (High Resolution Dynamics Limb Sounder)[19] with fluxes contoured as $\log_{10}$(Pa). Patterns are similar in the two estimates, but magnitudes differ by up to a factor of 10 because of differences in the treatment of the uncertainty in wave propagation direction.

Both CRISTA[25] and HIRDLS[26] were limb profiling instruments capable of measuring gravity wave temperature fluctuations at high vertical resolution and with close horizontal spacing between profiles. To convert wave temperature amplitude $\hat{T}$ to momentum flux F_M requires local measures of both the vertical λ_Z and horizontal λ_H wavelength.[18] Then,

$$F_M \propto (\lambda_Z/\lambda_H)\hat{T}^2. \tag{1}$$

The horizontal wavelength was estimated in these analyses using the change in phase $\Delta\phi$ between two closely spaced profiles separated by a distance Δr as $\lambda_r = 2\pi\Delta r/\Delta\phi$. λ_r here is the apparent horizontal wavelength along the line joining the two profiles. The true horizontal wavelength λ_H is that measured along the direction of wave propagation $\lambda_H = \lambda_r \cos\theta$ where θ is the angle between the line $\vec{r}$ joining the two profiles and the propagtion direction, which is unknown from the CRISTA and HIRDLS measurements. Since $\lambda_H \leq \lambda_r$, unknown propagation direction leads to a systematic underestimate in momentum flux.

Although there are numerous detailed differences between the CRISTA and HIRDLS measurements, the primary reason for discrepancies in the magnitude of momentum flux shown in Figure 1 is the treatment of uncertainty in horizontal wavelength. In the left panel, an attempt to account for latitudinal variations in the degree of overestimation of horizontal wavelength was made, however with the information available this correction could be considered little better than an educated guess. The right panel, in contrast, attempted no correction, reporting instead a reliably low limit on the momentum fluxes. Very recent measurements of latitudinal variations in propagation direction have been reported[27] using GPS (Global Positioning System) radio occultation measurements from low-earth orbiting satellites in the Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC)[28] that will greatly improve the correction factors for propagation direction applied to the momentum fluxes determined from CRISTA, HIRDLS, and other limb scanning techniques.

- *Through cooperation within the international team, our members can therefore correct the largest single uncertainty in current estimates of global momentum fluxes.*

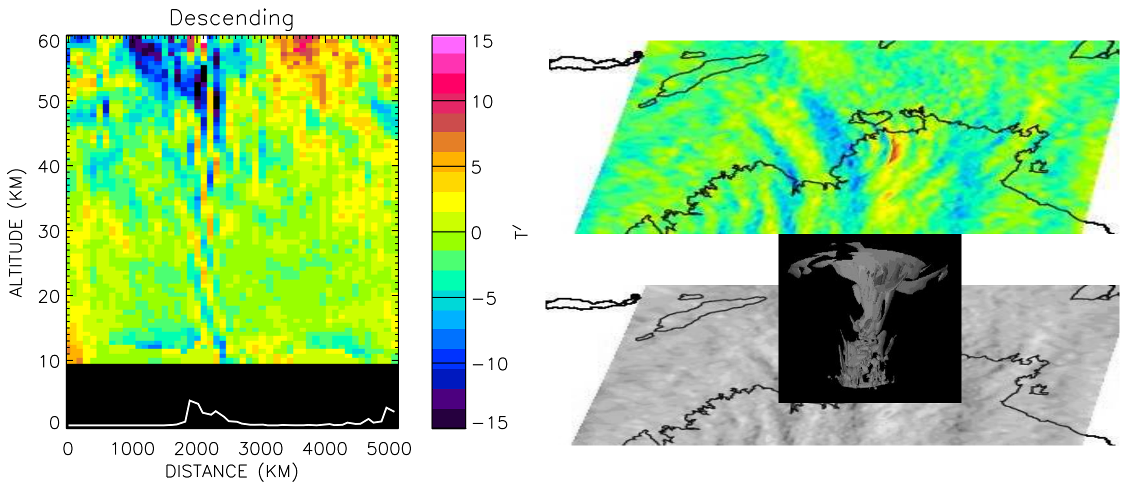

Figure 2. *The colors show satellite observations of wave temperature fluctuations in the atmosphere above the Andes mountains (left) and above a storm over Darwin, Australia (right).*

