Atmospheric Gravity Waves in Global Climate Prediction and Weather Forecasting Applications

Abstract:

Improving the accuracy of climate prediction models has become a crucial activity for Earth scientists in the 21st century because of the profound social impacts of climate change. In particular, the role of stratospheric processes on climate have been highlighted in many recent studies. These include the effects of stratospheric dynamical processes on short term and seasonal forecasts at extratropical latitudes and decadal-scale changes in ozone on the Southern Hemisphere circulation, ocean currents, and carbon uptake.

With the acceptance of a well-resolved stratosphere for accurate seasonal and regional climate change descriptions in global models, a realistic treatment of gravity waves of all types is recognized as important both for climate and long-range weather forecasting applications. Two key needs for climate modelling in the present era are: (1) reducing model wind biases with improved estimates of gravity wave forces, and (2) improving methods for specifying gravity wave sources that are physically justifiable. We therefore will propose two workshops to focus on each of these two topics: Forces and Sources. The workshops will start with an examination of zonal mean forces and evolve to regional studies, with one focus on the tropics and tropical convection, and a second focus on the Southern Hemisphere's mountain and jet sources.

The modern era of satellite data observations wedded with modern data assimilation system tools are leading to exciting new methods for estimating gravity wave forces in the middle atmosphere, but the results are in their infancy, and are not yet influencing global modelling methods. Global models are also evolving at a rapid pace, with improvements in resolution that allow the direct simulation of a significant portion of the gravity wave spectrum, while other portions still unresolved are parameterized. However, a methodology for adjusting parameters with resolution is lacking. These developments are driving our study. Our team includes experts in data assimilation, global forecasting models, climate models and observational analyses. The team members will bring a wide variety of different model systems, methods, and observational analyses to ISSI for direct intercomparison. We expect two to three review papers to result from these ISSI workshops. It is also possible that the discussions among this international team of researchers working at the forefront of the field may define a next generation approach to the problem of gravity wave effects in global models.

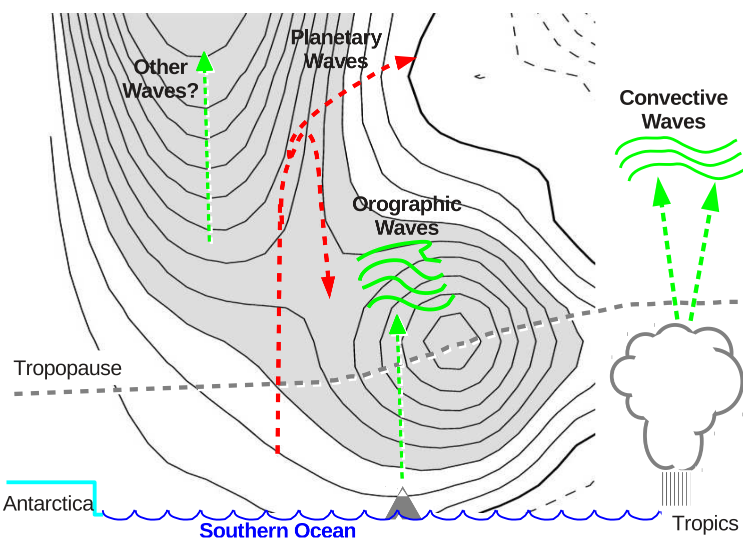

Figure 1. Schematic illustrating key gravity wave sources and their interaction with the stratosphere. Contours represent zonal mean winds in SH winter. At high latitudes, orographic waves are an important source of drag. Additional drag from waves of uncertain origin are needed in the jet core in climate models. In the tropics, waves of all scales (global to tens of km) are important.

A. Background

The last decade may have been a golden era for Earth-observing satellite measurements that may not be repeated in the near future. ESA's Envisat has been monitoring the surface and atmosphere for ten years. NASA's A-Train constellation of seven satellites has been providing a wealth of data on surface properties, clouds, and atmospheric composition and thermodynamics. COSMIC radio-occultation measurements are providing temperature and water vapor at high vertical resolution, and the TIMED satellite has scanned the atmospheric temperature to high altitudes through the mesosphere. These are in addition to the international suite of operational sounding satellites and other data sources for monitoring the atmosphere. Assimilation of these data has resulted in dramatic improvements in model initialization for improving global weather forecasting skill and for production of global reanalysis data sets, and the mesosphere measurements have provided new opportunities for assimilation experiments to higher altitudes.

Gravity wave drag is believed to be the solution to some of the common biases in climate model winds and temperatures. Gravity waves that are generated in the troposphere drive circulation changes in the stratosphere and mesosphere, and are one of the important unresolved atmospheric processes in global models that must be treated with physical parameterizations. Although the scales of the individual waves are small, collectively, they have important global-scale effects on the circulation. Orographic gravity wave drag in global circulation models has long been recognized as one of the important physical parameterizations in the extratropics. Waves from other sources, so-called non-orographic gravity waves, have long been recognized as controlling winds at mesospheric heights, and now known to be important throughout the stratosphere, particularly in the tropics for driving the prominent quasibiennial and semi-annual wind oscillations (QBO and SAO). Important non-orographic gravity wave sources include tropical convection and jet-stream instability, among others.

Current climate prediction models submitted for use in the next Assessment Report (AR5) of the Intergovernmental Panel on Climate Change are run at approximately 1° horizontal resolution. Dissipation at the shortest resolved scales ensures that waves with wavelengths shorter than ~500 km are not represented in these models. Current research at major climate prediction centers is focusing on high-resolution simulations at 10-20km with primary goals to better resolve cloud processes and mesoscale storm dynamics. Along the way, these models will include a spectrum of gravity waves, but with problems likely due to the lack of vertical resolution (e.g. see Evan et al., [2012]). Weather forecasting centers have been experimenting with high resolution of this scale now for many years. Climate models, in contrast, must run coupled to full ocean models for century timescales, so the need for gravity wave parameterization in climate models will continue for the foreseeable future. These models require new gravity wave parameterizations that can respond in realistic ways to large-scale climate change, and observational constraints needed for validation. *Our approach to this problem is through an ISSI workshop since satellite-derived information is the key to all aspects: Data assimilation, reanalysis products, forecast models, and gravity wave observations.*

B. Task 1: Gravity Wave Drag Forces

Model wind biases can be corrected with appropriate patterns in gravity wave dissipation or breaking. The factors controlling wave breaking include the stability and wind shear profile of the larger scale atmospheric state and wave characteristics such as the wave amplitude, horizontal wavelength, frequency, and phase speed. Wave characteristics must be set as parameters in the process of tuning a gravity wave parameterization. Gravity waves are highly variable phenomena, with very intermittent occurrence and characteristics that vary dramatically both in space and time. The simplified set of parameters used to tune parameterizations cannot completely represent the true variability of waves in nature, so a great deal of freedom remains in the tuning process when considering how to achieve a model simulation with minimal biases.

