Atmospheric Gravity Waves and Their Effects on General Circulation and Climate

American Geophysical Union Chapman Conference

Honolulu, Hawaii, USA

28 February - 4 March 2011

AGU Chapman Conference on Atmospheric Gravity Waves and Their Effects on General Circulation and Climate

Honolulu, Hawaii, USA
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Conveners

M. Joan Alexander, Northwest Research Associates (NWRA)
Kevin Hamilton, International Pacific Research Center
Kaoru Sato, The University of Tokyo

Program Committee

Hye-Yeong Chun, Department of Atmospheric Sciences (Korea)
Steve Eckermann, Naval Research Laboratory (USA)
Albert Hertzog, Laboratoire Meteorologique et Dynamique (France)
Takeshi Horinouchi, Hokkaido University (Japan)
Yoshio Kawatani, Research Institute for Global Change (Japan)
Elisa Manzini, Centro Euro Mediterraneo per i Cambiamenti Climatici (Italy)
Manuel Pulido, Universidad Nacional del Nordeste, Corrientes (Argentina)
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Financial Support

The conference organizers acknowledge the generous support of the following organizations:

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AGU Chapman Conference on Atmospheric Gravity Waves and Their Effects on General Circulation and Climate

Meeting At A Glance

Monday, 28 February 2011

0945h – 0955h Aloha and Introduction
0955h – 1020h General Circulation: Climate Effects of Parameterized Gravity Wave Drag
1020h – 1040h Stratospheric Sudden Warmings
1040h – 1110h Coffee Break
1110h – 1230h Stratospheric Sudden Warmings
1230h – 1400h Lunch on your own
1400h – 1540h Andes and Antarctic Peninsula Region I
1540h – 1610h Coffee Break
1610h – 1730h Andes and Antarctic Peninsula Region II
1755h Buses will depart for the Waikiki Aquarium
1815h – 2030h Welcome Reception – Waikiki Aquarium

Tuesday, 01 March 2011

0900h – 1020h Wave Dynamics and Momentum Transport I
1020h – 1050h Coffee Break
1050h – 1230h Wave Dynamics and Momentum Transport II
1230h – 1400h Lunch on your own
1400h – 1520h General Circulation II
1520h – 1600h Coffee Break
1600h – 1745h Poster Session I – Satellite and Other Observations/Extratropics

Wednesday, 02 March 2011

0900h – 1020h Brewer-Dobson Circulation
1020h – 1050h Coffee Break
1050h – 1150h Quasibiennial Oscillation
1150h Group Photo
1210h – 1400h Lunch on your own
1400h – 1540h Tropical Waves and Tides
1540h – 1600h Coffee Break
1600h – 1745h Poster Session II – Effects in the Tropics/Sources

Thursday, 03 March 2011

0900h – 1020h Observations: Momentum Flux & Parameterization Constraints – Observations I
1020h – 1050h Coffee Break
1050h – 1230h Satellite Observations: GPS Occultation – Observations II
1230h – 1400h Lunch on your own
1400h – 1540h Satellite and Other Observations – Observations III
1540h – 1610h Coffee Break
1610h – 1750h High-Resolution Global Models
1830h – 2100h Conference Dinner – Moana Surfrider, Westin Resort & Spa
1830h – 1930h Reception
1930h – 2100h Dinner

Friday, 04 March 2011

0900h – 1040h Jet/Imbalance Sources – Sources I
1040h – 1110h Coffee Break
1110h – 1230h Waves from Convection: Observations – Sources II
1230h – 1400h Lunch on your own
1400h – 1540h Waves from Convection: Parameterization Issues and Constraints – Sources III
1540h – 1610h Coffee Break
1610h – 1720h Waves from Convective Sources – Sources IV

SCIENTIFIC PROGRAM

MONDAY, 28 FEBRUARY

0945h – 0950h **Aloha and Introduction**

General Circulation: Climate Effects of Parameterized Gravity Wave Drag
Presiding: Kaoru Sato
Keoni Auditorium

0955h – 1020h **Rolando R. Garcia** | Gravity wave parameterizations in high-top models: Successes and problems (INVITED)

Stratospheric Sudden Warmings
Presiding: Tiffany A. Shaw
Keoni Auditorium

1020h – 1040h **Peter Hitchcock** | Gravity wave-driven descent of the stratopause following sudden warmings

1040h – 1110h Coffee Break

1110h – 1130h **Christoph Zülicke** | Response of the mesosphere to stratospheric warmings

1130h – 1150h **Yvan J. Orsolini** | The roles of gravity and planetary waves during a major stratospheric sudden warming characterized by an elevated stratopause

1150h – 1210h **Amal Chandran** | The role of planetary waves and gravity waves in SSW & elevated stratopauses as generated in WACCM

1210h – 1230h **Chihoko Yamashita** | Gravity wave variations during the 2009 stratospheric sudden warming

1230h – 1400h Lunch

Andes and Antarctic Peninsula Region I
Presiding: M. Joan Alexander
Keoni Auditorium

1400h – 1420h **Zhenhua Li** | Gravity wave characteristics in the mesopause over Andes mountains

1420h – 1440h **Teferi D. Demissie** | Climatology of mesospheric gravity waves and their sources above Rothera, Antarctica

1440h – 1500h **Dave Fritts** | SAANGRIA (Southern Andes ANtarctic GRavity wave InitiAtive): A program to study gravity wave coupling from the troposphere into the mesosphere and lower thermosphere

1500h – 1520h **Rene Heise** | How to obtain a large database of measurements on atmospheric gravity Waves

1520h – 1540h **X. Chu** | Long-term variations of gravity waves in the lower atmosphere at McMurdo and the South Pole derived from balloon radiosonde data

1540h – 1610h Coffee Break

Andes and Antarctic Peninsula Region II

Presiding: Albert Hertzog
Keoni Auditorium

1610h – 1630h **Riwal Plougonven** | Non-orographic and orographic sources of gravity waves above Antarctica and the Southern Ocean (INVITED)

1630h – 1650h **Vincent Noel** | Impact of Gravity Wave events on the properties of Polar Stratospheric Clouds over Antarctica from spaceborne lidar observations

1650h – 1710h **Gary R. Swenson** | Observations of High Frequency AGWs observed in mesospheric airglow, and the implication to the AGW imposed zonal stress and the residual circulation

1710h – 1730h **Kaoru Sato** | Program of the Antarctic Syowa MST/IS Radar (PANSY)

1815h – 2030h **Waikiki Aquarium**

Buses are scheduled to depart for Waikiki Aquarium at 1745h, and will return to the Sheraton Princess Kaiulani Hotel at 2030h

TUESDAY, 1 MARCH

Wave Breaking Dynamics and Momentum Transport I

Presiding: Stephen D. Eckermann
Keoni Auditorium

0900h – 0920h **Erich Becker** | Non-orographic gravity waves in general circulation models (INVITED)

0920h – 0940h **Pascale Lelong** | Mixing efficiency of breaking inertia-gravity waves

0940h – 1000h **Dale Durran** | The Up-Scale Influence of Gravity Wave Breaking

1000h – 1020h **Tiffany A. Shaw** | The application of wave-activity conservation laws to cloud resolving model simulations of multiscale tropical convection (INVITED)

1020h – 1050h Coffee Break

Wave Breaking Dynamics and Momentum Transport II

Presiding: Shuguang Wang
Keoni Auditorium

1050h – 1110h **Oliver Buhler** | Internal waves in the atmosphere and ocean

1110h – 1130h **Bruce R. Sutherland** | Parameterization of finite-amplitude internal waves in climate models

1130h – 1150h **Julie Vanderhoff** | Effect of time-dependent, spatially varying shear on vertical propagation of internal wave energy

1150h – 1210h **Steven Businger** | Simulating the effects of gravity waves over Mauna Kea

1210h – 1230h **Matthew O. Hills** | Momentum fluxes and drag profiles of trapped gravity lee waves, and their impact on the large scale flow

1230h – 1400h Lunch

General Circulation II

Presiding: Rolando R. Garcia
Keoni Auditorium

1400h – 1420h **Stephen D. Eckermann** | Gravity-wave Drag Parameterization in a High-Altitude Prototype Global Numerical Weather Prediction System (INVITED)

1420h – 1440h **Fabrizio Sassi** | The effect of temporal correlation on the predictability of the MLT region in a stochastic nonorographic gravity wave drag parameterization

1440h – 1500h **Peter Preusse** | Effects of oblique gravity-wave propagation on middleatmosphere forcing (INVITED)

1500h – 1520h **Erdal Yigit** | Dynamical and Thermal Effects of Gravity Waves in the terrestrial Thermosphere-Ionosphere

1520h – 1550h Coffee Break

1550h – 1745h Poster Session I

Keoni Auditorium

T-1 **Manuel Pulido** | A Comparison of Gravity Wave Drag Parameterizations using Inverse Techniques

T-2 **Kishore Pangaluru** | Study of gravity wave activity in the troposphere and lower stratosphere using the GPS satellite observations

T-3 **Corwin Wright** | HIRDLS gravity wave validation and case studies

T-4 **Peter Preusse** | The ESA gravity wave study

T-5 **Yvan J. Orsolini** | Mesoscale Simulations of Gravity Waves during the 2009 Major Stratospheric Sudden Warming

T-6 **Damian J. Murphy** | Using Antarctic observations to improve gravity-wave parameterization in climate models

T-7 **Simon Alexander** | Wintertime gravity-wave activity in the Antarctic upper stratosphere and lower mesosphere revealed by the Davis (69°S, 78°E) lidar

T-8 **Simon Alexander** | The effect of orographic waves on Antarctic Polar Stratospheric Cloud (PSC) occurrence and composition

T-9 **Charles Bardeen** | Effects of Subgrid Scale Temperature Variability Caused by Gravity Waves Upon Simulations of Polar Mesospheric Clouds

T-10 **Yanping Li** | Observation and theory of the diurnal continental thermal tide

T-11 **Gerd Baumgarten** | Gravity Wave Observations in the Strato- and Mesosphere by Lidar at 54°N and 69°N

T-12 **Bifford P. Williams** | Observations of Large Vertical Winds Associated with Short Period Gravity Waves in the Winter Polar Mesopause Region

T-13 **Ilgin Seker** | The relation between the E-region gravity waves and the Fregion plasma depletions observed with an all-sky imager at Arecibo

WEDNESDAY, 2 MARCH

Brewer-Dobson Circulation

Presiding: Erich Becker
Keoni Auditorium

0900h – 0920h **Kaoru Sato** | On the mechanism of the formation of the Brewer-Dobson circulation and the change in the age of air

0920h – 0940h **Saburo Miyahara** | A three-dimensional wave activity flux applicable to inertio-gravity waves (INVITED)

0940h – 1000h **Neal Butchart** | The response of parameterised gravity wave momentum fluxes in global models to secular changes in climate and ozone and the effects on the general circulation

1000h – 1020h **Edwin P. Gerber** | Probing the interaction between resolved and parameterized waves

1020h – 1040h Group Photo

1040h – 1110h Coffee Break

Quasibiennial Oscillation

Presiding: Takeshi Horinouchi
Keoni Auditorium

1110h – 1130h **Yoshio Kawatani** | The quasi-biennial oscillation in a double CO2 Climate (INVITED)

1130h – 1150h **Thomas Krismer** | Large scale equatorial waves and the quasi-biennial oscillation in ECHAM

1150h – 1210h **Andrew C. Bushell** | Assessing the impact of gravity waves on the tropical middle atmosphere in a General Circulation Model

1210h – 1400h Lunch

Tropical Waves and Tides

Presiding: Yoshio Kawatani
Keoni Auditorium

1400h – 1420h **Leonhard Pfister** | The Effects of Subgrid Scale Gravity Waves on Water Vapor and Clouds in the Tropical Tropopause Layer

1420h – 1440h **Stephanie Evan** | WRF model studies of tropical inertia-gravity waves with comparisons to observations

1440h – 1500h **Nedjeljka Zagar** | Lagre-Scale Equatorial Waves in the Middle Atmosphere Based on Multiyear ECMWF analyses

1500h – 1520h **David Ortland** | On the interaction of the migrating diurnal tide with inertia gravity waves generated by tropical heating

1520h – 1540h **Xian Lu** | Momentum budget analysis on the seasonal variation of the diurnal tide by using the Whole Atmosphere Community Climate Model (WACCM4) and its comparison with the meteor radar and satellite observations

1540h – 1600h Coffee Break

1600h – 1745h Poster Session II

Keoni Auditorium

W-1 **Masakazu Taguchi** | Connection of the Stratospheric Quasi-Biennial Oscillation with El Niño–Southern Oscillation

W-2 **Kiyotaka Shibata** | Gravity wave drag effects on the future quasi-biennial oscillation in the tropical stratosphere under greenhouse gas increase up to year 2100: Simulations with a chemistry-climate model

W-3 **Yoshio Kawatani** | The roles of equatorial trapped waves and internal inertia-gravity waves in driving the quasi-biennial oscillation

W-4 **Ji-Eun Kim** | Space-Time Variability in Precipitation at Scales Relevant to Gravity Waves from Observations and Model Results

W-5 **Fuqing Zhang** | Coupling between gravity waves and tropical convection at mesoscales

W-6 **P. Vinay Kumar** | First observation of quasi-two-day wave in the lower atmosphere over Hyderabad (17.4 N, 78.5 E)

W-7 **Ying-Wen Chen** | Excitation Sources of Ultra-Fast Kelvin waves Simulated by the Kyushu-GCM

W-8 **M.C. Ajay Kumar** | Charecteristics of inertia gravity waves in the lower atmosphere over Hyderabad (17.4 °N, 78.5 °E)

W-9 **Vishnu P. Prasanth** | LiDAR observations of middle atmospheric gravity wave activity over Reunion Island (20.8°S, 55.5°E): Climatological study

W-10 **Tai-Yin Huang** | Gravity Wave-induced Variations in Exothermic Heating in the MLT region

W-11 **Viswanathan L. Narayanan** | Case study of a mesospheric wall wave event

W-12 **Som Kumar Sharma** | Atmospheric Gravity Wave Activity over a Subtropical and Tropical Indian Locations

W-13 **Riwal Plougonven** | Gravity waves emitted from jets: lessons from idealized simulations

W-14 **Stephen D. Eckermann** | Momentum Fluxes of Gravity Waves Generated by Variable Froude Number Flow over Idealized and Realistic Three-Dimensional Orography

W-15 **Alexander S. Medvedev** | Influence of Vertically Propagating Gravity Waves on the Atmosphere of Mars

THURSDAY, 3 MARCH

Observations: Momentum Flux & Parameterization Constraints

Presiding: Robert A. Vincent
Keoni Auditorium

0900h – 0920h **Manfred Ern** | Global Distributions of Gravity Wave Momentum Flux Measured by Satellites: Some Implications for the Dynamics of the Stratoand Mesosphere (INVITED)

0920h – 0940h **Manuel Pulido** | Estimation of Optimal Gravity Wave Parameters for Climate Models using a Hybrid Genetic-Variational Technique (INVITED)

0940h – 1000h **Albert Hertzog** | Balloon-Borne Observations of Gravity-Wave Momentum Fluxes over Antarctica and Surrounding Areas (INVITED)

1000h – 1020h **M. Joan Alexander** | Mountain Wave Momentum Fluxes in the Southern Hemisphere from Satellite Measurements

1020h – 1050h Coffee Break

Satellite Observations: GPS Occultation

Presiding: Peter Preusse
Keoni Auditorium

1050h – 1110h **Takeshi Horinouchi** | Analysis of spatial structure of gravity waves using GPS occultation data (INVITED)

1110h – 1130h **Antonia Haser** | Detailed Analysis of Horizontal Wave Parameters using Radio Occultation Data

1130h – 1150h **Adrian McDonald** | Measuring gravity wave intermittency and propagation directions from satellite observations

1150h – 1210h **Pablo Llamedo Soria** | Long-term global GW activity in lower and middle atmosphere from CHAMP, GRACE and COSMIC radio occultation data between 2001 and 2010

1210h – 1230h **Simon Alexander** | Global observations of stratospheric gravity waves made with COSMIC GPS-RO and comparisons with an atmospheric general circulation model

1230h – 1400h Lunch

Satellite and Other Observations

Presiding: Madineni Venkat Ratnam
Keoni Auditorium

1400h – 1420h **Jie Gong** | Gravity wave signatures in AIRS radiances: Can AIRS observe wave scales shorter than its weighting function thickness?