Figure 2 shows two samples of the high-resolution satellite measurements that are used by team members. HIRDLS temperature fluctuations in a mountain wave event are shown in vertical cross-section in the left panel. The white line shows the topography below the measurements. The color image on the right shows a sample of Atmospheric Infrared Sounder (AIRS) radiance fluctuations that show wave temperature fluctuations in an event emanating from an intense tropical storm. HIRDLS, a limb profiler, provides high vertical resolution of 1 km but only coarse horizontal resolution: 100 km separation between profiles along the measurement track and 24° longitude separation between measurement tracks at the equator. AIRS, in constrast, is a nadir imaging instrument that observes the horizontal structure of gravity waves in fine detail with horizontal resolution of 13.5 km at the nadir, however the information in the vertical is blurred by deep weighting functions. HIRDLS can observe short vertical wavelength waves that are invisible to AIRS, while AIRS can image horizontal wavelength *and* propagation direction that will either be invisble to HIRDLS or at best coarsely undersampled. These limitations on horizontal and vertical wavelength define the observational filter for each measurement technique.[20]

The limb scanning and nadir imaging measurements are generally complementary, observing different portions of the the total spectrum of gravity waves that are present in the atmosphere. Certain waves with both moderately long horizontal and vertical wavelengths can be observed by both instruments. Figure 3 shows a map of the coverage of the relevant satellite measurements in this horizontal and vertical wavelength space. Observational filter functions for each measurement technique have already been defined by individuals on our team.[21,29–32] These will be used to combine the various measurements into a self-consistent set. Momentum fluxes derived from each technique also have unique uncertainties that will be carefully considered.

In addition to CRISTA, HIRDLS, AIRS and COSMIC/GPS, important measurements in the microwave from the Advanced Microwave Sounding Unit (AMSU) provide improved local time coverage compared to the other high-inclination orbiting satellite techniques.[33] Crucial calibration of the satellite momentum fluxes comes from balloon-borne measurements including high-resolution radiosondes that are launched from sites all over the world[34–36] and long-duration Lagrangian drift balloons that can complete multiple circuits of the globe before descent.[31] These balloon-borne measurements also provide direct determination of wave intrinsic frequencies, the frequencies measured by an observer moving with the wind, which allow estimation of momentum fluxes using very different means, and an independent test of the theory behind equation (1).

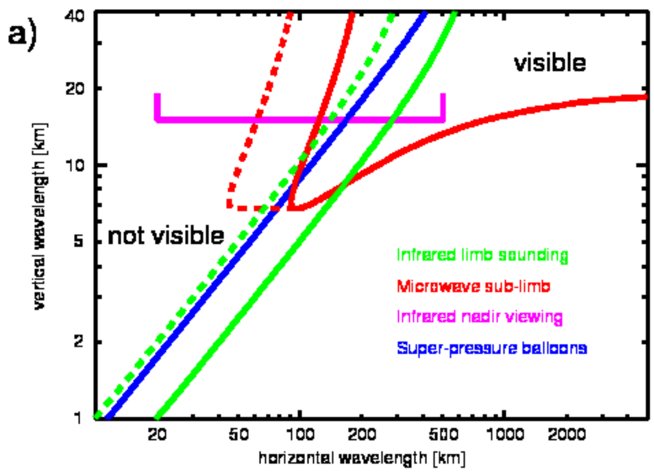

Figure 3. *Map of the sensitivity of different measurement techniques in horizontal and vertical wavelength space. Only a small region at short vertical and horizontal wavelength is not visible. Waves with horizontal wavelengths shorter than 30-km are easily trapped at low altitudes through the process of total internal reflection.*[37]

Expected output:

We envision each team member will contribute to a set of six to nine individual-led peer-reviewed articles, possibly published as a special journal collection. The articles will describe our coordinated efforts to constrain the global distribution and seasonal variations of gravity wave momentum flux in the stratosphere, to quantify the uncertainties, and to explain carefully what portion of the spectrum is included and what is missing.