A variety of different methods have been used to estimate or constrain gravity wave drag forces in the atmosphere. These include:

1. *Direct observation of gravity wave momentum fluxes.* Comparison of these data to momentum fluxes in climate models was the subject of 2009 ISSI International Team Project that resulted in a review paper [Geller et al., 2012]. (See Figure 2.)

2. *Tuning of parameterized gravity waves in low-resolution models to give realistic time-mean, and/or monthly mean circulations.* This method is currently state-of-the-art for climate and chemistry-climate models. Implementing new parameterizations or retuning after changing model resolution is known to be a laborious and often frustrating process.

3. *Direct simulation of gravity waves in high-resolution global models that have been validated with observations of both the mean flow and gravity waves.* Costly simulations at moderately high horizontal resolution and very high vertical resolution run for limited 3-yr periods have achieved fairly realistic middle atmosphere circulations without using any gravity wave parameterization [Watanabe et al., 2008; Sato et al., 2009]. These simulations are not resolving the full spectrum of waves, and sources like convection remain parameterized. The expectation is that the spectrum of waves may not have completely realistic characteristics, but the drag forces must be realistic to achieve a realistic circulation.

4. *Inference of missing forces in low-resolution global analyses using time-averaged observations and zonal-mean balance conditions.* The missing force, inferred as a difference between the free-running model and the analysis, can be used to estimate remaining unresolved gravity wave forcing [e.g. Shine, 1989; Alexander and Rosenlof, 1996]. Due to the averaging process, these methods cannot capture the feedbacks between resolved and unresolved waves.

5. *Data assimilation methods to capture the 3-dimensional time-evolving wave drag.* Data assimilation techniques provide a means to estimate model parameters and systematic biases objectively. Recently, they have been used to estimate the missing gravity wave drag [Pulido and Thuburn, 2008]. This drag is represented in the assimilation system as an uncertain forcing term added to the momentum equations. The model forecast is started with an initial observed state (or analysis) and is allowed to evolve with time. The inverse technique estimates the optimal forcing that gives the minimal bias between the forecast model and a set of observations distributed in time. The technique is able to determine temporally and spatially localized sources of missing forcing. Simpler variants use data assimilation to identify model biases in the stratosphere in 6-hr forecasts and attribute those to missing gravity wave drag (e.g. McLandress et al. [2012]).

These techniques all produce different answers to some degree, and the model techniques (2-5) produce different answers depending on which model is used. Controlled comparisons will shed new light on the commonalities and differences among the methods, will reveal robust features of the results, will help to quantify their uncertainties, and will point the way for both model improvements and directions for future research. These are the goals of the first workshop.

C. Task 2: Regional Sources

Common stratospheric biases remain in climate models, particularly in two regions: The tropics, and the high-latitude Southern Hemisphere. Our second focus will examine these two regions in more detail to study specific properties of gravity waves in these regions that are needed to reduce these biases. By using a gravity wave parameterization in the forecast model, data assimilation techniques can be used to estimate the optimal gravity wave parameters, those that produce the best fit between model evolution and observations [Pulido et al., 2012]. These can be compared directly to parameterized waves in climate models. We will also devise comparisons to resolved waves in high-resolution global models and to observations from balloon-borne Concordiasi measurements [Rabier et al. 2010].

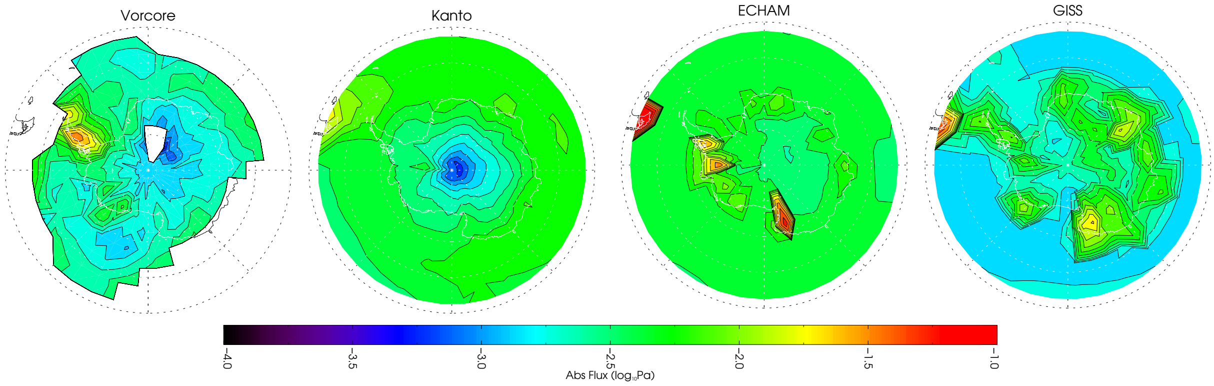

Figure 2. Gravity wave momentum fluxes derived from (left to right) long-duration balloons, a high-resolution model, and two parameterizations. (Geller et al. [2012] courtesy of P. Love.)

1. High Latitude Gravity Waves in the Southern Hemisphere:

Orographic gravity wave drag is widespread in the Northern Hemisphere stratosphere due to the widespread distribution of mountain regions, and this drag is important for slowing winter winds, moderating cold winter temperatures, and allowing penetration of planetary waves and influencing the timing of the seasonal transition in spring from westerlies to easterlies. The Southern Hemisphere in contrast has relatively little land area at the latitudes of the polar stratospheric jet. The narrow longitude region of South America and the Antarctic Peninsula are the primary sources, and there is an absence of large-scale mountainous land near 60°S precisely where drag is most needed in the models [McLandress et al., 2012]. To control model biases, non-orographic gravity wave parameterizations are used, but the sources are poorly understood, and the simplified parameterized waves tend to break higher in the mesosphere. The comparisons we plan will illuminate important source regions and source mechanisms and help to define characteristics of missing waves and wave drag.