1420h – 1440h **Amitava Guharay** | Rayleigh lidar observations of gravity wave seasonal variability over a tropical site

1440h – 1500h **Sherine R. John** | Investigations On Gravity Wave Potential Energy Seen By Different Satellites And Ground Based Techniques

1500h – 1520h **Viswanathan L. Narayanan** | Characteristics of high frequency gravity waves in the upper mesosphere observed in OH nightglow over low latitude Indian sector during 2007

1520h – 1540h **Gopa Dutta** | Frequency dependence of gravity wave energy and momentum flux estimates in the lower atmosphere using Gadanki MST radar observations

1540h – 1610h Coffee Break

High-Resolution Global Models

Presiding: Manuel Pulido
Keoni Auditorium

1610h – 1630h **Kevin P. Hamilton** | Topographic Drag in Ultra-Fine Resolution Global Simulations

1630h – 1650h **Shingo Watanabe** | Brief History of Ultra-High Resolution Global Model Studies and Future Plans (INVITED)

1650h – 1710h **Tomoki Ohno** | A new estimation method of the momentum fluxes associated with gravity waves: An application to gravity-wave-resolving general circulation model data

1710h – 1730h **Chikara Tsuchiya** | Universal frequency spectra of the short period fluctuations

1730h – 1750h **Kazuyuki Miyazaki** | Transport and mixing in the extratropical tropopause region in a high vertical resolution GCM

1830h – 2100h **Conference Dinner Moana Surfrider**

Moana Surfrider, Westin Spa & Resort
2365 Kalakaua Avenue
The Moana Surfrider is locate approximately 1 block down from the Princess Sheraton Kaiulani Hotel.

FRIDAY, 4 MARCH

Jet/Imbalance Sources

Presiding: Riwal Plougonven
Keoni Auditorium

0900h – 0920h **Shuguang Wang** | Gravity Wave Sources in Tropospheric Weather Systems (INVITED)

0920h – 0940h **Junhong Wei** | Aircraft Measurements And Numerical Simulations Of Gravity Waves In The Extratropical UTLS Region During The START08 Field Campaign

0940h – 1000h **Norihiko Sugimoto** | Spontaneous gravity wave radiation from unsteady rotational flows in a rotating shallow water system

1000h – 1020h **Paul D. Williams** | Gravity Waves in the Laboratory: Mechanisms, Properties, and Impacts

1020h – 1040h **Fuqing Zhang** | Dynamics and Impacts of Gravity Waves in the Baroclinic Jet-Front Systems with Moist Convection (INVITED)

1040h – 1110h Coffee Break

Waves from Convection: Observations

Presiding: Hye-Yeong Chun
Keoni Auditorium

1110h – 1130h **Alison W. Grimsdell** | Model study of waves generated by convection with direct validation via satellite

1130h – 1150h **Robert A. Vincent** | Gravity Wave Generation by Tropical Convection and Middle Atmosphere Response (INVITED)

1150h – 1210h **Jia Yue** | Concentric gravity waves generated by deep convections in the Great Plain and observed by all-sky airglow imager in the mesopause

1210h – 1230h **Debashis Nath** | Characterization of the sources of Gravity Waves over the Tropical Region, using High Resolution Measurements

1230h – 1400h Lunch

Waves from Convection: Parameterization Issues and Constraints

Presiding: Manfred Ern
Keoni Auditorium

1400h – 1420h **Hye-Yeong Chun** | Convective Gravity Waves and Their Parameterization: Current Status and Issues (INVITED)

1420h – 1440h **Michael J. Reeder** | Nonlinear Processes and Their Role in the Generation of Gravity Waves by Convective Clould

1440h – 1500h **Peter T. Love** | Observational Constraints on the Spectrum of Gravity Waves Generated by Tropical Convection

1500h – 1520h **Hyun-Joo Choi** | Momentum Flux Spectrum of Convective Gravity Waves: Impacts of an Updated Parameterization in a GCM

1520h – 1540h **Young-Ha Kim** | Effects of the Convective Gravity-Wave Drag Parameterization in the Global Forecast System of the Met Office Unified Model in Korea

1540h – 1610h Coffee Break

Waves from Convective Sources

Presiding: Fuqing Zhang
Keoni Auditorium

1610h – 1630h **Madineni Venkat Ratnam** | Gravity wave forcing and its effects in entire middle atmosphere: Study under Atmospheric Forcing and Responses (SAFAR), a major NARL campaign (INVITED)

1630h – 1650h **Dong L. Wu** | Gravity waves and cloud structures: AIRS observations

1650h – 1710h **Timothy J. Dunkerton** | Sources of Gravity Waves in Hurricanes

1710h – 1730h **So-Young Kim** | Influence of gravity waves generated by typhoon on the typhoon development

Final ID:

Gravity wave parameterizations in high-top models: Successes and problems (*INVITED*)

R. R. Garcia; [1]; *L. de la Torre;* [2]; *D. Marsh;* [1];
1. NCAR, Boulder, CO, United States.
2. Universidade de Vigo, Ourense, Spain.

Body: Gravity waves parameterizations, based on Lindzen's saturation hypothesis, were first introduced into comprehensive, two-dimensional models of the middle atmosphere over a quarter century ago, and where quickly shown to improve fundamentally the simulation of the circulation, temperature and chemical structure of the mesosphere and lower thermosphere (MLT). Since that time, new and more refined parameterizations have been deployed, which have further improved the performance of (now three-dimensional) middle atmosphere models, although these improvements are arguably incremental rather than fundamental. This talk reviews the state of gravity wave parameterizations using as an example NCAR's Whole Atmosphere Community Climate Model (WACCM). It is shown that gravity wave effects are important for simulating certain middle atmospheric phenomena, including trends in summer mesospheric temperatures and in the Brewer-Dobson circulation, the behavior of separated-stratopause events following stratospheric sudden warnings, and the tropical quasi-biennial oscillation. Nevertheless, many difficult to treat problem areas remain, which arise from the necessary simplifications embodied in the typical implementations of gravity wave parameterizations.

Contact Information: Contact Information

Rolando R. Garcia, Boulder, Colorado, USA, 80307-3000, click here to send an email

Final ID:

Gravity Wave-Driven Descent of the Stratopause Following Sudden Warmings

P. Hitchcock;[1]; T. Shepherd;[1];
1. Physics, University of Toronto, Toronto, ON, Canada.

Body: The zonal mean winds and temperatures in the Arctic polar vortex undergo a characteristic and robust evolution for up to several months following certain stratospheric sudden warmings as planetary wave propagation into the vortex is strongly suppressed. Zonal mean temperature anomalies from satellite observations show a tripolar structure corresponding to the initial, planetary wave-driven warming in the lower stratosphere, radiatively-driven cooling in the mid stratosphere, and gravity wave-driven warming in the upper stratosphere and mesosphere.

We present a dynamical analysis of the gravity-wave driven features of these episodes as modeled by the Canadian Middle Atmosphere Model, a chemistry-climate model. The suppression of planetary wave activity during these events allows the stratospheric flow to evolve on radiative timescales, making the effects of gravity waves in the polar mesosphere clear. These events may also provide a useful means of testing gravity wave drag parameterizations.

Contact Information: Contact Information

Peter Hitchcock, Toronto, Ontario, Canada, M5S 1A7, <a href='mailto:
peterh@atmosp.physics.utoronto.ca?subject=agu-cc11gw: Question regarding '>click here to send an email

Final ID:

Response of the mesosphere to stratospheric warmings

C. Zülicke; [1]; *E. Becker;* [1];

1. Theory and Modelling, Leibniz Institute of Atmospheric Physics, Kühlungsborn, Germany.

Body: The appearance of mesospheric coolings and wind reversals during sudden stratospheric warmings is studied as an example of vertical coupling in the middle atmosphere. The data are simulations of the Kühlungsborn Mechanistic Circulation Model. First the statistics of such events is compared with the indices proposed Charlton & Polvani (2007). As well the frequency as well as the intensity appear to be realistic. Second, the relation of stratospheric warmings to mesospheric coolings is studied. These appear correlated in 92 % of the variance as is shown with a specially developed coherency index. The third phenomenon, the correlation of wind reversals in the stratosphere and the mesosphere, is not as clear – 75 % of the variance appears to be coherent, while 25 % are anticoherent. This behavior is consistent with the thermal wind equation as has been proven. The question for cause and reason for different structures of the mass and flow field is discussed.

Contact Information: Contact Information

Christoph Zülicke, Kühlungsborn, Germany, 18119, click here to send an email

Final ID:

The roles of gravity and planetary waves during a major stratospheric sudden warming characterized by an elevated stratopause

Y. J. Orsolini; [1]; *V. Limpasuvan;* [2]; *J. B. Richter;* [3];
1. Norwegian Institute for Air Research, Kjeller, Norway.
2. Coastal Carolina University, Conway, SC, United States.
3. NCAR, Boulder, CO, United States.

Body: Stratospheric sudden warmings (SSWs) contribute significantly to the inter-annual variability of the wintertime polar middle atmosphere, and couple the stratospheric circulation with that of the mesosphere, as well as that of the troposphere. During SSWs, the separation of the winter polar stratopause has long been recognized as a gravity wave (GW) driven feature, and GWs play a large role in the observed mesospheric coupling. While historical observations have demonstrated that the polar stratopause plunges down during the onset of SSWs, recent satellite observations further reveal that SSWs can be accompanied by an abrupt "jump", or reformation, of the stratopause near 75km, at what are normally mesospheric altitudes. The reformed stratopause then descends to its climatological altitude over a period of 1-2 months as the polar vortex recovers.

We show evidence of such stratopause "jumps" in mesospheric temperatures from microwave observations from the Odin satellite. We analyze cases of SSWs simulations of the National Center for Atmospheric Research (NCAR) Whole Atmosphere Community Climate Model (WACCM3.5), which show a realistic SSW occurrence frequency. The planetary and gravity wave forcings are examined in detail using the Transform Eulerian Mean diagnostic. We investigate the respective roles of parametrized orographic and non-stationary (frontal or convective) GWs, during the development of the SSW and of the zonal wind reversal, and demonstrate that eastward GWs of frontal origin and planetary waves play key roles during the stratopause reformation at high altitudes. The impact on the residual circulation in the opposite, summer hemisphere is discussed.

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Yvan J. Orsolini, Kjeller, Norway, 1900, click here to send an email

Final ID:

The role of planetary waves and gravity waves in SSW & elevated stratopauses as generated in WACCM

A. Chandran; [1]; *R. Collins;* [1]; *R. Garcia;* [2]; *D. Marsh;* [2];

1. Geophysical Institute and Department of Atmospheric Sciences, University of Alaska , Fairbanks, AK, United States.

2. ACD, NCAR, Boulder, CO, United States.

Body: The Whole Atmosphere Community Climate Model (WACCM) spontaneously generates multiple stratospheric sudden warming (SSW) events in simulations of the period between 1953-2006. These SSWs include extreme warming events where the polar vortex breaks down throughout the stratosphere followed by the reformation of an elevated stratopause at a high altitude, which then gradually drops in altitude and warms. This is similar to the 2005/2006 major SSW in the northern hemisphere which has been extensively documented and studied from observations. In this study we analyze the general circulation and dynamics of the upper stratosphere and mesosphere during winters with both major and minor warming events as well as during quiet years with no SSW. The SSW is triggered by strong planetary wave activity, which then reverses the polar jet-stream and changes the gravity wave forcing in the middle atmosphere. We also quantify the role of gravity waves in the formation of the elevated stratopause, reformation of the polar vortex, and coupling between the stratosphere, mesosphere, and lower thermosphere. The latitudinal and longitudinal variations in both planetary waves and gravity wave forcing and the relative contributions of each to the circulation during these events are also studied. We present statistics on the frequency of occurrence of SSW events and elevated stratopause events over the 53 winters in the free running version of WACCM and assess the inter-annual variability in the polar circulation.

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Final ID:

Gravity Wave Variations during the 2009 Stratospheric Sudden Warming

C. Yamashita;[1, 2]; H. Liu;[1]; X. Chu;[2];

1. HAO / NCAR, Boulder, CO, United States.

2. CIRES and University of Colorado, Boulder, CO, United States.

Body: Gravity waves are one of the key elements for driving the atmospheric coupling from the stratosphere to the thermosphere during stratospheric sudden warmings (SSWs). The limited knowledge of gravity wave variations and their source distribution leads to the uncertainty in the SSW simulations by general circulation models. In this study, ECMWF-T799 (0.25° horizontal resolution and 91 vertical levels up to 0.01 hPa) is used to study gravity wave variations and their source variations during the 2009 SSW. Resolved gravity waves in ECMWF-T799 are validated with COSMIC/GPS and lidar observations in the polar regions.