We also plan to upload the merged data to the Data Center (http://www.sparc.sunysb.edu) for the World Climate Research Programme's SPARC Project (Stratospheric Processes & their Role in Climate) for broad access, and to publish a summary of the merged data sets as a SPARC report. Team Leader Alexander is currently coordinator for a SPARC gravity wave focus group, and Member Geller has maintained the Data Center.

What special value does ISSI provide?

ISSI provides a central location and comfortable meeting facilities where the international team members can address and work through the technical details required to merge the various data sets contributing to the combined global constraints. ISSI's original mandate was that of "generating for relatively low cost more high-quality science from the projects conducted by the various space agencies." Our project fits this mandate exactly. We note that none of the space-based measurements we will be using were designed to observe small-scale atmospheric waves. Instead, innovative researchers, many of whom are on our team, found ways to extract this information from measurements designed for different purposes. Despite this handicap, the field has advanced considerably, and now ESA is considering a new mission with one of its primary goals the measurement of gravity wave momentum fluxes from space. The results of our project will set the standard for these proposed ESA measurements and may refine instrument specifications.

List of confirmed team members:

Joan Alexander (Team Leader, USA), Julio Bacmeister (USA), Stephen Eckermann (USA), Manfred Ern (Germany), Marvin Geller (USA), Albert Hertzog (France), Takeshi Horinouchi (Japan), Elisa Manzini (Italy), Peter Preusse (Germany), Kaoru Sato (Japan), Adam Scaife (UK), and Robert Vincent (Australia).

Our international team is comprised of twelve leading scientists from the US (four), Australia (one), Japan (two) and Europe (five), including Germany, France, Italy, and the UK. A short CV for each team member is appended.

- *The team brings leading expertise on all of the relevant satellite measurements plus crucial additional measurements needed for calibration, and members include experts from the global modeling community to ensure that the observational constraints we derive can be utilized at major modeling centers around the world.*

The broad expertise of our team members includes detailed knowledge of satellite instrumentation, dynamical theory, data analysis, and climate modeling. The problem we address demands the focused attention of this broad group to accomplish the goals. The best testimonial to both the urgent need for this project and the timeliness is that this broad-based team of world leaders on the subject have all enthusiastically agreed to participate.

Schedule of the project: We plan two 5-day face-to-face meetings in Bern. The first meeting will focus on details of the various data sets where we define the requirements for data analysis for the next phase. The second meeting will focus on cross-calibration and on the publications. The publications will likely be coauthored by several team members. This second meeting will provide valuable face time for developing/finishing these collaborative publications.

Tentative schedule: Meeting 1 in late winter-early spring 2010, duration 5 days; Meeting 2 in fall 2010 or spring 2011, duration 5 days; Journal article submissions in late spring 2011; Final report to ISSI in summer 2011.

Facilities required: We will require a meeting room with a large-table for seating 12-14 people. Participants will bring their own laptops. A computer projector and screen will be required and a black board/white board would be useful. Internet connection (preferably wireless) will be needed for all team members. Communication between members' laptops can be handled via the internet (email) and via portable storage media that individual members will bring. Coffee/Tea/Snacks for refreshment during the discussions and for breaks will also be needed.

Financial Support requested: We request per diem for 12 participants plus two additional young scientists (UK and Australia) that we hope to add to the team at a later date in accordance with the proposal guidelines. Per diem will be needed for 6-7 days for each participant for each of the two meetings. We also request round trip airfare for Dr. Vincent who is partially retired and will not be able to attend without travel support. (The Team Leader will defer her travel support.)

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