2. Tropical Gravity Waves:

In the tropics, the largest changes in winds occur on a quasibiennial timescale, much larger even than the annual cycle. The QBO is still not represented in many climate models. High vertical resolution has been shown to be required [Giorgetta et al., 2002], and a broad spectrum of tropical waves is also needed [Scaife et al., 2000; Kawatani et al., 2010]. The resolved waves in the model may not have the right properties to drive the QBO because of poor representation of the variability of convection resulting from model convection parameterizations. Parameterized non-orographic gravity wave drag is also generally required to obtain a QBO. Models that achieve a QBO do so with a variety of techniques and combinations of resolved and parameterized waves. The need for prescribed non-orographic gravity waves in most models means they cannot respond to changes in convective gravity waves in a future climate. We plan a detailed comparison of resolved and parameterized tropical wave forcing, and comparison to inferred drag from data assimilation methods to shed light on this important region.

D. Logistical Information

List of Confirmed Team Members: M. Joan Alexander (Team Leader, USA), Julio Bacmeister (USA), Andrew Bushell (UK), Stephen Eckermann (USA), Marvin Geller (USA), Albert Hertzog (France), Francois Lott (France), Elisa Manzini (Germany), Charles McLandress (Canada), Manuel Pulido (Argentina), Kaoru Sato (Japan), Nedjeljka Zagar (Slovenia)

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 plan, collect, and discuss the data and interpretation of our intercomparisons. The global suite of satellite observations included in present day data assimilation systems are the primary data source for global reanalysis data sets that underlie so much of the international research on Earth's atmosphere and climate. Our work collects results from the latest innovative uses of these systems for estimating gravity wave forces that underlie many common climate model biases. Our team includes members from 8 different countries and many of the worlds leading climate and forecasting centers. By facilitating our meeting and the intercomparison of results, ISSI may help to advance the state-of-the-art in these models and highlight the special value of certain research satellite observations for the problem of gravity waves in global models.

Schedule of the project: We plan two 5-day face-to-face meetings in Bern. Prior to the first meeting we will collect details of the various data sets that will be contributed, and define a preliminary set of requirements via email. Team members will be encouraged to bring existing data on gravity wave forces to the first meeting planned for winter/spring 2012-13 to complete preliminary comparisons for Task 1. We will also discuss regional comparisons for Task 2 and finalize the data plan for both topics. Data will be collected between the first and second meetings. The second meeting will partly be used for final interpretation and figure selection for the first publication on Task 1, but the discussion will focus on the more exploratory regional comparisons for Task 2.
Tentative schedule: Meeting 1 in late winter-early spring 2012-13, duration 5 days; Meeting 2 in fall 2013 or spring 2014, duration 5 days; Journal article submissions in spring 2014; Final report to ISSI in summer 2014.

Financial Support requested: We request hotel and per diem for 12 team members plus two additional young scientists that we hope to add to the team at a later date in accordance with the proposal guidelines. Per diem will be needed for approximately 6 days for each participant for each of two meetings, and travel support for either the team leader or a designated participant in need. In addition to this support from ISSI, we plan to request travel support from the World Climate Research Program (WCRP) for our young scientists and for our team members from under-developed countries.

Expected Outcomes: We expect up to three review papers may come out of our team's work: (1) A review on the use of data assimilation methods for understanding gravity wave effects in the middle atmosphere. (2) A focused review on Southern Hemisphere gravity waves in models and observations. (3) A review summarizing key wave properties in the tropical stratosphere with implications for simulating the QBO in climate models.

Facilities Required: Meeting room for 14 people (12 team members plus two YS). Wired and/or wireless internet connection. Projector and cables. Open website with a password protected team directory. IT support for website.

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Curriculum Vitae for M. Joan Alexander

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Education: Ph.D. University of Colorado, Boulder, (1992) Planetary & Atmospheric Sciences
M.S. University of Colorado, Boulder, (1989) Planetary & Atmospheric Sciences
B.S. Purdue University, Indiana, (1981) Chemistry

Experience: Research Scientist at the NWRA CoRA/Boulder office, since 1998 and Senior Scientist since 2003, Boulder office management since 2006, and simultaneous affiliate faculty appointment at the University of Colorado, Atmosphere and Ocean Sciences (since 1999). Prior to NWRA, held a Postdoctoral Faculty position at the University of Washington (UW), Atmospheric Sciences and became Research Assistant Professor in 1994, also teaching courses in Dynamic Meteorology.

Current Research Interests: Dr. Alexander's research focus is tropical convection and atmospheric waves, particularly gravity waves and equatorial waves. Her work involves both observational analyses and theoretical modeling to better understand the properties of these waves, their sources, and their many effects in the atmosphere. Observation techniques include satellite remote sensing, balloon-borne radiosondes, and aircraft platforms. Theoretical models focus on the dynamics and thermodynamics of storms, wave propagation and wave interactions with the background atmosphere, and the global circulation and temperature structure of the middle atmosphere.

Activities, Awards, and Memberships: Dr. Alexander is Adjoint Professor in Atmosphere and Ocean Sciences at at the University of Colorado where she mentors graduate students in their Ph.D. Research; She received the Annual Teaching Award in 1998 at the Univ. of Washington before moving to Colorado. She was elected Fellow of the American Meteorology Society in 2006, elected President of the American Geophysical Union Atmospheric Sciences Section in 2002, and served on the AGU Council for 4 years. She also served as a member of the National Research Council's Board on Atmospheric Sciences and Climate, and was a Marie-Tharp Fellow at Columbia University. She is also former Secretary of the International Commission on Dynamical Meterorology and member of the American Meteorology Society committees on Atmospheric/Oceanic Fluid Dynamics and the Middle Atmosphere. She has been a frequent invited lecturer at national and international meetings, including the award Bjerknes Lecture. Her record includes Participant and Science Team member for numerous NASA field campaigns and satellite experiments, currently on the Atmospheric Infrared Sounder (AIRS), High Resolution Dynamics Limb Sounder (HIRDLS), and Airborne Tropical Tropopause Experiment (ATTREX) Science Teams, with her research highlighted in NASA publications and public websites.

Recent Relevant Publications: (Full list at http://www.cora.nwra.com/~alexand/publications.html)

Alexander, M. J., and H. Teitelbaum, 2011: Three-dimensional properties of Andes mountain waves observed by satellite: A case study. *J. Geophys. Res.*, **116,** D23110, doi:10.1029/2011JD016151.