ECMWF results show that overall gravity wave strength increase prior to the 2009 SSW. The magnitude and occurrence of gravity waves correlate well with the location and strength of the polar vortex that is strongly distorted by planetary wave growth. During the development and onset of SSW, the zonal-mean gravity wave potential energy density (GW-Ep) increases on January 5 and 15-22 in association with the growth of planetary wave wavenumber 1 and wavenumber 2, respectively. The altitude where PWs reach maximum amplitude is initially in the lower mesosphere, and then progress downward. GW-Ep enhancement also seems to show a corresponding descent from January 5-22. GW-Ep peaks before the wind reversal and significantly weakens after the SSW. These variations are confirmed by COSMIC/GPS observations. To better understand the gravity wave variations, both statistical study and case study of gravity wave source variations will be presented.

Contact Information: Contact Information

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Chihoko.Yamashita@colorado.edu?subject=agu-cc11gw: Question regarding '>click here to send an email

Final ID:

Gravity Wave Characteristics in the Mesopause over Andes Mountains

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3. Physical Sciences, Embry-Riddle Aeronautical University, Daytona Beach, FL, United States.

Body: Gravity wave parameters in the mesopause region were analyzed from newly acquired all sky imager data taken at the Andes Lidar Observatory (ALO) at Cerro Pachón, Chile (30 S, 71W) with collocated meteor radar providing background wind (Sep 2009 to present). The wave propagation directions, phase speed, and horizontal and vertical wavelengths were derived. The results from this mountainous site were compared with results using the data from Maui (21N, 157 W, 2002-2007), an oceanic site. The comparisons between the results at these two sites show common features such as dominant wave phase speed, and horizontal wavelength. However, the directionality of wave propagation shows strong seasonal and geographical differences. Gravity wave momentum flux shows a strong seasonal and diurnal variation that is anti-correlated with the background mean wind. The implications of the roles played by the momentum flux deposition on the mean flow are explored on both seasonal and diurnal time scale. The seasonal/diurnal variations of occurrence frequencies of propagating and evanescent waves are also examined. Several unusual wave events, including bore-like features and large amplitude waves will be presented.

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Final ID:

Climatology of mesospheric gravity waves and their sources above Rothera, Antarctica

T. D. Demissie; [1]; *P. J. Espy;* [1]; *H. Lund;* [1]; *R. E. Hibbins;* [1, 2];

1. Norwegian University of Science and Technology, Trondheim, Norway.
2. The British Antarctic Survey, Cambridge, United Kingdom.

Body: A ten-year time series of hydroxyl airglow measurements from 68 S have been used to infer the wintertime climatology of gravity-wave variance above the Antarctic Peninsula. The hydroxyl temperature and radiance fluctuations have been combined with simultaneous radiosonde and radar observations of the wind field to trace the mesospheric gravity waves back to their source regions. This has been carried out during periods of high and low gravity-wave activity to examine the effects of source region and wind direction on the net flux of gravity waves reaching the mesosphere. The climatology of the gravity-wave variance and source regions will be presented, and the implications of variations in gravity-wave flux for inter-hemispheric coupling will be discussed.

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Final ID:

SAANGRIA (Southern Andes ANtarctic GRavity wave InitiAtive): A program to study Gravity Wave Coupling from the Troposphere into the Mesosphere and Lower Thermosphere

S. Eckermann; [4]; *D. Fritts;* [1]; *R. Smith;* [2]; *J. Doyle;* [3]; *M. Taylor;* [5];

1. CoRA, NorthWest Research Associates, Boulder, CO, United States.
2. Department of Geology and Geophysics, Yale University, New Haven, CT, United States.
3. Naval Research LAboratory, Monterey, CA, United States.
4. Naval Research LAboratory, Washington DC, DC, United States.
5. Department of Physics, Utah State University, Logan, UT, United States.

Body: SAANGRIA is a major airborne and ground-based measurement and modeling program intended to quantify gravity wave (GW) sources in the lower atmosphere, their propagation through the stratosphere, and their interactions, instability dynamics, momentum deposition, and effects in the MLT.

These objectives will be addressed by comprehensive measurements and advanced modeling. Ground-based and airborne measurements would assess mean, tidal, and GW structures from ~30 to 70S. A suite of numerical modeling capabilities will permit detailed comparisons with observations, a singular vector evaluation of upstream influences and initial conditions, assessments of the effects of OGW instability dynamics on momentum transport, and the impacts of these dynamics on the circulation, structure, and variability of the MLT. Testing of OGW drag parameterizations in global models would be enabled by comprehensive observations, well-defined OGW forcing conditions, and high-resolution models of local terrain responses.

SAANGRIA would employ the NCAR/NSF Gulfstream V (G-V) research aircraft with existing and newly funded remote-sensing instrumentation during a 10-week field program during austral winter 2013 from a base at Punta Arenas, Chile. The southern Andes, Drake Passage, and Antarctic Peninsula region includes a number of major GW sources and exhibits the largest gravity wave variances in the stratosphere observed anywhere on Earth, making this a natural laboratory for such a study. New instruments for the G-V include Rayleigh and resonance lidars and a mesospheric temperature mapper that will extend G-V measurement capabilities from a current ceiling of ~20 km to ~100 km. These measurement capabilities will be augmented by new ground-based measurements of MLT structure and dynamics at sites from ~30 to 68 degrees south.

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Final ID:

How to obtain a large Database of Measurements on atmospheric Gravity Waves

R. Heise; [3]; *A. Ultsch;* [1]; *J. Hacker;* [2];
1. Databionics, University of Marburg, Marburg, Germany.
2. Flinders Centre for Airborne Research, Flinders University, Adelaide, SA, Australia.
3. Mountain Wave Project, Berlin, Germany.

Body: The accurate prediction of atmospheric gravity waves and the associated turbulence is a challenge for meteorological forecasting. A collection of empirical flight data is essential in order to improve the prediction quality of meteorological models for atmospheric gravity waves. Inflight measures using research airplanes are costly and such data is rare. There is, however, a low cost source of empirical data on atmospheric gravity waves: GPS-logger files of glider flights. In 2009, for example, more than 100 such flights have been made in the Andes of South America covering more of 50.000 km, most of them in mountain waves (MTW). This work describes the mathematical and statistical Data Mining and Knowledge Discovery techniques that are necessary in order to make meteorological use of this data source. Results on the occurrence, location and probabilities of MTW in the South-American Andes as extracted from such flights are presented. Furthermore an approach to verify the identification of gravity wave patterns in GPS logger data based on Machine Learning techniques is presented. With these results, a first approach to a wave-climatology of the Andes and the visualization of turbulence classification of the rotor-wave system for briefing products in general and commercial aviation is possible. As part of the Mountain Wave Project (MWP) several flights with state-of-the-art meteorological and flight-parameter instrumentation were made over the Andes near Mendoza, Argentina. This data serves as a benchmark for the accuracy of the GPS-logger derived data.

URL: www.mountain-wave-project.com

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Final ID:

Long-term variations of gravity waves in the lower atmosphere at McMurdo and the South Pole derived from balloon radiosonde data

X. Chu; [1]; *Z. Yu;* [1]; *A. J. McDonald2;* [2]; *C. Yamahsita;* [1]; *C. S. Gardner;* [3];
1. Aerospace Engineering and Sci., Univ. of Colorado at Boulder, Boulder, CO, United States.
2. University of Canterbury, Canterbury, New Zealand.
3. ECE, University of Illinois, Canterbury, IL, United States.

Body: Gravity wave perturbations in vertical profiles of temperature and wind are extracted from meteorological balloon radiosonde measurements during 1997-2010 at McMurdo station and 1993-2010 at the South Pole. Based on these perturbations, the seasonal, long-term and vertical variability of potential energy density, Ep, and kinetic energy density, Ek,are investigated. Preliminary results show that Ep and Ek exhibit large seasonal variations, and also suggest the ratio of Ek/Ep may change with geographical locations. Background temperature and wind effects on propagation conditions (e.g. critical level filtering) and, variations in the gravity wave source spectra, are all potential factors that play roles in the observed climatology. The correlation between gravity wave energy in the lower atmosphere and the mean wind is examined. We will also study the seasonal and long-term variations of the slope of the vertical wavenumber spectrum, derived from temperature and wind perturbations, and the probability of wave propagation directions using the Stokes parameter methodology.

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Final ID:

Non-orographic and orographic sources of gravity waves above Antarctica and the Southern Ocean (*INVITED*)

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2. Laboratoire de Meteorologie Dynamique, Ecole Polytechnique, Palaiseau, France.

Body: A major weakness of Gravity Wave (GW) parameterizations is the representation of sources, in particular non-orographic ones. These are most often arbitratily set, and tuned to yield a satisfactory circulation in the middle atmosphere. This stems both from our lack of physical understanding of the mechanisms involved, in particular GW radiation from jets and fronts, and from insufficient constraints from observations and modelling.

We will present results from meso-scale simulations covering two months (October 21 to December 18, 2005) for a domain covering Antarctica and the Southern Ocean (10,000 x 10,000 km, with a resolution dx = 20 km). These simulations contribute to both endeavours:

- they constitute a realistic counterpart to the idealized baroclinic life cycles which have strongly contributed over the past fifteen years to our understanding of GW radiation from jets;
- they complement the Vorcore observational campaign, during which 27 superpressure balloons were launched into the stratospheric polar vortex (September 2005-Januray 2006).

The first issues investigated in these simulations are:

1- how comparable are the simulated GW relative to the balloon observations from the Vorcore campaign?

2- how similar are non-orographic waves in these real-case simulations to those found in idealized baroclinic life cycles?

In answer to 1, it appears that the simulations succeed in capturing the overall distribution of momentum fluxes due to GW in the lower stratosphere, with a distinct maximum over the Antarctic Peninsula, yet these fluxes are somewhat underestimated relative to the estimations from the balloons. The resolution used (dx=20km) is generally insufficient for a detailled comparison to be made for individual wave packets. To test the sensitivity to resolution, nine days were simulated with doubled horizontal resolution. Momentum fluxes are nearly doubled, most of the changes affecting the vertical velocity (finer structure, enhanced amplitudes). In agreement with Vorcore observations, the overall contribution from oceanic regions is comparable to that from regions with orography, but intermittency is far greater over the latter. The comparison also sheds new light on the uncertainties and limitations of the estimations made from Vorcore measurements.

In answer to 2, the real case simulations do show cases of gravity waves present in jet exit regions, with wave capture playing a role, similar to the configuration emphasized in several studies of idealized simulations (baroclinic waves and dipoles). However, the wave field has significantly greater complexity than that analyzed in the idealized simulations, indicating that contributions from other generation mechanisms need to be taken into account.

The third set of questions we can investigate in these simulations concern the sources: what diagnostic from the large-scale flow is relevant to quantify emission from jets and fronts? How wide an area is affected by waves originating from mountains, including through secondary generation? Preliminary results on these issues will be discussed.

URL: http://www.lmd.ens.fr/plougon/

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Final ID:

Impact of Gravity Wave events on the properties of Polar Stratospheric Clouds over Antarctica from spaceborne lidar observations

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2. LMD, UPMC, Paris, France.

Body: The formation and properties of Polar Stratospheric Clouds (PSCs) are extremely dependent on their formation temperature. Depending on the stratospheric concentrations of chemical species, various temperature thresholds define PSC composition: Nitric Acid Trihydrate (NAT) or Sulfuric Ternary Solutions (STS) particles, ice crystals, or a mixture thereof. Most notably, ice-based PSCs (Type II in lidar observation terminology) require colder temperatures than NAT- or STS-based PSCs (Type Ia and Ib). On the other hand, ice-based PSC form in a relatively short time, while other PSCs require temperature to stay below their formation threshold for a much longer period (days or weeks). During the Antarctic winter, stratospheric temperatures are generally in a range conducive to the formation of Type Ia and Ib PSCs, even if their dominant nucleation mechanisms are still not well understood. Type II PSCs are rarer overall, as temperatures cold enough for their formation is less frequent.

This description based on temperature is generally considered sufficient to explain the spatial and temporal distribution of PSCs. A recent theory however suggests that ice-based PSCs might play a more substantial role in the formation of NAT- and STS-based PSCs. According to the mountain-wave seeding hypothesis, ice-based PSCs form quickly following intense temperature drops due to gravity wave events propagating in the mid-stratosphere ; melting ice crystals exiting the gravity wave region then act as the basis for fast NAT nucleation. NAT particles are then widely disseminated around the Antarctic continent by the strong winds of the polar vortex.

We aim to study the validity of this hypothesis by evaluating the impact of gravity wave events on the population of PSCs. PSC observations will be presented from the spaceborne lidar CALIOP, which is able to identify PSC altitude and composition with high accuracy. These observations will be correlated with high-resolution mesoscale simulations over the Antarctic peninsula and extensive time periods to detect gravity wave events and evaluate their importance on PSC properties over the course of a full PSC season.

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Final ID:

Observations of High Frequency AGWs observed in mesospheric airglow, and the implication to the AGW imposed zonal stress and the residual circulation

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2. Physical Sciences, Embry Riddle Aeronautical University, Daytona Beach, FL, United States.
3. Atmospheric Sciences, University of Illinois, Urbana, IL, United States.

Body: An important circulation system described by Houghton (1978), is the residual circulation associated with the stress imposed on the zonal winds by AGWS in the upper stratosphere and mesosphere. Several subsequent studies have further characterized the residual circulation including Holton and Zhu (1984) and Zhu et al. (1997, 2001, and 2010). The zonal stress from the filtered AGWs for the respective hemisphere (winter and summer) drives the flow from the summer to winter polar regions, with a peak near solstice, and induces an upwelling in summer and downwelling in winter. This important circulation system constitutes a dynamic coupling between the mesosphere and lower atmosphere which drives composition exchange, including triatomic molecules, some of which are greenhouse gases. Observations of the climatologies of AGW directions and momentum fluxes have been made by a number of imagers at low, mid, and high latitude stations. The directional climatologies of those observations are assembled here to show that the dominant wave fluxes are meridional, toward the summer pole for low and mid latitude sites. The AGW hot spot, near the Antarctic circle is shown to be exclusively zonal. These results will be presented along with a discussion of the implications for the high frequency AGW effects on the residual circulation.

Houghton, J. T., (1978) The stratosphere and mesosphere, Quart. J. R. Met. Soc., 104, 1-29.

Holton, J. R. and X. Zhu, (1984) A further study of gravity wave induced drag and diffusion in the mesosphere, J. Atmos. Sci., 41, 2653-2662.

Zhu, X., P. K. Swaminathan, J. H. Yee, D. F. Strobel, and D. Anderson, (1997) A globally balanced two-dimensional middle atmosphere model: Dynamical studies of mesopause meridional circulation and stratosphere-mesosphere exchange, J. Geophys. Res., 102, 13,095-13,112.

Zhu, X, J-H Yee, and E. R. Talaat, (2001) Diagnosis of dynamics and energy balance in the mesosphere and lower thermosphere, J. Atmos. Sci., 58, 2441-2453.