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Education

Swarthmore College	Honors Program in Physics	B.A., 1982
Princeton University	Program in Geophysical Fluid Dynamics	Ph.D., 1987

Employment

7/2009-	Scientist III, Climate and Global Dynamics Division, National Center for Atmospheric Research, Boulder, CO
1998-2009	Research Scientist, Goddard Earth Science and Technology Center, Univ. of Maryland, Baltimore County (GEST UMBC), NASA Goddard Space Flight Center, Greenbelt MD
1992-1998	Research Physicist (GS-13) Middle Atmosphere Dynamics Group, Naval Research Laboratory, Washington, D.C. .
1989-1992	Assistant Research Associate, Department of Earth and Planetary Sciences, Johns Hopkins University, Baltimore MD.
1987-1989	National Research Council Fellow , NASA Goddard Space Flight Center, Greenbelt MD

Selected Papers

Bacmeister, J. T., P. A. Newman, B. L. Gary, and K. R. Chan, 1994: An algorithm for forecasting mountain wave related turbulence in the stratosphere. *Weather and Forecasting* , 9, 241-253

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Curriculum Vitae

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1992 Ph.D. Department of Physics, University of Warwick, United Kingdom.
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2003 – Date : Middle Atmosphere Research Scientist, Met Office, Exeter, U.K.
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Summary:
18 years research and model development experience in atmospheric physics processes and parametrizations. Currently member of Stratosphere & Large-Scale Dynamics group with specific responsibility for maintenance and development of non-orographic gravity wave parametrization in the Met Office's global climate prediction / weather forecasting Unified Model (MetUM). Partner in active research collaboration between Met Office and LMD on FP7 project EMBRACE sub-task 1.5 *Convectively forced gravity waves and impact on the upper troposphere and stratosphere* with strands that include introduction of convective gravity wave sources into our respective earth-system models, with comparison of their behaviour, and analysis of high resolution model runs for comparison with in-situ observations.
Other European interactions include, previously, lead Met Office scientist in the FP6 GEO6 project, prospecting global ionospheric data assimilation and, currently, lead Met Office scientist in FP7 project ESPAS collaborating to test a developing e-infrastucture for space weather data (through a user case aimed at validation of a data assimilation system based on a physical model for the thermosphere-ionosphere).

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A.C. Bushell, A.A. Scaife, C.D.Warner (2007), Non-orographic (spectral) gravity wave parametrization, *Unified Model Documentation Paper 34*, Met Office, Exeter, UK.

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Education: Ph. D., Physics, University of Adelaide, 1990; B. Sc. (Hons.), Physics, University of Adelaide, Australia, 1986.

Relevant Research/Professional Experience: Dr. Eckermann has been a Federal research physicist at the Naval Research Laboratory's (NRL) Space Science Division since 1998. He headed NRL's Middle Atmosphere Dynamics Section from its inception in 2002 until 2012, when he assumed leadership of NRL's Near-Space Environments Section. Dr. Eckermann led development of an advanced-level physics, high-altitude (ALPHA) prototype of the Navy's Operational Global Atmospheric Prediction System (NOGAPS-ALPHA), the Department of Defense's global numerical weather prediction system. He now leads operational transitioning of NOGAPS-ALPHA technology into the next-generation Navy Global Environmental Model (NAVGEM), consisting of semi-Lagrangian forecast model coupled to a four-dimensional variational data assimilation system. This system will provide global forecast-assimilation capabilities extending to ~100 km altitude.

Dr. Eckermann has authored or co-authored 99 papers either published or accepted for publication in the peer-reviewed scientific literature. His formal recognitions include 1994 and 2007 Editor's Citations for Excellence in Refereeing for The Journal of Geophysical Research and a 2008 Navy Meritorious Civilian Service Award, the second highest award available to a civilian employee of the Navy.

Selected Recent/Relevant Publications:

(all listed at http://uap-www.nrl.navy.mil/uap/?content=eckermann/pubs;code=7646)

Coy, L., S. D. Eckermann, K. W. Hoppel, and F. Sassi (2011), Mesospheric precursors to the major stratospheric sudden warming of 2009: Validation and dynamical attribution using a ground-to-edge-of-space data assimilation system, J. Adv. Model. Earth Syst., 3, M10002, 7pp., doi:10.1029/2011MS000067.

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Short Curriculum Vitae for Marvin A. Geller

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1989-2000: Professor and Director, Institute for Terrestrial and Planetary Atmospheres, Stony Brook University
1985-1989: Chief, Laboratory for Atmospheres NASA/Goddard Space Flight Center Greenbelt, MD
1980-1985: Space Scientist, Atmospheric Chemistry Branch, Laboratory for Planetary Atmospheres, NASA Goddard Space Flight Center, Greenbelt MD
1977-1980: Professor (Meteorology and Physical Oceanography) University of Miami
1973-1977: Associate Professor (Atmospheric Science and Electrical Engineering) Univ. Illinois at Urbana-Champaign (Promotion to Full Professor approved 5/77)
1969-1973: Assistant Professor (Atmospheric Science and Electrical Engineering) Univ. Illinois at Urbana-Champaign

Honors and Awards
1984 Elected as Fellow, American Meteorological Society; 1995 Editor's Award, American Meteorological Society; 1998 Elected President of the Atmospheric Sciences section of the American Geophysical Union; 1999 Elected President of the Scientific Committee for Solar-Terrestrial Physics (re-elected in 2003); 2000 Elected Councilor of the American Meteorological Society; 2001 Lifetime National Associate of the National Academies (member of first selected group) ; 2004 Elected as Fellow, American Geophysical Union; 2006 Awarded NASA Distinguished Public Service Medal; 2008 Awarded COSPAR International Cooperation Medal

Professional Society Memberships
American Meteorological Society (Fellow), Councilor 2001-2003
American Geophysical Union (Fellow) President AS section 2000-2002
Scientific Committee on Solar-Terrestrial Physics (SCOSTEP) (President 2001-2007)

Research
Dr. Geller has 105 refereed papers published or in press. The following are a few relevant publications.

Gravity wave kinetic, potential, and vertical fluctuation energies as indicators of different frequency gravity waves. Geller, M. A., and J. Gong, *J. Geophys. Res.*, *115*, D11111, doi:10.1029/2009JD012266, 2010.

Vertical fluctuation energy in United States high vertical resolution radiosonde data as an indicator of convective gravity wave sources, Gong, J., and M. A. Geller, *J. Geophys. Res.*, *115*, D11110, doi:10.1029/2009JD012265, 2010.