Zhu, X., J.-H Yee, W. H. Swartz, E. R. Talaat, and L. Coy, (2010) A spectral parameterization of drag, eddy diffusion and wave heating for a three-dimensional flow induced by breaking gravity waves, J. Atmos. Sci., 67, 2520-2536.

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Final ID:

Program of the Antarctic Syowa MST/IS Radar (PANSY)

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1. Department of Earth and Planetary Science, University of Tokyo, Tokyo, Japan.
2. National Institute of Polar Research, Tokyo, Japan.
3. Kyoto University, Kyoto, Japan.

Body: Syowa Station is one of the distinguished stations, where various atmospheric observations for research purposes by universities and institutes as well as operational observations by Japan Meteorological Agency and National Institute of Information and Communications Technology are performed continuously. National Institute of Polar Research plays a central part in the operations. The observation of the Antarctic atmosphere is important in two senses. First, it is easy to monitor weak signal of the earth climate change because contamination due to human activity is quite low. Second, there are various unique atmospheric phenomena in the Antarctic having strong signals such as katabatic flows, the ozone hole, noctilucent clouds, and auroras. The middle atmosphere is regarded as an important region to connect the troposphere and ionosphere. However, its observation is sparse and retarded in the Antarctic compared with the lower latitude regions; nevertheless the vertical coupling through the mechanisms such as momentum transport by gravity waves is especially important in the polar region.

Since 2000, we have developed an MST/IS radar to be operational in the Antarctic and have made feasibility studies including environmental tests at Syowa Station. Various significant problems have been already solved, such as treatment against low temperature and strong winds, energy saving, weight reduction, and efficient construction method. A current configuration of the planned system is a VHF (47MHz) Doppler pulse radar with an active phased array consisting of 1045 yagis.

The value of the PANSY project has been approved internationally and domestically by resolutions and recommendations from international scientific organizations such as IUGG, URSI, SPARC, SCOSTEP, and SCAR. The scientific research objectives and technical developments have been frequently discussed at international and domestic conferences and at a scientific meeting at NIPR organized by the PANSY group every year. Special and union sessions of PANSY were organized at related scientific societies such as MSJ (Meteorological Society of Japan), SGEPSS (Society of Geomagnetism and Earth, Planetary and Space Sciences) and JpGU (Japan Geophysical Union) to deepen the discussion. The PANSY project was authorized as one of main observation plans for the period of JARE52-57 in 2008, and funded by Japanese government in 2009. We will start the radar construction in early 2011. After one year for initial test observations, MST/IS observations will be made over 12 years which covers one solar cycle.

URL: http://pansy.eps.s.u-tokyo.ac.jp

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Final ID:

Non-orographic gravity waves in general circulation models (*INVITED*)

E. Becker; [1];

1. Theory and Modelling, Leibniz-Institute of Atmospheric Physics, Kuehlungsborn, Germany.

Body: This contribution focusses on the extratropical effects of non-orographic gravity waves (GWs) in the mesosphere and discusses issues concerning the representation of GWs in general circulation models (GCMs). First, the wave driving concept along with Lindzen's explanation of the summer-winter-pole circulation in the upper mesosphere is recapitulated. Current GW parameterizations are based on this framework with regard to quasi-linear theory, the single-column approximation, and a stationary GW kinetic energy equation. Beside these strong assumptions, the interaction between GWs and turbulent diffusion is often not clear. This holds in particular for parameterizations that describe a continuous GW spectrum and specify some instability criterion for spectral truncation: Conservative wave propagation is usually assumed up to a level of wave obliteration; the resolved large-scale flow, on the other hand, is subject to the turbulent diffusion estimated from wave obliteration while the unobliterated GWs continue to propagate conservatively. This inconsistency is avoided in the framework proposed by Becker and McLandress (2009, JAS). Some results obtained with a correspondingly extended version of the Doppler-spread parameterization are presented. Furthermore, the general framework for the direct thermal GW effects is outlined.

A high-resolution GCM with explicit simulation of GWs is a possible measure to circumvent the aforementioned problems and assumptions. However, a suitable turbulent diffusion still must be specified in order to properly describe GW-mean flow interaction. Some results obtained with a mechanistic GCM are presented where the diffusion scheme is based on a combination of Smagorinsky's mixing length approach and the Richardson criterion for dynamic instability (Becker, 2009, JAS). Besides the expected resolution dependence of the relevant GW scales, the model concept describes non-orographic extratropical GWs and their effects in the mesosphere in a quite satisfactory way. A sensitivity experiment shows that the dynamical GW sources in the storm tracks increase with a more intense energy cycle, leading to a robust cooling of the summer mesosphere in accordance with downward control.

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Final ID:

Mixing efficiency of breaking inertia-gravity waves

P. Lelong; [1]; *P. Bouruet-Aubertot;* [2];
1. Northwest Research Associates, Seattle, WA, United States.
2. LOCEAN-IPSL, Univ. of Paris VI, Paris, France.

Body: The energy budgets of numerically simulated monochromatic breaking inertia-gravity waves are analyzed for a broad range of wave frequencies and amplitudes. Whereas low-frequency waves are most unstable to shear instability, higher-frequency waves break preferentially via convective instability and intermediate-frequency waves exhibit a hybrid shear-convective instability. We find that at high frequencies, the bulk of the mixing occurs in the pre-turbulent phase of wave breaking. This corresponds to the regime where dissipation is weak relative to the diapycnal flux. At low frequencies and high amplitudes, the peak in mixing is in phase with the fully turbulent regime. For convectively stable low-frequency waves, significant mixing occurs once again in the pre-turbulent regime. The relative duration (in wave periods) of pre-turbulent to turbulent phases appears to govern whether a wave will mix efficiently or not prior to turbulent breakdown. These results are in general agreement with those of Inoue and Smyth (JPO, 2009) who considered the mixing associated with instability of shear flows subjected to time-periodic forcing. We also find that mixing efficiencies are highest for high-frequency waves. The dependence on Prandtl number is also examined, with higher Prandtl numbers leading to weaker mixing rates.

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Final ID:

The Up-Scale Influence of Gravity Wave Breaking

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1. Atmospheric Sciences, University of Washington, Seattle, WA, United States.
2. National Center for Atmospheric Research, Boulder, CO, United States.

Body: The interaction of breaking mountain waves with the large-scale flow is examined during the passage of dynamically consistent time-evolving synoptic-scale flow over an isolated 3D mountain. At the ridgetop, the synoptic-scale flow accelerates and then decelerates with a period of 50 hours; the maximum wind arrives over the mountain at 25 hours. The impact of transient mountain-wave breaking is to produce a region of flow deceleration downstream of the mountain, flanked by broader regions of weak flow acceleration in the zonally averaged momentum field (see Fig. 1). Cancellation between the accelerating and decelerating regions results in weak fluctuations in the volume-averaged zonal momentum, suggesting that the mountain-induced circulations are primarily redistributing momentum. Potential vorticity anomalies develop in a region of wave breaking near the mountain and induce local regions of flow acceleration and deceleration that alter the large-scale flow.

A "perfect" conventional gravity-wave-drag parameterization is tested in a coarser-resolution model without a mountain. This parameterization scheme only produces a weak spatial response in the momentum field, and it fails to produce enough flow deceleration near the jet core. These results suggest that the potential vorticity sources attributable to gravity-wave breaking have a controlling affect on the synoptic-scale response that ultimately develops downstream of the mountain.

URL: http://www.atmos.washington.edu/~durrand/pdfs/AMS/2007Chen_Hakim_Durran.pdf

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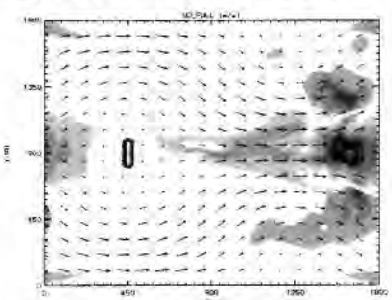

Fig. 1: Large-scale horizontal wind vectors and perturbation x-component velocities (gray scale, contour interval 1 m/s). The region on the centerline near the jet exit is decelerated, the two patches to the north and south are accelerated. The ridge is shown by elevation contours.

Final ID:

The application of wave-activity conservation laws to cloud resolving model simulations of multiscale tropical convection (*INVITED*)

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2. Department of Applied Physics and Applied Mathematics, Columbia University, New York, NY, United States.
3. School of Earth Sciences, The University of Melbourne, Melbourne, VIC, Australia.

Body: Pseudomomentum and pseudoenergy wave-activity diagnostics are applied to cloud resolving model simulations of multiscale tropical convection. Wave-activity conservation laws are the relevant budgets to consider when examining the transfers of momentum and energy between a disturbance (the convection and waves) and a background (shear-stratified) flow. The vertical fluxes of pseudomomentum represent those parameterized in climate models and include pseudomomentum transfers due to convection (convective momentum transport) and gravity waves (gravity wave drag).

The wave-activity diagnostics reveal that both non-conservative (diabatic) and transient processes contribute to the generation of the vertical fluxes of pseudomomentum and pseudoenergy. A spectral decomposition reveals that each horizontal phase speed spectral element has a source region between the surface and the uppermost cloud level with peaks associated with shallow through deep clouds and a sink region above. The fluxes are subsequently separated into upward and nonupward propagating contributions to isolate the pseudomomentum transfer by convection from those due to upward propagating waves. The nonupward propagating contribution to the pseudomomentum fluxes is confined below the cloud layer. The corresponding upward propagating contribution is large above and below the cloud level and highlights the importance of accounting for the source region in gravity wave drag parameterizations. The evolving convective organization is clearly seen in the transience term both above and below the cloud layer. The results highlight important connections between pseudomomentum transfers due to convection and upward propagating waves.

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Final ID:

Internal waves in the atmosphere and ocean

O. Buhler; [1];
1. Courant Institute, New York University, New York, NY, United States.

Body: Internal waves are crucial dynamical components of both the atmosphere and the ocean, but for very different reasons. Consequently, research in atmospheric and oceanic gravity waves has followed different paths, and this means that each side can probably learn something from the other!

This talk will briefly compare and contrast the role of internal waves in both systems, and then discuss recent results in fundamental dynamics of internal waves to do with interactions with a 3d mean flow and with energy transfer mechanisms between waves and vortices.

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Final ID:

Parameterization of Finite-Amplitude Internal Waves in Climate Models

B. R. Sutherland; [1]; *H. V. Dosser;* [1]; *J. Scinocca;* [2];

1. Physics, University of Alberta, Edmonton, AB, Canada.
2. Canadian Centre for Climate Modelling and Analysis, Victoria, BC, Canada.

Body: The diagnoses of internal wave propagation, anelastic growth and breaking in the middle atmosphere are assessed in general circulation models through heuristics based upon observations and the predictions of linear theory. Before wave breaking occurs, however, internal waves grow to moderately large amplitude and so the predictions of linear theory are drawn into question. Weakly nonlinear theory shows that the dominant weakly nonlinear dynamics are determined by interactions between internal waves and the mean flow (the `Stokes drift') that they induce. Fully nonlinear simulations show, as a consequence, that the nonlinearly modulated waves break at lower levels in the atmosphere than predicted by linear theory. These ideas have been introduced into an efficient parameterization of gravity wave drag in general circulation models thus giving better physical justification for the low tuning of breaking parameters used in climate simulations.

Contact Information: Contact Information

Bruce R. Sutherland, Edmonton, Alberta, Canada, T6G 2G7, <a href='mailto:
bruce.sutherland@ualberta.ca?subject=agu-cc11gw: Question regarding '>click here to send an email

Final ID:

Effect of time-dependent, spatially varying shear on vertical propagation of internal wave energy

J. Vanderhoff; [1];

1. Brigham Young University, Provo, UT, United States.

Body: Significant energy is contained in internal waves and when and where that energy is transferred to varying flows throughout the atmosphere may define global scale circulations. Specifically the vertical flux of horizontal momentum due to these internal waves propagating is dependent on their path through the atmosphere. Interactions with spatially varying large-scale winds can shift their propagation direction and expected location of energy dissipation significantly. In addition, time-dependent large-scale flows may shift the waves' location and alter the internal wave energy spectrum. Using linear ray tracing theory an analysis of wave refraction of a realistic spectrum of waves is accomplished and conclusions are drawn on the resulting energy spectra and regions of probably energy dissipation. Estimates of these time-dependent effects in varying extratropical regions are made and their cumulative effect on global circulation patterns is discussed.

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Final ID:

Simulating the Effects of Gravity Waves Over Mauna Kea

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1. Meteorology Deptartment, University of Hawaii, Honolulu, HI, United States.

Body: Mauna Kea, Hawaii, a nearly symmetric summit rising to ~4 km from sea level in the Central North Pacific Ocean, provides an ideal laboratory to study gravity wave generation and propagation. Mauna Kea is highly instrumented with a multitude of meteorological and custom instrumentation. We will present preliminary results from a study of the relationship between gravity waves and turbulence profiles over the summit. Jumper et al. (2007) show a relationship between atmospheric turbulence and gravity waves. The presence of turbulence can be correlated to the crossing of inertial gravity waves, which locally increases the wind shear leading the Richardson number to cross the 1/4 threshold, after which clear-air turbulence is triggered (Vernin et al. 2007). As part of this research, gravity wave initiation, propagation, breaking, and reflection at the top of the model atmosphere will be evaluated with reference to observed turbulence profiles. Favorable conditions for gravity wave breaking include interactions between the jet stream and the mountain orography, and the passage of cold or warm frontal systems. During periods when the synoptic weather patterns are favorable to gravity waves generation and breaking, observational data will be investigated for signatures of gravity waves in the turbulent profiles. High resolution modeling studies will be run over the summit of Mauna Kea for selected cases. The model's ability to produce gravity waves will be studied and validated by comparing the observed and simulated turbulence profiles to quantify the model performance.

URL: http://mkwc.ifa.hawaii.edu/

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Final ID:

Momentum fluxes and drag profiles of trapped gravity lee waves, and their impact on the large scale flow

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Body: While earlier work has suggested that trapped lee wave trains may play an important role in the global momentum budget, they remain difficult to represent within weather and climate models. Observations show that current models commonly overestimate momentum fluxes aloft, and the neglect of gravity wave drag by lee wave trains has been cited as a potential cause of this behavior. Trapped waves are not included in most models, with standard parameterizations of mountain wave drag tending to be focused on momentum transport by vertically propagating waves in a steady flow. To address these issues, 3D simulations of trapped waves in a time-evolving barotropic flow with a localized jet are performed to illustrate drag mechanisms within the waves and the resultant momentum profile. Waves generated in this study are compared to earlier 2D and steady work on trapped lee waves and to observations.

Trapped waves are forced by a 2-layer stability profile. Ray-tracing arguments are applied to the wave train, and can describe the evolution (and eventual decay) of the waves in relation to the background flow. Properties of both the wave train and the large-scale flow are considered in order to analyze the impacts of the trapped waves.

A slowly evolving background flow (33.3 hour timescale) produces trapped waves with characteristics that differ notably from the steady case. Waves forced prior to the time of peak flow at the mountain top are able to persist, while those forced later when the flow is decelerating will eventually decay – becoming untrapped by the background flow they find themselves within. This untrapping produces momentum and drag profiles that also vary strongly in time and space. These properties are quantified, and the origins of the behavior identified. The impact of the wave-train on the large-scale flow is also analyzed. Simulations have also been produced using a 3-layer atmosphere – with a stratosphere added aloft, and similar behavior observed.

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Final ID:

Gravity-wave Drag Parameterization in a High-Altitude Prototype Global Numerical Weather Prediction System (*INVITED*)

S. D. Eckermann; [1]; *F. Sassi;* [1]; *K. W. Hoppel;* [2]; *A. Kochenash;* [3]; *L. Coy;* [1]; *J. P. McCormack;* [1]; *N. Baker;* [4]; *D. D. Kuhl;* [5, 2];

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Body: An Advanced-Level Physics High-Altitude (ALPHA) prototype of the Navy Operational Global Atmospheric Prediction System (NOGAPS) has been developed by scientists at the Naval Research Laboratory (NRL). NOGAPS is the Department of Defense global operational numerical weather prediction (NWP) system. The NOGAPS-ALPHA prototype extends the entire system – both the global forecast model and the data assimilation system (DAS) – to ~100 km altitude. The system has been run in a nonoperational production configuration to generate 6-hourly global analysis fields from 0-100 km for key periods in 2005-2010, based on assimilating both the archived suite of low-altitude observations assimilated operationally by NOGAPS, plus high-altitude temperature and constituent measurements up to 0.002 hPa from the Sounding of the Atmosphere Using Broadband Emission Radiometry (SABER) instrument and Microwave Limb Sounder (MLS) on NASA's TIMED and Aura satellites, respectively.

Extension of this system through the mesosphere and into the lower thermosphere has required significant work on the parameterizations of both orographic and nonorographic gravity-wave drag in the forecast model, specifically: (a) tuning, to reduce analysis-forecast (A-F) and observation-forecast (O-F) biases, and (b) numerical efficiency, to make the parameterizations viable for future operational transitions. We discuss a single-wave stochastic analogue of a deterministic multiwave parameterization of nonorographic gravity-wave drag that we developed and implemented. The stochastic scheme: (a) is an order of magnitude faster computationally than the deterministic parent scheme; (b) produces essentially identical time-mean climate; (c) generates explicit stochastic drag intermittency that obviates the need for small tuned bulk intermittency factors, and (d) increases ensemble spread. We also discuss efforts to use large-scale subgrid-scale drag fields derived diagnostically from the observations-based DAS products to tune the gravity-wave drag parameterizations more objectively. The sensitivity of the system to model resolution is discussed in terms of the issue of resolved versus parameterized gravity-wave drag.

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Final ID:

The effect of temporal correlation on the predictability of the MLT region in a stochastic nonorographic gravity wave drag parameterization

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Body: A stochastic parameterization of nonororgaphic gravity-wave drag (NGWD), recently developed at the Naval Research Laboratory (Eckermann, 2011), is implemented in the general circulation model that comprises the forecast model component of a high-altitude (0-100 km) prototype global numerical weather prediction (NWP) system. The model's default configuration uses the Whole Atmosphere Community Climate Model (WACCM) NGWD parameterization of Garcia et al. (2007) that uses a deterministic source spectrum with multiple waves. The new scheme simply replaces this deterministic multiwave discretization of the source spectrum with a random discretization governed by a single wave whose phase velocity is assigned randomly. While this stochastic parameterization reproduces well the mean climate of the deterministic scheme, it also produces large variances in the mesosphere and lower thermosphere (MLT). In its original formulation, each random wave in the stochastic scheme is uncorrelated in time. By running the NWP system with full 6-hourly forecast and data assimilation (DA) update cycles, and introducing perturbations to generate ensembles, we investigate how different levels of imposed temporal auto-correlation among parameterized stochastic waves affect the quality of the resulting MLT simulations, as judged objectively using NWP statistics based on the forecasts and verifying analysis fields. We specifically study how the introduction of the stochastic scheme and different levels of temporal auto-correlation affect MLT predictability for solstice and equinox conditions.

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Final ID:

Effects of oblique gravity-wave propagation on middle-atmosphere forcing (*INVITED*)

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Body: The current generation of GCMs used for climate prediction rely on gravity wave (GW) parameterizations for taking into account mean-flow acceleration by GW dissipation. Conventional GW parameterizations consider vertical propagation only. We perform an offline study with prescribed background winds and a spectral source distribution tuned to satellite GW measurements. Runs with pure vertical and full three-dimensional oblique wave propagation are performed. The effects of oblique wave propagation on the GW-induced acceleration of the mean flow and of planetary waves are discussed.

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Dynamical and Thermal Effects of Gravity Waves in the terrestrial Thermosphere-Ionosphere

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2. Max Planck Institute for Slar System Research, Katlenburg-Lindau, Germany.

Body: It is well established that small-scale internal gravity waves (GWs) play an important role in the dynamics of the middle atmosphere. Their contributions to the momentum budget of the mesosphere and the lower thermosphere, i.e., up to the turbopause, have been investigated extensively. Historically, their propagation above the turbopause and the resulting effects could not be studied due primarily to the lack of an appropriate GW parameterization for the whole atmosphere system.

Recently, we have developed a new spectral nonlinear GW parameterization that accounts for the penetration of GWs of lower atmospheric origin into the upper atmosphere, and quantifies the resulting dynamical and thermal effects from wave damping [1]. In addition to nonlinear wave-wave interactions and self-interactions, wave dissipative mechanisms such as ion drag, molecular viscosity and conduction, eddy viscosity, and radiative damping are additionally accounted for. Our results based on general circulation modeling [2-4] suggest that GWs penetrate significantly into the upper atmosphere up to F2 layer altitudes, and the associated momentum deposition and neutral gas heating rates are comparable to ion drag and Joule heating, respectively, at those heights. We demonstrate that proper accounting for GW dissipation above the turbopause improves model simulation with respect to two widely used empirical models of the upper atmosphere. An overarching implication of our results is that small-scale GWs must be considered in the observational and modeling studies of the thermosphere-ionosphere system similar to the mesosphere and lower thermosphere.

1. Yigit, E., A. D. Aylward, A.S. Medvedev (2008), J. Geophys. Res., 113, D19106,doi:10.1029/2008JD010135.

2. Yigit, E., and A. S. Medvedev (2010), J. Geophys. Res., 115, A00G02, doi:10.1029/2009JA015106.

3. Yigit, E., and A. S. Medvedev (2009), Geophys. Res. Lett., 36, L14807, doi:10.1029/2009GL038507.

4. Yigit, E., A. S. Medvedev, A. D. Aylward, P. Hartogh, and M. J. Harris (2009), J. Geophys. Res., 114, D07101, doi:10.1029/2008JD011132.

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Final ID: T-1

A Comparison of Gravity Wave Drag Parameterizations using Inverse Techniques

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Body: This work attempts to make a comparison between different gravity wave drag parameterizations. To perform a throughout comparison two inverse techniques are used. The inverse techniques offer a robust framework to perform the drag comparison: for a given 'observed' gravity wave drag, the inverse techniques estimate the optimal parameters and therefore the optimal gravity wave drag given by each parameterization. In this way the error of each parameterization can be inferred.

The estimation of optimal parameters is performed with two different inverse techniques: the genetic algorithm and the ensemble Kalman filter. We show that the parameter estimation can be carried out efficiently using both inverse techniques. An hydrostatic non-rotational version of Scinocca gravity wave drag scheme and a version of the Warner & McIntyre ultra-simple spectral gravity wave drag scheme are used as parameterization schemes. The 'observed' gravity wave drag used in this work is the one estimated in Pulido & Thuburn 2008. For both parameterizations, the impact on the drag field of using optimal parameters compared to the use of standard tuned values is shown. In general, Scinocca parameterization gets a closer match to the 'observed' gravity wave drag using optimal parameters. Both parameterizations do not present a realistic drag in the lower tropical stratosphere. The inverse technique based on the ensemble Kalman filter is a feasible data assimilation technique to be implemented in a full GCM due to its low computational cost.

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Final ID: T-2

Study of gravity wave activity in the troposphere and lower stratosphere using the GPS satellite observations

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2. California Institute of technology, Jet propulsion Laboratory, Pasadena, CA, United States.

Body: It is now well confirmed that gravity waves play a crucial role in determining the circulation and mean state of the atmosphere. In recent years a significant effort has been made in quantifying the general characteristics of lower and middle atmosphere gravity waves. Satellite observations provide a valuable source for gravity wave studies in the lower and middle atmosphere, especially over oceans and other radiosonde-sparse regions. GPS satellites provide global atmospheric profiling with high vertical resolution (0.1-1 km) and high accuracy under all weather conditions. The present study considers a data sample for 89 months that begins from June 2001 to October 2008 for CHAMP and 50 months from May 2006 to June 2010 for COSMIC occultation data sets. Potential energy (Ep) are evident at 20-30 km; in particular, Ep values are highly enhanced near the equator.

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Final ID: T-3

HIRDLS gravity wave validation and case studies

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Body: The HIRDLS instrument on NASA's Aura satellite provides temperature soundings across the globe, with a high vertical resolution and narrow along-track profile spacing which greatly facilitates the detection of gravity wave signals in the stratosphere. In this poster, we will firstly show comparisons of the gravity wave detection capabilities of HIRDLS with SABER and COSMIC, and then show two cases studies of the use of HIRDLS data to analyse gravity wave results, one considering the dynamics of the Arctic stratosphere during Arctic winter 2006 (previously published as Wright et al (2010)) and the other considering gravity waves produced by the Indian, African and American monsoons.

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Final ID: T-4

The ESA gravity wave study

P. Preusse; [1]; *L. Hoffmann;* [1]; *J. Ma;* [2]; *S. Hoefer;* [1]; *A. Hertzog;* [3]; *M. J. Alexander;* [4]; *D. Broutman;* [2]; *M. Bittner;* [13]; *H. Chun;* [5]; *A. Dudhia;* [6]; *M. Ern;* [1]; *M. Hoepfner;* [7]; *S. Kim;* [5]; *W. Lahoz;* [8]; *J. C. McConnell;* [9]; *M. Pulido;* [10]; *J. Remedios;* [11]; *H. Sembhi;* [11]; *K. Semeniuk;* [9]; *V. Sofieva;* [12]; *S. Wüst;* [13]; *J. Orphal;* [7]; *M. Riese;* [1];

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10. Universidad Nacional del Nordeste, Corrientes, Argentina.
11. University of Leicester, Leicester, United Kingdom.
12. Finnish Meteorological Institute, Helsinki, Finland.
13. Deutsches Zentrum fuer Luft- und Raumfahrt, Wessling, Germany.

Body: New detector technology has matured in recent years and now allows an instrument to be built which can measure atmospheric trace species and temperature from orbit with unprecedented three-dimensional spatial resolution. The ability of such an infrared limb imager to resolve gravity
waves (GWs) is assessed in a study sponsored by the European Space Agency (ESA) and the following questions are addressed:

* can high-resolution temperature measurements be processed to infer GW momentum flux?
* how does the validity or otherwise of WKB and polarization relations affect such calculations?
* how does the spatial observing geometry influence:
– the separation of GWs from the global background
– GW amplitudes, horizontal and vertical wavelengths
* which waves are visible to the instrument

We assess these questions by end-to-end simulations of measurements and GW products. The potential of a new mission to measure GWs using infrared limb imaging will be summarized based on these simulations, and compared to existing GW-measurement techniques, such as satellite, ground-based and in-situ.

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Final ID: T-5

Mesoscale Simulations of Gravity Waves during the 2009 Major Stratospheric Sudden Warming

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Body: A series of 24-hour mesoscale simulations (of 10-km horizontal and 400-m vertical resolution) are performed to examine the characteristics and forcing of gravity waves (GWs) relative to planetary waves (PWs) during the 2009 major stratospheric sudden warming (SSW) event. Just prior to SSW occurrence, widespread GW activities are found along the vortex's edge and associated predominantly with major topographical features and strong near-surface winds. Momentum forcing due to GW surpasses PW forcing in the upper stratosphere and tends to decelerate the polar westerly jet in excess of 30 m s-1 day-1. With SSW onset, PWs dominate the momentum forcing, providing decelerative effects in excess of 50 m s-1 day-1 throughout the upper polar stratosphere. GWs related to topography become less widespread largely due to incipient wind reversal as the vortex starts to elongate. During the SSW maturation and early recovery, the polar vortex eventually splits and both wave signatures and forcing greatly subside. Nonetheless, during SSW, propagating GWs are found in the polar region and may be generated in situ by flow adjustment processes in the stratosphere or by wave breaking. The simulated large-scale features agree well with those resolved in satellite observations and analysis products.

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Final ID: T-6

Using Antarctic observations to improve gravity-wave parameterization in climate models

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4. Department of Physics, Utah State University, Logan, UT, United States.
5. School of Chemistry and Physics, University of Adelaide, Adelaide, SA, Australia.

Body: An extensive suite of instruments capable of measuring winds and temperatures in the lower and middle atmosphere operates at Davis station (69S, 78E) in Antarctica, including some instruments which have been making observations for a decade or more. Recently, a project has begun that seeks to use the instruments available at Davis station to improve observational constraints on the gravity-wave parameterization schemes used in numerical climate and weather prediction models, assist in driving them towards their next generation and so improve predictions of atmospheric change.

The breadth of character of gravity waves, along with the complexity of numerical models, makes it necessary to focus the observations of this project. Gravity-wave parameterization schemes share two common characteristics; they assume a gravity wave source distribution near the model base; and they have the force applied to the atmosphere as their output. This project will take a multi-instrument approach to observing these two parts of the life cycle of gravity waves. It will then use the resultant observational constraints to identify improvements to parameterization schemes. A parallel focus on understanding the effects of observational filtering will ensure the comparability of the observations from the various instruments.

To achieve this, the project will:

- Expand the base of gravity-wave observations relevant to gravity-wave parameterization schemes. This will principally use the suite of instruments at Davis ;
- Use past and present observations to measure gravity-wave source characteristics both directly and by employing ray-tracing techniques to relate middle atmosphere waves to source regions lower in the atmosphere;
- Measure the vertical flux of horizontal momentum due to gravity waves above Davis;
- Verify its dominant role in the atmosphere's momentum budget; and
- Relate these observations to gravity-wave parameterization schemes through comparison with model output.