Recent developments in gravity-wave effects in climate models and the global distribution of gravity-wave momentum flux from observations and models. Alexander MJ, Geller M, McLandress C, Polavarapu S, Preusse P, Sassi F, Sato K, Eckermann, S, Ern M, Hertzog A, Kawatani YA, Pulido M, Shaw T, Sigmond M, Vincent R, Watanabe S., *Q. J. R. Meteorol. Soc.* **136**: 1103–1124.DOI:10.1002/qj.637, 2010.

New Gravity Wave Treatments for GISS Climate Models. Geller, M. A., T. Zhou, R. Ruedy, I. Aleinov, L. Nazarenko, N. L. Tausnev, S. Sun, M. Kelley, and Y. Cheng, *J. Climate*, **24**, 3989-4002, doi:10.1175/2011JCLI4013.1, 2011.

Albert HERTZOG Born on January 4, 1971
albert.hertzog@lmd.polytechnique.fr French

Lecturer, École Polytechnique, Palaiseau, France
Member of Laboratoire de Météorologie Dynamique, Palaiseau, France

Cursus

1998	PhD, University Pierre et Marie Curie. Laboratory: Service d'aéronomie, Adviser: Alain Hauchecorne. Title: Study of mesoscale stratospheric dynamics with wind lidar observations
1999 – 2002	Post-doc at Laboratoire de Météorologie Dynamique, Adviser: François Vial. Equatorial and polar stratospheric dynamics, long-duration balloon observations.
2003–2010	Lecturer, University Pierre et Marie Curie, Paris, France
2011–	Lecturer, École Polytechnique, Paris, France

Research Activities

I mainly work on stratospheric dynamics, from mesoscale to global scale. I am particularly interested in quantifying the forcing exerted by various kinds of waves on the global circulation, as well as in studying the effect of wave motions on the microphysics and chemistry of the stratosphere. I work on original datasets, collected during long-duration balloon flights in the lower stratosphere. I was co-PI of the Stratéole-Vorcore (2005) and Concordiasi (2010) balloon projects in Antarctica. I am PI of Stratéole-Phase 2 (2017-2018), a international long-duration balloon campaign aimed at studying dynamics, transport and dehydration processes in the equatorial upper troposphere and lower stratosphere. I also contribute to the development of new instruments able to perform meteorological and chemical observations on such balloons.
I have collaborations with several foreign researchers, like Joan Alexander and K. Hamilton (USA) and R. Vincent (Australy).

Publications

I am author or co-author of 34 articles in peer-reviewed journals. My recent publications include:

Boccara, G., A. Hertzog, R. A. Vincent, et F. Vial, Estimation of gravity wave momentum flux and phase speeds from quasi-Lagrangian stratospheric balloon flights. 1: Theory and simulations, *J. Atmos. Sci.*, **65**, 3042-3055, 2008.

Hertzog, A., G. Boccara, R. A. Vincent, F. Vial, et Ph. Cocquerez, Estimation of gravity wave momentum flux and phase speeds from quasi-Lagrangian stratospheric balloon flights. 2: Results from the Vorcore campaign in Antarctica, *J. Atmos. Sci.*, **65**, 3056-3070, 2008.

Plougonven, R., A. Hertzog, et H. Teitelbaum, Observations and simulations of a large amplitude mountain wave breaking over the Antarctic Peninsula, *J. Geophys. Res.*, **113**, D16113, doi:10.1029/2007JD009739, 2008.

Rabier, F., et al., The Concordiasi project in Antarctica, *Bull. Am. Meteorol.Soc.*, **91**, 69-86, doi:10.1175/2009bams2764.1, 2010.

Alexander, M. J., et al., Recent developments in gravity-wave effects in climate models and the global distribution of gravity-wave momentum flux from observations and models, *Q. J. R. Meteorol. Soc.*, **136**, 1103-1124 , 2010.

Teaching activities

I teach or have teached electricity, electronics, meteorology, wave physics, informatics, numerical methods, and statistics at graduate and undergraduate level.
Graduate students advised recently: Kristell Perot, Benoît Labbouz, Antonin Arsac, Valerian Jewtoukoff
PhD students advised recently: Gillian Boccara, Jérôme Clech

Responsabilities

Project scientist during Vorcore campaign in McMurdo, Antarctica (2005)
Co-PI of Concordiasi campaign in McMurdo, Antarctica (2010)
PI of Stratéole Phase 2
Member of the International Space Science Institute group: Merging Space- and Ground-based Observational Constraints for Gravity Wave Parameterizations in Climate Models (2010-2011)
Organising committe of the 20th PAC symposium on balloon and rocket, 2011.
Member of LMD laboratory council since 2010.

François Lott's CV, March 2012 Date of birth 22/11/1963

Senior scientist at CNRS (DR2) since Octobre 2008

Assistant Professor at Ecole Polytechnique, France (1998-2010)

Scientific expertise:

Atmospheric dynamics from the mesoscales to the planetary scales. A large part of the scientific production is about gravity waves dynamics, mountain meteorology and stratospheric dynamics. The methodologies go from purely theoretical approaches to contributions to the development of global climate models. These contributions can take the form of parameterizations, model validations against observations, or use to test large scale circulation theories (for instance about cold surges or the Arctic Oscillation).

Diploma:

Juin 1986: Marine Engineer from ENSTA (Ecole Nationale Supérieure des Techniques Avancées)

Nov. 1989: PhD from University Paris 6, Speciality: Oceanography et Meteorology.

Oct. 1996: "Habilitation à diriger des recherches", Speciality: Oceanography et Meteorology..

Research and Mobility:

Sept. 1986-Nov. 1988: PhD at Laboratoire de Météorologie Dynamique (LMD), Ecole Polytechnique, France: Interaction between gravity waves and critical levels

Dec. 1988-Nov.1989: Military Service done at LODYC (Laboratoire D'Océanographie Dynamique et de Climatologie, today LOCEAN), at Paris 6.

Influence of bathymetry on deep water formation in the mediterranean sea

Dec. 1989-Sept. 1992: Post-doc done at LMD, Ecole Polytechnique: Mountain waves theory, shear instability theory and gravity waves emission.

Septembre 1992: Hired as a reasearch Scientist at CNRS (level CR1)

Nov. 1992-Dec. 1994: Staff at ECMWF (Reading-England)

Parameterisation of subgrid-scale mountains in the ECMWF global model. des montagnes

Dec. 1994-Aug. 1997: Research scientist at LMD, Ecole Normale Supérieure.

Influence of mountains at climatic scales and theories for trapped mountain waves.

Sept. 1997-Août 1998: Research scientist at DAS-IGPP, UCLA, (Los Angeles-Etats Unis).

Impact of mountains on atmospheric low-frequency variability

Sept. 1998-Dec 2001: Research at LMD, Paris 6.

Impact of mountain at the synoptic and mesoscales.

Jan. 2002-today (March 2012, and except for the stays at in India): Research at LMD, ENS.

Stratospheric Dynamics and its simulation in global models. Impact on the surface climate, parameterization of non-orographic gravity waves.

Sept. 05-Dec. 05 et Sept. 06-Dec. 06: StaysNational at Institute of Oceanography (NIO, Inde).

Indian monsoon dynamics and climate variability in south-eastern Asia.

Main lectures:

2003-2010: 36h course+exercises: Under Graduate level, Ecole Polytechnique: "Simple climate models"

2004-2005: 6h course: graduate level, "Middle atmosphere dynamics"

2005-2009:36h course+exercises: graduate level, "Middle atmosphere dynamics and atmospheric waves"

2009-today (March 2012 and with B. Legras): **42 hr courses+exercises: Under-graduate level** "Atmospheric dynamics and meteorology"

Supervisions:

3 tutorings from Ecole Polytechnique (under-graduate); 3 student group supervisions (3x7 students from Ecole Polytechnique, under-graduate); 14 times in a PhD thesis Jury (member or referee); 7 graduate students (including 3 in co-supervision); 3 under graduate students. 3 PhD students; 2 PhD students in co-supervision; 4 Post-doctoral, 1 Post-doctoral in co-supervision.

Few collective responsabilities:

Initiator of the IPSL Scientific Project"Influence of the Stratosphère on Climate".

Management of the CNRS research team «Fluide Stratifié et Tournant» (9 staffs around 10 Doc and Post-Doc)

Partner of the EU projects IGWOC (1997-2000), COMBINE (2009-2014) and EMBRACE (2011-2016)

Membre of the Scientific council of the franco-Argentinian laboratory IFAECI

Publications:

1rst rank international journal: 52, with 26 as a first author.

Book Chapters, proceeding of conference, ...: 17, with 13 as a 1rst author.

Distinction: Young Scientists' Publication Award, 1990, European Geophysical Society

MARCH 2012

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EXPERTISE & RESEARCH INTEREST

Dr. Elisa Manzini is a senor scientist with ~20 years of experience in the development and evaluation of numerical global models of the troposphere and stratosphere system, including gravity wave parameterizations, coupling to chemistry, coupling to ocean, and the carbon cycle. Her scientific research interest focuses on assessing and understanding the role of stratospheric dynamical variability in the climate/Earth system. She has coauthored ~50 peer reviewed publications. She has contributed to scientific assessments (WMO ozone, SPARC CCMVal, IPCC) in various roles (author and/or reviewer). She is member of AGU (since 1993) and EGU (on and off).

EDUCATION

- *Doctor of Philosophy in Atmospheric and Oceanic Sciences, 1992.* Princeton University, USA
- *Master of Arts in Atmospheric and Oceanic Sciences, 1989.* Princeton University, USA.
- *Laurea in Physics, 1985.* Università degli Studi di Bologna, Bologna, Italy.

PROFESSIONAL EXPERIENCES

- *Max-Planck-Institut für Meteorologie, Hamburg, Germany*. February 2010-present
- *Centro Euro-Mediterraneo per i Cambiamenti Climatici (CMCC), Bologna, Italy.* October 2006-Jaunary 2010.
- *Istituto Nazionale di Geofisica e Vulcanologia (INGV), Bologna, Italy.* October 2002-January 2010.
- *Max-Planck-Institut für Meteorologie, Hamburg, Germany.* February 1992-September 2002.

SELECTED PROFESSIONAL & OROGANIZATIONAL ACTIVITIES

- Coordinator of the *SPARC DynVar Activity: Modelling the Dynamics and Variability of the Stratosphere-Troposphere System* of the *Stratospheric Processes and their Role in Climate* (SPARC), a core project of the *World Climate Research Programme* (WCRP). 2009-present.
- Member of the *International Space Science Institute* International Team: *The Gravity Wave Project: Merging Space- and Ground-based Observational Constraints for Gravity Wave Parameterizations in Climate Models*. 2010-211.
- Member of the *International Commission on the Middle Atmosphere* (ICMA/IAMAS). 2008-2012.
- Member of the Scientific Steering Group of *SPARC/WCRP*. 2005-2010.
- PhD Lecturer at Universita' Ca' Foscari di Venezia, Italy (2008-2010)
- Co-Chair of the Local Organizing Committee *SPARC 4th General Assembly,* 2008, Bologna, Italy.
- Executive Editor: *Climate Dynamics*, 2001 - 2007.
- Associate Editor: *Journal of Geophysical Research*, 2001 - 2002.
- Reviewer for a number of journals.

SELECTED REFEREED PUBLICATIONS

- Manzini, E., C. Cagnazzo, P.G. Fogli, A. Bellucci and W. Müller, 2012: Stratosphere - Troposphere coupling at inter-decadal time scales: Implications for the North Atlantic Ocean. Geophys. Res. Lett., 39, L05801.
- Cagnazzo, C., and E. Manzini, 2009: Impact of the startosphere on the winter tropospheric teleconnections between ENSO and the North Atlantic and European Region. J. Climate 22, 1223-1238. DOI: 10.1175/2008JCLI2549.1.
- Butchart, N., A.A. Scaife, M. Bourqui, J. de Garndpre, S.H. Hare, J. Kettleborough, U. Langematz, E. Manzini, F. Sassi, K. Shibata, D. Shindell, and M. Sigmond, 2006: Simulations of anthropogenic change in the strength of the Brewer–Dobson circulation. Climate Dynamics, DOI 10.1007/s00382-006-0162-4.
- Manzini, E., M.A. Giorgetta, M. Esch, L. Kornblueh, and E. Roeckner, 2006: The influence of sea surface temperatures on the Northern winter stratosphere: Ensemble simulations with the MAECHAM5 model. J. Climate, 19, 3863-3881.
- Sigmond, M., P.C. Siegmond, E. Manzini, H. Kelder, 2004: A Simulation of the separate climate effects of middle atmospheric and tropospheric CO_2 doubling. J. Climate, 17, 2352-2367.
- Horinouchi,T., S. Pawson, K. Shibata, U. Langematz, E. Manzini, M.A. Giorgetta, F. Sassi, R.J. Wilson, K.P. Hamilton, J.de Granpre, and A.A. Scaife, 2003: Tropical cumulus convection and upward propagating waves in middle atmospheric GCMs. J. Atmos. Sci., 60, 2765-2782.
- Manzini, E., B. Steil, C. Brühl, M.A. Giorgetta, and K. Krüger, A new interactive chemistry-climate model: 2. Sensitivity of the middle atmosphere to ozone depletion and increase in greenhouse gases and implications for recent stratospheric cooling. 2003: J. Geophys. Res., 108(D14), 4429, DOI: 10.1029/2002JD002977.
- Giorgetta, M.A., E. Manzini, and E. Roeckner, 2002: Forcing of the Quasi-Biennial Oscillation from a broad spectrum of atmospheric waves. Geophys. Res. Lett., 29(8), DOI: 10.1029/ 2002GL014756.
- Charron, M. and E. Manzini, 2002: Gravity waves from fronts: Parameterization and middle atmosphere response in a general circulation model. J. Atmos. Sci., 59, 923-941.
- Manzini, E., and N.A. McFarlane, 1998: The effect of varying the source spectrum of a gravity wave parameterization in a middle atmosphere general circulation model. J. Geophys. Res., 103, 31523-31539.