Enhancements to our current capabilities are planned: A gravity-wave ray-tracing capability will be developed; The existing meteor radar at Davis will be upgraded to allow measurements of the momentum flux in the MLT; and an airglow imager will be installed to allow high resolution images of gravity waves to be collected.

Observations of gravity-wave source characteristics, ray path distributions and a climatology of momentum flux will be provided to the modelling community both directly and through the peer-reviewed literature. Collaboration with developers of the NOGAPS-ALPHA model will allow direct comparison of parameterization scheme outputs to our observations. This link (and engagement with other interested modelling groups) will aid in the development of the next generation of parameterization schemes, mindful of the complex relationship between the parameterization scheme and the rest of the model.

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Final ID: T-7

Wintertime gravity-wave activity in the Antarctic upper stratosphere and lower mesosphere revealed by the Davis (69°S, 78°E) lidar

S. Alexander; [1]; *A. Klekociuk;* [1]; *D. Murphy;* [1];
1. Australian Antarctic Division, Kingston, TAS, Australia.

Body: Gravity-wave activity throughout the Antarctic upper stratosphere and lower mesosphere (USLM) is investigated using temperature data collected with a Rayleigh lidar at Davis, Antarctica (69°S, 78°E) during the 2007 and 2008 winters. We present the first results of gravity-wave activity in the Antarctic lower mesosphere obtained using lidar measurements. Potential energy per unit mass shows a seasonal cycle throughout the USLM with the winter peak resulting from gravity wave Doppler shifting by the strong background winds. Significant variability in gravity-wave activity occurs on short time scales between observations (between one day and one week apart). The stratopause temperature and height vary between observation nights on scales of several kilometres and tens of Kelvin as a result of planetary wave activity. The stratopause is also affected by gravity-wave activity during the night, with the regular passage of inertia-gravity waves changing the stratopause altitude by up to ~10km over the course of 18 hours. Gravity wave dissipation above 40 km occurs during winter, while significant dissipation is only noted below the stratopause during autumn. Temporally filtered data with ground based periods of 2 – 6 hours are examined in addition to the non-filtered data, with similar seasonal cycles and short-term variability noted. We compare the seasonality of gravity-wave energy with other high latitude sites and suggest that the main contribution to wave energy above Davis is from non-orographic sources.

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Final ID: T-8

The effect of orographic waves on Antarctic Polar Stratospheric Cloud (PSC) occurrence and composition

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Body: The first seasonal analysis of the relationship between mesoscale orographic gravity-wave activity and polar stratospheric cloud (PSC) composition occurrence around the whole of Antarctica is presented, for austral winter 2007. Gravity-wave variances are derived from temperature measurements made with the Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) Global Positioning System Radio Occultation (GPS-RO) satellites. Data from the Cloud-Aerosol LIdar with Orthogonal Polarization (CALIOP) instrument onboard the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite are used to determine the PSC composition class distribution and spatial volume. The results show intermittent large wave activity above the Antarctic Peninsula which is co-incident with large volumes of water ice PSCs. These ice PSC volumes advect downstream, where increases in nitric acid trihydrate (NAT) PSC volumes occur, supporting the mountain wave seeding hypothesis throughout winter. We calculate the approximate amount of PSCs attributable to these orographic gravity waves. While we show that planetary waves are the major determinant of PSC presence at temperatures close to the NAT formation threshold, we also demonstrate the important role of mesoscale, intermittent orographic gravity-wave activity in accounting for the composition and distribution of PSCs around Antarctica.

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Final ID: T-9

Effects of Subgrid Scale Temperature Variability Caused by Gravity Waves Upon Simulations of Polar Mesospheric Clouds

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Body: Polar mesospheric clouds (PMC) are ice clouds that routinely form in the polar summer mesopause region, where extremely cold temperatures exist because of gravity waves. Simulations of PMCs using WACCM/CARMA, a three-dimensional chemistry climate model based upon the Whole-Atmosphere Community Climate Model (WACCM) with sectional microphysics from the Community Aerosol and Radiation Model for Atmospheres (CARMA) compare well with observations from the Solar Occultation for Ice Experiment (SOFIE); however, despite using a relatively low nucleation barrier the model underestimates the ice particle number density. In this study, we add subgrid scale temperature variability from unresolved gravity waves to the model and examine its impact on nucleation rates and PMC number density.

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Final ID: T-10

Observation and theory of the diurnal continental thermal tide

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Body: Harmonic analysis of summer ASOS data over North America shows sun-following diurnal temperature and pressure oscillations with amplitudes increasing in the western USA, i.e. 5 to 8 degC and 60 to 120 hPa respectively, due to larger sensible heating in the dryer western terrains. The phases of temperature and pressure (i.e. 220deg and 110deg) are constant with longitude after an interfering eastward propagating wave is subtracted. Tidal amplitudes and phases shift significantly with season.

A linear Boussinesq model can capture these observed tidal properties with properly selected parameters. A damping parameter alpha=5~9*10-5 1/s, comparable to the inertia and Coriolis parameters, is needed to explain the temperature phase lag relative to local solar noon (40deg to 50deg). The phase lag between surface pressure minimum and temperature maximum (45deg to 70deg) requires a 3 to 5 hour time delay between surface and elevated heating. The ratio of pressure and temperature amplitude requires a heating depth varying between 550 to 1250 meters; winter to summer. Both the heating delay and depth are consistent with a vertical heat diffusivity of about 10 m2*s-1 in winter, but K-theory give inconsistent summer values. The tide amplitude requires diurnal heating amplitudes in the range of 100 to 200 W/m2.

When the tuned model is applied to an idealized but inhomogeneous continent, the traveling diurnal heating generates gentle tides over the large uniform interior regions but causes vigorous sea breezes and mountain-plain circulations in regions of heating gradient. These gradient regions have significant vertical motions and are moderately sensitive to the critical latitude and the mean wind speed. Surprisingly, these local circulations do not alter the phases of the temperature and pressure oscillations, in agreement with observations.

URL: http://journals.ametsoc.org/doi/abs/10.1175/2010JAS3384.1

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Final ID: T-11

Gravity Wave Observations in the Strato- and Mesosphere by Lidar at 54°N and 69°N.

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Body: We present characteristics of gravity waves observed by Rayleigh- and resonance-lidars at Kühlungsborn (54°N, 15°E) and ALOMAR (69°N, 16°E). A dataset of hourly resolved temperature measurements covering the years since 1997 was analyzed. Gravity waves are usually directly visible in the residual temperature fluctuations with a downward phase progession.
The combination of lidar systems allows to study waves with periods of several hours and vertical wavelengths from 5 to about 50 km.
We have derived the potential energy density (GWPED) and found that it increases with altitude throughout the strato- and mesosphere, but slower than expected for freely propagating gravity waves. The GWPED seasonal variation depends on altitude and latitude.
The Rayleigh-lidar at ALOMAR was recently upgraded for measuring wind speed by direct detection of the Doppler shift between about 30 and 80 km with two hours time resolution.
We present a climatological study on mean GW characteristics as derived from temperature fluctuations and case studies of simultaneous observation of both components of the horizontal wind and temperature.

URL: www.iap-kborn.de

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Final ID: T-12

Observations of Large Vertical Winds Associated with Short Period Gravity Waves in the Winter Polar Mesopause Region

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Body: The sodium wind-temperature lidar at the ALOMAR observatory (69N,16E) can measure the sodium density from 85-100km altitude with 150 m height and 15 sec time resolution during winter under good conditions. Radial winds and temperatures can be measured with 1-2 m/s and 1-2 K error after averaging to 1 min in time and 1-2 km in altitude. This allows determination of the short period wave spectrum down to 30sec in Na density and 2min in wind and temperature. Preliminary analysis shows a number of short period oscillations with large vertical wind amplitudes of up to 25m/s in extreme cases with corresponding vertical motion of the Na layer and adiabatic temperature perturbations. We will present the properties of these waves and compare with gravity wave theory for waves near the buoyancy period.

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Final ID: T-13

The relation between the E-region gravity waves and the F-region plasma depletions observed with an all-sky imager at Arecibo

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Body: At mid-latitudes, F-region plasma depletions called plumes and medium scale traveling ionospheric disturbances (MSTIDs) have been regularly observed with all-sky imagers using the 630 nm airglow emission. On the other hand, various types of gravity waves are commonly observed in the E-region using the 557.7 nm airglow emission. Atmospheric gravity waves (AGWs) have commonly been suggested as a potential seeding mechanism for F-region instabilities. Recent studies have discovered an electrodynamic coupling between the E and F regions. In this study, we use 557.7 nm and 630 nm airglow data from an all-sky imager located at Arecibo Observatory (AO) to statistically compare the occurrences of the E-region gravity waves and the F-region plasma depletions (e.g., MSTIDs and plumes) during the period of 2003-2008. A correlation is observed between the events in these two ionospheric layers suggesting that the gravity waves are one of the major seeding sources of the mid-latitude F-region irregularities. Example case studies when events in both layers have been observed simultaneously are also presented to compare various properties of gravity waves, plumes, and MSTIDs.

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Final ID:

On the mechanism of the formation of the Brewer-Dobson circulation and the change in the age of air

K. Sato; [1]; *K. Okamoto;* [1]; *H. Akiyoshi;* [2];

1. Department of Earth and Planetary Science, The University of Tokyo, Tokyo, Japan.
2. National Institute for Environmental Studies, Tsukuba, Japan.

Body: The stratospheric meridional distribution of atmospheric minor constituents such as ozone is largely affected by the Brewer-Dobson circulation (BDC) consisting of upwelling in the low latitudes and downwelling in the middle to high latitudes of each hemisphere. This circulation is considered to be driven by the body force in the middle latitudes in the stratosphere induced by the breaking and/or dissipation of waves propagating mainly from the troposphere. Previous studies indicate that planetary waves are a main driver of the BDC. However, it is also recognized that the momentum deposition by synoptic-scale waves and gravity waves is important for the zonal momentum balance in the lower stratosphere. The purpose of this study is to quantify the relative role of each kind of waves to the BDC driving mechanism. The contribution of different types of waves to the BDC in the Center for Climate System Research/National Institute for Environmental Studies (CCSR/NIES) Chemistry Climate Model (CCM) for the present climate was diagnosed using the “downward control principle (DC)”. Orographic gravity wave drag (OGWD) has a great influence on the BDC in middle latitudes of the lower stratosphere. In addition, OGWD is a dominant factor to form the ascent in the summer low-latitude part of winter circulation at all heights of the stratosphere. The DC analysis was also applied to the ERA-Interim data. The result is consistent with that of the CCM analysis. Thus, it is concluded that the gravity waves play an important role in maintaining the BDC.

Moreover, we analyzed long-term changes of the BDC by comparing the “age of air” (AOA) using CCM data for the recent past (1985), present (2005) and future (2085) climates. In this study, the AOA was estimated by calculating backward trajectories from a given latitude and pressure level to the 100 hPa level in the residual velocity fields that were obtained using the CCM data. Since the mixing processes by subgrid-scale motions are ignored in the AOA estimates, the long-term change in the “AOA” should be explained by the change of the BDC. The AOA in the future is smaller than that in the present, which is consistent with the acceleration of the BDC as shown by simulations using most CCMs under the scenario of greenhouse gases increase. However, the difference in AOA between the past and present climates depends on the region. The difference is significantly positive in high latitudes of the middle atmosphere, while it is negative in the other regions of the stratosphere. In order to clarify the cause of the positive difference, namely larger AOA in the present climate than in the past, the trajectory characteristics were examined in detail. As a result, it turned out that the larger AOA in the present climate is mostly due to longer transport paths rather than slower speeds of the BDC. This result may explain the observational evidence of little or slightly positive AOA trend which is, at a glance, in contradiction to the positive trend in the BDC strength shown by most CCMs.

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Final ID:

A Three-Dimensional Wave Activity Flux Applicable to Inertio-Gravity Waves (*INVITED*)

S. Miyahara; [1];

1. Department of Earth and Planetary Sciences, Kyushu University, Fukuoka, Japan.

Body: In the last decade, global distributions of activity of gravity waves have been extensively revealed numerically and observationally. It is shown that the activity substantially varies in longitudinal direction. If the activity were almost homogeneous in longitudinal direction, the Eliassen-Palm flux (EP flux) analysis would be useful to investigate wave propagation in the meridional plane and zonal mean eddy forcing by the wave disturbances (e.g., Andrews and McIntyre 1976; Andrews et al. 1987). The EP flux analysis, however, is not practical to analyze longitudinally varying disturbances, because the EP flux is based on the zonal mean. To remedy this drawback, the EP flux has been extended to three-dimensional fluxes that are applicable to longitudinally varying quasi-geostrophic disturbances (e.g., Plumb 1985, 1986; Trenberth 1986; Takaya and Nakamura 2001).

In this presentation a three-dimensional wave activity flux that is applicable to non-hydrostatic and non-geostrophic disturbances such as gravity waves, and a three-dimensionally extended transformed Eulerian-mean equation system are explained using a Boussinesq fluid on beta-plane (Miyahara 2006).

The three-dimensional flux tensor is equal to the flux related to the wave-action density relative to time-mean flow at the WKB limit. The three-dimensional transformed Eulerian-mean equation can be derived by introducing a three-dimensional residual mean circulation and by the divergence of the flux tensor. The residual mean circulation gives the Eulerian-mean circulation plus Stokes drift in the three-dimensional space, and the divergence of the flux tensor gives local east-west and north-south time-mean eddy forcing on time-mean flow. The results of the Boussinesq case can be readily applied to hydrostatic non-geostrophic disturbances denoted by the log-pressure coordinate system on spherical geometry.

Some examples of the application of the flux to non-geostrophic wave disturbances in several General Circulation Models will be shown in the presentation.

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Final ID:

The response of parameterised gravity wave momentum fluxes in global models to secular changes in climate and ozone and the effects on the general circulation

N. Butchart; [1]; *A. Scaife;* [1]; *S. Hardiman;* [1];
1. Met Office Hadley Centre, Exeter, United Kingdom.

Body: Apart from orographically forced waves, parameterised gravity waves in current global models generally have fixed amplitude sources and can only respond to climate and ozone changes through a change in the filtering of the vertically propagating waves. This change in the filtering can, nonetheless, have a significant impact on the parameterised momentum fluxes reaching different levels in the atmosphere and thereby affect the modeled general circulation. A notable consequence is the contribution of parameterised orographic gravity wave drag in accelerating the Brewer-Dobson circulation in climate change simulations. Here we analyze the response of parameterised momentum fluxes to climate and ozone changes in a range of CCM and GCM simulations. The feedback of these changes on the climate and circulation is discussed.