March 2012

Charles McLandress

Department of Physics, University of Toronto
60 St. George St., Toronto, Ontario, Canada, M5S 1A7
Phone: 416-978-1810, Fax: 416-978-8905, Email: charles@atmosp.physics.utoronto.ca

Research Interests:
- Climate modelling
- Gravity wave drag parameterizations and their impact on the global circulation
- Atmospheric tides, planetary waves, and gravity waves

Professional Experience:
- 2000 – present: Senior Research Associate, University of Toronto, Toronto, Canada
- 1998 – 2000: Research Scientist, York University, Toronto, Canada
- 1997 – 1998: Acting Assistant Professor, University of Washington, Seattle, USA
- 1991 – 1996: Research Scientist, Institute for Space and Terrestrial Science, Toronto, Canada
- 1988 – 1990: Visiting Scientist (postdoc), Canadian Climate Centre, Toronto, Canada

Education:
- Ph. D., Meteorology, McGill University, 1988
- M. Sc., Meteorology, McGill University, 1983
- B. Sc., Physical Geography, University of Winnipeg, 1979

Professional Activities:
- Coauthor of chapters 3 and 4 of the 2010 WMO Scientific Assessment of Ozone Depletion
- Member of the International Committee of the Middle Atmosphere from 2003-2011
- Co-organizer of several session at international conferences or workshops
- More than 50 publications in peer-reviewed journals
- Lecturer at several summer schools on atmospheric modelling and dynamics

Selected Relevant Publications:

- McLandress, C., T. G. Shepherd, S. Polavarapu, and S. R. Beagley, Is missing orographic gravity wave drag near 60S the cause of the stratospheric zonal wind biases in chemistry-climate models?, J. Atmos. Sci., 69, 802-818, 2012
- McLandress, C., T. G. Shepherd, J. F. Scinocca, D. A. Plummer, M. Sigmond, A. I. Jonsson, and M. C. Reader, Separating the dynamical effects of climate change and ozone depletion: Part 2. Southern Hemisphere Troposphere, J. Clim., 24, 1850-1868, 2011
- Shepherd, T. G., and C. McLandress, A robust mechanism for strengthening of the Brewer-Dobson circulation in response to climate change: critical-layer control of subtropical wave breaking, J. Atmos. Sci., 68, 784-797, 2011
- McLandress, C., A. I. Jonsson, D. A. Plummer, M. C. Reader, J. F. Scinocca, and T. G. Shepherd, Separating the dynamical effects of climate change and ozone depletion: Part 1. Southern Hemisphere Stratosphere, J. Clim., 23, 5002-5020, 2010
- Alexander, M. J., M. Geller, C. McLandress, S. Polavarapu, P. Preusse, F. Sassi, K. Sato, S. Eckermann, M. Ern, A. Hertzog, Y. Kawatani, M. Pulido, T. Shaw, M. Sigmond, R. Vincent, and S. Watanabe, Recent developments in gravity-wave effects in climate models and the global distribution of gravity-wave momentum flux from observations and models, Q. J. Roy. Meteor. Soc., 136, 1103-1124, 2010
- McLandress, C., and T. G. Shepherd, Simulated anthropogenic changes in the Brewer-Dobson circulation, including its extension to high latitudes, J. Clim., 22, 1516-1540, 2009
- McLandress, C., and J. F. Scinocca, The GCM response to current parameterizations of nonorographic gravity wave drag, J. Atmos. Sci., 62, 2394-2413, 2005
- McLandress, C., M. J. Alexander, and D. L. Wu, Microwave Limb Sounder observations of gravity waves in the stratosphere: A climatology and interpretation, J. Geophys. Res., 105, 11947-11967, 2000
- McLandress, C., On the importance of gravity waves in the middle atmosphere and their parameterization in general circulation models, J. Atmos. Solar-Terr. Phys., 60, 1357-1383, 1998

Brief Curriculum Vitae

Dr. Manuel Arturo Pulido
`pulido@unne.edu.ar`

Current positions

- Professor. Department of Physics. Universidad Nacional del Nordeste, Corrientes, Argentina
- Adjoint Researcher. National Scientific and Technical Research Council (CONICET)

Education - Visiting positions

- PhD in Physics, 2001, Universidad Nacional de Cordoba (Argentina).
- PostDoc. 2001-2004. Department of Meteorology University of Reading, UK.
- Visiting Professor. June-July 2007. Laboratoire de Météorologie Dynamique, ENS (France).
- Visiting researcher. 2008-2009. Department of Physics University of Toronto, Canada.

Significant responsabilities

- Core member in the gravity wave momentum budget initiative (WCRP, SPARC) 2007-2008.
- Member. SPARC Scientific Steering Group. World Climate Research Program. From 1/1/2011.
- Co-chair Earth Atmosphere Science Comission, ANPCyT, Ministry of Science and Technology, Argentina. 2010.
- Convener Data Assimilation Session AGU The meeting of the Americas. Foz Iguazu (Brasil). August 2010.
- February 2011 Program Comittee AGU Chapman Conference. Atmospheric gravity waves and their effects in climate. Hawaii USA.