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Final ID:

Probing the Interaction Between Resolved and Parameterized Waves

E. P. Gerber; [1];

1. Center for Atmosphere Ocean Science, New York University, New York, NY, United States.

Body: I will present a modeling framework to investigate the interaction between parameterized gravity wave momentum transport and the resolved atmospheric circulation. State-of-the-art gravity wave parameterizations, both orographic and non-orographic, are set up in a global atmospheric general circulation model. The model integrates the dry primitive equation dynamics with comparable resolution to that of comprehensive climate models, but with a simplified forcing designed to create a realistic circulation, with particular focus on capturing troposphere-stratosphere interactions. The idealized forcing allows greater control over the climate and resolution than possible with comprehensive models. To illustrate the utility of this new model framework, a simple experiment is designed to highlight the interaction between resolved and parameterized waves in driving the Brewer-Dobson Circulation. The model is configured so that the stratospheric circulation is dominated by wavenumber 2 planetary waves. The wavenumber 2 component of the subgrid-scale topography input to the orographic gravity wave scheme is then systematically varied to alter its phase relationship with the resolved waves. Downward control analysis reveals substantial changes to the circulations driven by the resolved and parameterized waves as their phase relationship varies, but the overall overturning circulation remains remarkably robust. This suggests a compensation between resolved and unresolved wave drag, a large scale constraint that maintains a smooth circulation. I will argue that this compensation may relate to results from comprehensive models, where gravity wave drag sometimes appears to seamlessly mesh with resolved wave drag to produce a smooth Brewer-Dobson Circulation, despite the rather complex wave driving structure shown by downward control analysis.

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Final ID:

The quasi-biennial oscillation in a double CO2 Climate (*INVITED*)

Y. Kawatani;[1]; *K. Hamilton;*[2]; *S. Watanabe;*[1];

1. JAMSTEC, Yokohama, Japan.

2. International Pacific Research Center, The University of Hawaii, Honolulu, HI, United States.

Body: The effects of anticipated 21st century global climate change on the stratospheric quasi-biennial oscillation (QBO) has been studied using a high-resolution version of the MIROC atmospheric GCM. This version of the model is notable for being able to simulate a fairly realistic QBO for present day conditions including only explicitly-resolved nonstationary waves. We ran a long control integration of the model with observed climatological sea-surface temperatures (SSTs) appropriate for the late 20th century, and then another integration with increased atmospheric CO2 concentration and SSTs incremented by the projected 21st century warming in a multi-model ensemble of coupled ocean-atmosphere runs that were forced by the SRES A1B scenario of future atmospheric composition. In the experiment for late 21st century conditions the QBO period becomes longer and QBO amplitude weaker than in the late 20th century simulation. The downward penetration of the QBO into the lowermost stratosphere is also curtailed in the late 21st century run. These changes are driven by a significant (30-40 %) increase of the mean upwelling in the equatorial stratosphere, and the effect of this enhanced mean circulation overwhelms counteracting influences from strengthened wave fluxes in the warmer climate. The momentum fluxes associated with waves propagating upward into the equatorial stratosphere do strengthen overall by ~10-15% in the warm simulation, but the increases are almost entirely in zonal phase speed ranges which have little effect on the stratospheric QBO, but which would be expected to have important influences in the mesosphere and lower thermosphere.

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Final ID:

Large scale equatorial waves and the quasi-biennial oscillation in ECHAM

T. Krismer; [1]; *M. Giorgetta;* [1];

1. Max Planck Institute for Meteorology , Hamburg, Germany.

Body: The quasi-biennial oscillation (QBO) in the tropical stratosphere is driven by wave mean flow interactions involving different types of waves occurring in the equatorial stratosphere. This study aims at a quantification of the contribution of large scale waves, defined by spectral filters, to the QBO simulated in ECHAM5 and ECHAM6 at resolutions ranging from T42 (2.8°) L90 to T127 (0.94°) L95. These simulations show QBOs with realistic periods and amplitudes, resulting from resolved and parameterized wave mean flow interaction. The wave analysis performed on these simulations gives special emphasis to representation, source regions and propagation properties of the resolved equatorial trapped waves and large scale inertia gravity waves. Fields of outgoing long wave radiation, temperature and divergence clearly show these waves as predicted by linear theory, suggesting that the modeled tropospheric weather generates a realistic wave spectrum. The contribution of the different wave types to the momentum budget of the QBO is illustrated by the momentum flux divergence of the filtered wind and temperature fields and compared to ERA40 data.

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Final ID:

Assessing the impact of gravity waves on the tropical middle atmosphere in a General Circulation Model

A. C. Bushell; [1]; *D. R. Jackson;* [1]; *G. J. Shutts;* [1]; *S. B. Vosper;* [1]; *S. Webster;* [1]; *H. Wells;* [1];
1. Met Office, Exeter, Devon, United Kingdom.

Body: A recent paper (Bushell et al., 2010) investigated the sensitivity of the tropical middle atmosphere quasi-biennial oscillation (QBO) in the MetUM general circulation model to changes in the monthly zonal mean distribution of climatological ozone. Results from this experiment showed that the increase in QBO period, which was consistent with locally enhanced upwelling in the tropical pipe, could be reversed by enhancing by 36% the contribution from the MetUM parameterized spectral non-orographic gravity wave scheme.

Investigation of the contributions to zonal wind acceleration at 10hPa over the equatorial belt (5°S-5°N) indicate a reduced role for resolved waves relative to parameterized waves in that particular version of the MetUM compared with alternative models, most specifically its predecessor. As the horizontal resolution and non-orographic gravity wave parametrization of the two versions were similar, it was concluded that the differences arose from the numerical formulation of the current MetUM. Damping of fast propagating signals at the resolved length scale can arise from the MetUM's semi-implicit off-centring in time and from interpolation prior to the semi-Lagrangian advection. This area was already generating interest because it has implications for comparison of model output with satellite observations that are currently resolving gravity waves at length scales bordering on those which global GCMs potentially have the horizontal resolution to resolve (Shutts & Vosper, in press).

Results from recent experiments to explore sensitivities of the relative contributions of resolved and parameterized waves following changes in model resolution (spatial or temporal) will be presented.

A.C. Bushell, D.R. Jackson, N. Butchart, S.C. Hardiman, T.J. Hinton, S.M. Osprey, L.J. Gray (2010) Sensitivity of GCM tropical middle atmosphere variability and climate to ozone and parameterized gravity wave changes. J. Geophys. Res., 115, D15101.

G.J. Shutts, S.B. Vosper (in press) Stratospheric gravity waves revealed in NWP model forecasts. Quart. J. Roy. Meteorol. Soc..

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Final ID:

The Effects of Subgrid Scale Gravity Waves on Water Vapor and Clouds in the Tropical Tropopause Layer

L. Pfister; [1]; *E. Jensen;* [1];

1. NASA Ames Research Center, Moffett Field, CA, United States.

Body: Previous work has shown that horizontal motion through cold regions in the Tropical Tropopause Layer (TTL) is the critical mechanism for dehydrating the air entering the stratosphere. Large scale cold regions (for example, the cold pool at 100mb over the Western Pacific in boreal winter) play the largest role. However, previous work by the authors has shown that small scale motions that are not realized in analyses are important for both water vapor and clouds. By making cold temperatures and saturation more frequent at higher altitudes, sub grid scale motions (in the TTL and stratosphere these are almost exclusively inertia-gravity waves) effectively raise the level of dehydration, reduce water vapor in the upper TTL, and increase the incidence of clouds. The latter are important because of their effect on the radiation budget and the overall temperature of the TTL.

Previous inclusions of sub-grid scale motions have relied on longitude-independent statistical spectral models of the gravity wave motions. In this paper, we reexamine the role of gravity waves in governing TTL water vapor and clouds using a trajectory-based microphysical model in the light of: (1) more recent radiosonde data on waves in the lower TTL, (2) more recent, higher resolution global meteorological analyses, and (3) different microphysical nucleation schemes more consistent with observed cloud data. We also explore the implementation of longitude-dependent statistical models.

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Final ID:

WRF model studies of tropical

inertia-gravity waves with comparisons to observations

S. Evan; [1]; *M. Alexander;* [2]; *J. Dudhia;* [3];

1. ATOC, University of Colorado, Boulder, CO, United States.

2. Northwest Research Associates, Colorado Research Associates Division, Boulder, CO, United States.

3. National Center for Atmospheric Research, Boulder, CO, United States.

Body: The NCAR Weather Research Forecast (WRF) model was initially developed and tested for regional simulation and weather forecasting in the troposphere. Little has been reported on WRF performance in stratospheric simulations, or in particular stratospheric gravity wave simulations. To address WRF ability to resolve stratospheric gravity

waves generated by convection, we conducted a series

of numerical experiments in the tropics for January-February 2006. The model domain is configured as a tropical channel and to minimize wave reflection effects the model top is placed at 1hPa with a 15km damping layer depth. The ECMWF analyses provide the initial conditions and boundary conditions at the north/south boundaries throughout the

simulations. Different simulations have been performed to determine the model sensitivity to vertical resolution, cumulus schemes and initial conditions. The model performance for gravity wave studies has been evaluated with high-resolution radiosonde horizontal wind and

temperature measurements of a 2-day inertia gravity wave event observed during the TWP-ICE experiment. The 2-day wave properties resulting from the WRF experiments have been compared to those retrieved from the radiosonde data and from the ECMWF analyses. The WRF model gives comparable results for the horizontal structure and shows better skill than ECMWF to resolve the vertical

structure of the wave. Additional experiments are conducted for the austral summer 2006. General properties of other gravity waves in the WRF model results are further compared to ECMWF analyses and HIRDLS data.

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Final ID:

Lagre-Scale Equatorial Waves in the Middle Atmosphere Based on Multiyear ECMWF analyses

N. Zagar; [1];

1. University of Ljubljana, Ljubljana, Slovenia.

Body: Three-dimensional global normal-mode function expansion is applied to operational analysis of ECMWF which extend up to 80 km height (1 Pa). The normal-mode expansion allows to quantify energy in balanced and inertio-gravity motions, various horizontal scales and vertical structures.

The diagnosis is concentrated on most energetic waves in the middle atmosphere in the tropics and their spatio-temporal characteristics. The vertical wave propagation is diagnosed in the space of normal modes based on 91-model level analysis fields for the last 4 years.

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Final ID:

On the interaction of the migrating diurnal tide with inertia gravity waves generated by tropical heating

D. Ortland; [1]; *M. Alexander;* [2];

1. NorthWest Research Associates, Redmond, WA, United States.
2. NWRA, Colorado Research Div., Boulder, CO, United States.

Body: High resolution data of rainfall rate and infrared cloud top brightness temperature derived from the Tropical Rainfall Measuring Mission have been used to construct estimates of latent heating and cloud top height every 3 hours on a .25 x .25 longitude-latitude grid. This heating is used to force a global time-dependent model that includes the mesosphere and lower thermosphere, from which we study the spectrum of wave motion produced in response to the heating. The main component of the wave spectrum that remains in the mesosphere consists of inertia gravity waves (IGW) and Kelvin waves with phase speed greater than 40 m/s. We also realistically force the migrating diurnal tide in our model and study the interaction of the IGW spectrum with the tides.We find that the IGWs significantly impact the amplitude and structure of the tide. Model simulations in which the wave spectrum is filtered through climatological mean winds derived from UARS observations do not reproduce the strong seasonal and interannual (quasi-biennial) variations in the amplitude of the migrating tide that are observed. We shall compare the modulation of the resolved IGW spectrum by the tide winds to the modulation predicted by the Alexander-Dunkerton parameterization scheme for small-scale gravity waves.

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Final ID:

Momentum budget analysis on the seasonal variation of the diurnal tide by using the Whole Atmosphere Community Climate Model (WACCM4) and its comparison with the meteor radar and satellite observations

X. Lu; [1]; *A. Z. Liu;* [2]; *H. Liu;* [3]; *Z. Li;* [1]; *G. R. Swenson;* [4]; *Q. Wu;* [3]; *J. Yue;* [3]; *S. J. Franke;* [4];

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2. Physical Sciences, Embry Riddle Aeronautical University, Daytona Beach, FL, United States.
3. High Altitude Observatory, National Center for Atmospheric Research, Boulder, CO, United States.
4. Electrical and Computer Engineering, University of Illinois, Urbana, IL, United States.

Body: By using the meteor radar and TIDI satellite wind observations, it is found that the seasonal variation of the diurnal tide is dominated by the semiannual oscillation (SAO) at low latitudes, which reaches the maximum amplitude at equinox and minimum at solstice. The phase of the diurnal tide is also changing seasonally. The tidal heating by the absorption of infrared solar radiation in the troposphere is thought to be playing an important role to cause the SAO as it has more symmetric and efficient projection on the gravest diurnal tide component W1 at equinox than at solstice. The linear advection, nonlinear advection and gravity waves may also contribute to the seasonal variation of the diurnal tide.

The comparison with observation shows that the seasonal variation of the diurnal tide is well reproduced by the Whole Atmosphere Community Climate Model 4 (WACCM4) while the magnitude is smaller than observation. To study the mechanisms contributing to the seasonal variation, we carry out a momentum budget analysis on the diurnal tide and evaluate the effects from Coriolis and geopotential gradient forces, linear advection, nonlinear advection and gravity waves. This analysis identifies the most dominant terms contributing to the seasonal variation of the diurnal tide.

The momentum budget is modulated by the mean temperature and winds, which are sensitive to the GW parameterization. This sensitivity is investigated using the GW parameterization scheme in the WACCM4, which relates GW generation to orography, convective and frontal activities individually. The sensitivity of GW effects on the diurnal tide is also analyzed for this scheme.

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Final ID: W-1

Connection of the Stratospheric Quasi-Biennial Oscillation with El Niño–Southern Oscillation

M. Taguchi; [1];

1. Dept of Earth Sciences, Aichi Univ of Education, Kariya, Japan.

Body: Using a stratospheric zonal wind data archive of radiosonde observations at equatorial stations for 1953–2008, this study investigates whether or not signals of the quasi-biennial oscillation (QBO) vary with the El Niño–Southern Oscillation (ENSO) cycle. The signals of the QBO are represented by trajectories in a phase space spanned by time series of two leading modes of wind variability. Two properties of the trajectories, distance from the origin and time rate of change in argument, which are proxies for amplitude and phase progression rate of the QBO, respectively, are first examined in relation to seasons and QBO phases. The examination confirms known features of the QBO including the so-called seasonal locking and more regular phase propagation for the westerly phase. A further comparison of the properties between cold and warm ENSO conditions (La Niña and El Niño, respectively) reveals unprecedented evidence of clear variations of the QBO with ENSO: the QBO signals exhibit weaker amplitude and faster phase propagation for El Niño conditions. Such variations are also supported by a composite analysis of zonal wind anomalies. A preliminary analysis using the ERA40 reanalysis data shows that the ENSO-associated QBO modulation in the zonal wind is largely unexplained by the resolved wave driving. This suggests an important role of unresolved small-scale waves, such as gravity waves.