Last relevant publications

- Pulido M. and J. Thuburn, 2008: The seasonal cycle of gravity wave drag in the middle atmosphere. *J. Climate*, **21**, 4664-4679. doi: 10.1175/2008JCLI2006.1
- Pulido, M., C. Rodas, 2011: A Higher-Order Ray Approximation Applied to Orographic Gravity Waves: Gaussian Beam Approximation. *J. Atmos. Sci.*, **68**, 46–60.
doi: 10.1175/2010JAS3468.1
- Pulido M., S. Polavarapu, T. Shepherd and J. Thuburn, 2011: Estimation of optimal gravity wave parameters for climate models using data assimilation. In press in *Q. J. Roy. Meteorol. Soc.*.

Curriculum vitae in March 2012

Kaoru Sato

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Research Topics

◊ Dynamics of atmospheric gravity waves in terms of generation, propagation and dissipation
◊ Dynamics of trapped waves on the equator, mid-latitude tropopause and polar vortex edge
◊ Interaction of large-scale circulation/oscillation and waves
◊ Three-dimensional transport and mixing of minor constituents
◊ Polar atmospheric dynamics such as the katabatic winds and Antarctic ozone hole

Professional Experience

◊ Researcher, Opto-Electronics Research Laboratories, NEC Corporation, 1986-1987
◊ JSPS Research Fellow, Graduate School of Science, Kyoto University, 1991-1993
◊ Assistant Professor, Center for Climate System Research, The University of Tokyo, 1993-1995
◊ Assistant Professor, Graduate School of Science, Kyoto University, 1995-1999
◊ Associate Professor, National Institute of Polar Research, 1999-2005
◊ Professor, Graduate School of Science, The University of Tokyo, 2005-present

Education

◊ B.S. (Geophysics), The University of Tokyo, 1984
◊ M.S. (Geophysics), The University of Tokyo, 1986
◊ PhD (Geophysics), Kyoto University, 1991

Awards

◊ Yamamoto-Syono Award for Outstanding Papers, the Meteorological Society of Japan, 1991
◊ The Award of the Meteorological Society of Japan, 1998
◊ JMSJ Award, the Meteorological Society of Japan, 2010

Professional Activities

◊ Visiting Scientist, Northwest Research Associates, 1995-2000
◊ Wintering Party Member, The 44th Japanese Antarctic Research Expedition, 2002-2004
◊ Director of the Meteorological Society of Japan, and Japan Geoscience Union
◊ Member of American Meteorological Society, American Geophysical Union, Society of Geomagnetism and Earth, Planetary and Space Sciences
◊ Member, Science Council of Japan, 2005-present
◊ Chief Editor, Journal of the Meteorological Society of Japan, 2008-present
◊ Commission Member, ICMA/IAMAS/IUGG, 2002-2006
◊ Scientific Discipline Representative, SCOSTEP, 2002-present
◊ 65 peer-reviewed articles
◊ PI, The Program of the Antarctic Syowa MST/IS radar, 2000-present

Nedjeljka Žagar, PhD

University of Ljubljana, Faculty of Mathematics and Physics, Department of Physics
Jadranska ulica 19, SI-1000 Ljubljana, Slovenija
Email: nedjeljka.zagar@fmf.uni-lj.si, Tel: +386 1 4766 642, Fax: +386 1 251 72 81

Education

2004	Ph.D. in Dynamical Meteorology, Stockholm University, Sweden
1997	M.Sc. in Atmospheric Physics, University of Zagreb, Croatia
1994	B.Sc. in Physics/Geophysics with Meteorology, University of Zagreb, Croatia

Professional Experience

2005 – 2012	Professor of Meteorology, University of Ljubljana, Slovenia
2006 – 2008	Postdoctoral fellow of the Advanced Study Program at the National Center for Atmospheric Research, Boulder, Colorado, USA
2000 – 2004	PhD student, Department of Meteorology, Stockholm University, Sweden
1994 – 2000	Research Assistant and meteorologist at the Meteorological and Hydrological Service, Zagreb, Croatia

Research Interests

- Dynamics and general circulation: atmospheric large-scale and synoptic dynamics, balance dynamics, tropical motions, predictability issues, climate dynamics and predictability, coupling between the atmosphere, ocean and land surfaces.
- Data assimilation: variational data assimilation, ensemble assimilation methods, background-error modelling, observing system simulation experiments.
- Numerical weather prediction: limited area modelling, dynamical downscaling, the influence of orography, numerical modelling using spectral methods, verification methods, wind modelling in the complex terrain, atmosphere-ocean couplings.

Selected Research Activities

- Leader of the meteorological work package "Satellite applications in meteorology" within the Center of Excellence "SPACE-SI", www.space.si (2010-2013).
- Principal investigator on the project funded by the European Space Agency "Mesoscale wind profiles and data assimilation for numerical weather prediction" (2011-2014)
- Principal investigator on the European Research Council (ERC) Starting Grant MODES: Modal analysis of atmospheric balance, predictability and climate, Grant No. 280153. (2011-2014)

Teaching and Mentoring

- Lecturer of the undergraduate and gradute-level courses in meteorology (Dynamical meteorology, Weather analysis and forecasting, Numerical modelling, General circulation) at University of Ljubljana.
- Supervisor for undergraduate, MSc and PhD diploma thesis

Selected Publications

1. Žagar, N., G. Skok and J. Tribbia, 2011: Climatology of the ITCZ derived from ERA Interim reanalyses. J. Geophys. Res., 116, D15103, doi:10.1029/2011JD015695.
2. Žagar, N., J. Tribbia, J. Anderson and K. Raeder, 2011: Balance of the background-error variances in the ensemble assimilation system DART/CAM. Mon. Wea. Rev., 139, 2061-2079.
3. Žagar, N., J. Tribbia, J. L. Anderson and K. Raeder, 2009a: Uncertainties of estimates of inertio-gravity energy in the atmosphere. Part I: Intercomparison of four analysis systems. Mon. Wea. Rev., 137, 3837-3857.
4. Žagar, N., M. Žagar, J. Cedilnik, G. Gregorič and J. Rakovec, 2006: Validation of mesoscale low-level winds obtained by dynamical downscaling of ERA40 over complex terrain. Tellus A, 58, 445-455.
5. Žagar, N., E. Andersson and M. Fisher, 2005: Balanced tropical data assimilation based on study of equatorial waves in ECMWF short-range forecast errors. Q.J.R. Meteorol. Soc., 131, 987-1011.