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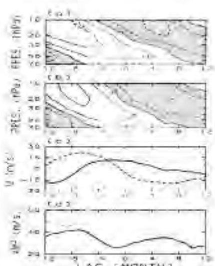

(a,b) Time-height sections of equatorial zonal wind anomalies composited with respect to the westerly wind peaks at 50 hPa during (a) La Niña and (b) El Niño conditions.The panel (c) shows the composite wind at 50 (solid) and 20 (broken) hPa. Amplitude of the composite wind is also denoted in (d). In (c) and (d), thin lines are used for La Niña, and thick for El Niño conditions.

Final ID: W-2

Gravity wave drag effects on the future quasi-biennial oscillation in the tropical stratosphere under greenhouse gas increase up to year 2100: Simulations with a chemistry-climate model

K. Shibata; [1]; *M. Deushi;* [1];
1. Meteorological Research Institute, Ibaraki, Japan.

Body: Simulations on the past and future middle atmosphere were made with the chemistry-climate model (CCM) of Meteorological Research Institute (MRI), MRI-CCM. The model includes full stratospheric chemistry and simplified tropospheric chemistry. The model resolution is T42L68 with top at 80 km and reproduces spontaneously the quasi-biennial oscillation (QBO) by incorporating a Hines gravity wave drag scheme, the period of which is about 27-month, being very close to the observed 28-month. Three different forcing runs were performed for 140 years from 1960 to 2100 without solar cycle and volcanic aerosols. The first run uses the SRES A1B GHG scenario and the adjusted A1 halogen scenario. The second uses the same SRES A1B GHG scenario with the halogens fixed at 1960 levels, and the third uses the same adjusted A1 halogen scenario with the GHGs fixed at 1960 levels. SST/sea-ice conditions are imposed to be compatible with the GHG scenarios. These runs correspond to CCMVal-2 reference simulations of REF-B2, and sensitivity simulations of SCN-B2b and SCN-B2c, respectively. It is found that the QBO amplitude in zonal wind in the tropical stratosphere is decreased in future under the global warming due to the greenhouse gas increase, while the QBO amplitude is scarcely decreased under the fixed GHGs conditions.

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Final ID: W-3

The roles of equatorial trapped waves and internal inertia-gravity waves in driving the quasi-biennial oscillation.

Y. Kawatani; [1]; *K. Sato;* [2]; *T. J. Dunkerton;* [3]; *S. Watanabe;* [1]; *S. Miyahara;* [4]; *M. Takahashi;* [5];

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2. University of Tokyo, Tokyo, Japan.
3. Northwest Research Associates, Redmond, WA, United States.
4. Kyushu University, Fukuoka, Japan.
5. AORI, University of Tokyo, Tokyo, Japan.

Body: The roles of equatorial trapped waves (EQWs) and internal inertia-gravity waves in driving the quasi-biennial oscillation (QBO) are investigated using a high-resolution atmospheric general circulation model with T213L256 resolution integrated for 3 years. The model, which does not use a gravity-wave drag parameterization, simulates a QBO. Although the simulated QBO has a shorter period than that of the real atmosphere, its amplitudes and structure in the lower stratosphere are fairly realistic. In the eastward wind shear of the QBO, eastward EQWs including Kelvin waves contribute up to ~25–50% to the driving of the QBO. On the other hand, westward EQWs contribute up to ~10% to driving the QBO during the weak westward wind phase but make almost zero contribution during the relatively strong westward wind phase. Extratropical Rossby waves propagating into the equatorial region contribute ~10–25%, whereas internal inertia-gravity waves with zonal wavelength ≤~1000 km are the main contributors to the westward wind shear phase of the simulated QBO. In both the eastward and westward wind shear phases of the QBO, nearly all Eliassen–Palm flux (EP-flux) divergence due to internal inertia-gravity waves results from the divergence of the vertical component of the flux. On the other hand, EP-flux divergence due to equatorial trapped waves (EQWs) results from both the meridional and vertical components of the flux in regions of strong vertical wind shear. Longitudinal dependence of wave forcing is also investigated by three-dimensional wave activity flux applicable to gravity waves. Near the top of the Walker circulation, strong eastward (westward) wave forcing occurs in the Eastern (Western) Hemisphere due to internal inertia-gravity waves with small horizontal phase speed. In the eastward wind shear zone associated with the QBO, the eastward wave forcing due to internal inertia-gravity waves in the Eastern Hemisphere is much larger than that in the Western Hemisphere, whereas in the westward wind shear zone, westward wave forcing does not vary much in the zonal direction. Zonal variation of wave forcing in the stratosphere results from (1) zonal variation of wave sources, (2) the vertically sheared zonal winds associated with the Walker circulation, and (3) the phase of the QBO.

This presentation reviews our recently published papers (Kawatani et al. 2010a,b, J. Atmos. Sci).

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Final ID: W-4

Space-Time Variability in Precipitation at Scales Relevant to Gravity Waves from Observations and Model Results

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Body: Convectively coupled equatorial waves are closely linked to variability in tropical precipitation. At higher frequencies relevant to inertia-gravity waves (IGW) the variability in tropical precipitation can also describe the sources for vertically propagating waves. To evaluate the convective precipitation variability at high frequency scales in a general circulation model and reanalyses, rainfall data from the Middle Atmosphere configuration of the European Centre Hamburg Model (MAECHAM5), the ECMWF reanalysis (ERA-interim), and NCEP/NCAR reanalysis are used in space-time spectral analysis and the results compared with the satellite observations from the Tropical Rainfall Measuring Mission (TRMM). At high frequencies corresponding to IGW, the spectra display prominent lobes following preferred propagation speeds, but the model speeds disagree with the ones obtained from TRMM. While westward IGW modes are stronger than eastward IGW modes in the TRMM spectrum, the model shows more symmetric propagation of IGW. Moreover, the phase speeds of pronounced IGW modes in the model are faster than the ones in TRMM, implying that the equivalent depths in the model are scaled to deeper than the observed values. Spectra of reanalysis data generally agree with the TRMM results at low frequencies since they are based on observations. However, spectra have significant problems at higher frequencies, at periods of 1-day and shorter. They tend to highly overestimate harmonics of the diurnal cycle, and so IGW modes do not stand out clearly against the background. These problems with the diurnal cycle are likely related to the parameterized convection in the model and reanalyses. Our findings would give useful insights for the parameterization of transient waves in current climate models.

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Final ID: W-5

Coupling between gravity waves and tropical convection at mesoscales

F. Zhang; [2]; *T. P. Lane;* [1];

1. The University of Melbourne, Melbourne, VIC, Australia.

2. The Pennsylvania State University, University Park, PA, United States.

Body: In this study, an idealized cloud-system resolving model simulation and linear theory are used to explore the coupling between a tropical cloud population and the mesoscale gravity waves it generates. Spectral analyses of the cloud and gravity wave fields identify a clear signal of coupling between the clouds and a deep tropospheric gravity wave mode with a vertical wavelength that matches the depth of the convection, which is about 2/3 the tropospheric depth. This vertical wavelength and the period of the waves, defined by the characteristic convective timescale, means that the horizontal wavelength is constrained through the dispersion relation. Indeed, the wave-convection coupling manifests at the appropriate wavelength, with the emergence of quasi-regular spacing of order 100 km. It is shown that clouds at this spacing achieve a resonant state, at least for a few convective lifecycles. Such regular spacing is a key component of cloud organization and is likely a contributor to the processes controlling the upscale growth of convective systems. Other gravity wave processes are also elucidated, including their apparent role in the maintenance of convective systems by providing the mechanism for renewed convective activity and system longevity.

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Final ID: W-6

First observation of quasi-two-day wave in the lower atmosphere over Hyderabad (17.4 N, 78.5 E)

P. Kumar; [1]; *G. Dutta;* [1]; *S. Mohammad;* [1];
1. R&D Cell, Vignana Bharathi Institute of Technology, Hyderabad, Andhra Pradesh, India.

Body: The quasi-2-day wave is a global oscillation frequently observed in the middle and upper atmosphere during solstices. The 2 - day wave has been associated with Rossby-gravity mode of zonal wave number 3 and also baroclinic instability of summer easterlies. In this paper, we have investigated the characteristics of this wave in the lower atmosphere (1-31 km) of a tropical station Hyderabad (17.4 N, 78.5 E). India Meteorological Department (IMD) conducts regular GPS radiosonde flights twice a day from Hyderabad. The high resolution (1 sec) data of wind and temperature between 15 May and 24 September, 2009 in the altitude range of 1 – 25 km have been used for the present study. Two - day waves of appreciable amplitude could be observed in both zonal and meridional winds and also in temperature data. FFT analyses identified the waves in two period bands (44-52 h and 56-60 h) with longer periods becoming more prominent in the months of August and September. Maximum amplitudes of ~ 4-5 m/s are found in the upper troposphere and lower stratosphere with downward phase propagation. The thermal amplitude maximum is ~ 2.2 K in the same region. Wavelet analysis shows a continuous systematic bursts of QTDW during the summer solstice and a clear modulation of 2 - day wave amplitude by a planetary wave of 7-10 days period. The propagating QTDW appears to interact with background wind and the zonal wind is found to change systematically before, during and after the wave bursts.

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Final ID: W-7

Excitation Sources of Ultra-Fast Kelvin waves

Simulated by the Kyushu-GCM

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1. Earth and Planetary Sciences, Kyushu University, Fukuoka, Fukuoka, Japan.

Body: It has been revealed by model studies that Ultra-Fast-Kelvin waves (UFKs) in the upper mesosphere and lower thermosphere (MLT) can be generated by the convective heating in the troposphere and propagate vertically (e.g. Forbes, 2000). On the other hand, Mayr et al. (2004) indicated that UFKs can be generated in the upper mesosphere with periods between 1 and 3 days. Origins of UFKs in the MLT region are still an interesting unsolved problem.

In the previous version of this study (Chen and Miyahara, in preparation), we have found that UFKs in the MLT region are possibly generated in the lower atmosphere, especially in the troposphere, and propagate vertically penetrating into the MLT region of the T42L250 Kyushu University general circulation model (the Kyushu-GCM).

Using a newly made dataset sampling the convective heating in the troposphere, our preliminary investigation shows that there are some relationships between the convective heating in the troposphere and UFKs activities in the MLT region, as shown in Figure 1. It shows the time series of zonal wind and geopotential height of UKFs with zonal wavenumber s=1 in the period band of 2.5-3.4 days at 100 km height, and the time series of eastward moving convective heating in the troposphere with zonal wavenumber s=1 in the same period band. It can be seen that there are time lags about 10 days between the heating in the troposphere and the wave amplitude of UFKs at 100 km height from day-10 to day-60. It takes about 10 days for UFKs traveling through 100 km, which can be estimated based on the vertical group velocity of UKFs. This result shows that UFKs in the MLT region from day-10 to day-60 are likely excited by the convective heating in the troposphere. On the other hand, in the time span from day-60 to day-90, no time lags are seen. This may indicate that UFKs in this time span may be excited by other physical processes besides the convective heating in the troposphere. To identify the excitation source we need further analysis.

The detailed analysis on the relationship between excitation sources and UFKs activities in the MLT region is now going on. Results of detailed analysis will be shown in our presentation.

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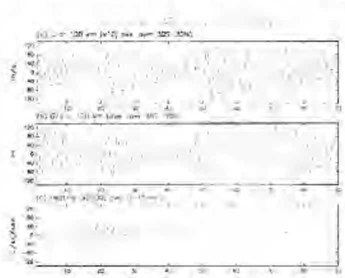

Figure 1: Time series of (a) zonal wind, (b) geopotential height of UKFs, and (c) eastward moving convective heating in the troposphere with zonal wavenumber s=1 in the period band of 2.5-3.4 days.

Final ID: W-8

Charecteristics of inertia gravity waves in the lower atmosphere over Hyderabad (17.4 °N, 78.5 °E)

M. Kumar; [2]; *M. Satyakumar;* [3]; *Y. K. Reddy;* [3]; *G. Dutta;* [1];

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2. Physics, Vanjari Seethaiah Memorial College of Engg., Hyderabad, Andhra Pradesh, India.
3. Indian Meteorological Department, Hyderabad, Andhra Pradesh, India.

Body: Gravity waves with short vertical scales are observed to have pronounced activity in the tropics. We report here the characteristics of short vertical wavelength inertia gravity waves using the high resolution (~ 50 m) GPS radiosonde measurements of horizontal winds and temperature made by India Meteorological Department (IMD) Hyderabad. The balloon flights are carried out twice a day at 0000 GMT and 12) GMT with on-board GPS receiver and radiosonde manufactured by MODEM company of France. The accuracies of wind and temperature are 0.15 m/s and ±5°C respectively. The data collected between 15 May and 24 September, 2009 have been used for the present study. Hodograph analysis have been carried out to delineate vertical and horizontal propagation characteristics. Most of the hodographs in the middle and upper troposphere show anticlockwise rotation signifying downward energy propagation. This indicates that the jet velocity observed during this period might be a strong source of IGW. The stratospheric analysis show predominantly upward propagation of energy. The direction of propagation of IGW were further confirmed by analyzing hodographs of u' - t'. A systematic change of the direction of IGW from south-west to south-east could be observed between May to September. Similar observations were made for both tropospheric and stratospheric regions. A typical vertical wavelength was 2.5 – 3.5 km and the horizontal wavelength varied between 250 to 1000 km. Vertical profiles of wind and temperature fluctuations were subjected to spectral analysis to form vertical wave number spectra and were compared with saturated model spectrum. Spectral indices of the wind spectra were found to be -2.2 and -2.5 for tropospheric and stratospheric regions respectively. The corresponding spectral slopes for temperature spectra are -3.2 and -3.5.

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Final ID: W-9

LiDAR observations of middle atmospheric gravity wave activity over Reunion Island (20.8°S, 55.5°E): Climatological study

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1. Department of Physics, Sree Vidyaniketan Engineering College, Tirupati, India.
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3. National Laser Centre, Council for Scientific and Industrial Research, Pretoria, South Africa.
4. Laboratoire Atmosphères Milieux Observations Spatiales, France, France.
5. Laboratoire Atmosphères Milieux Observations Spatiales, France, France.

Body: In this Paper, climatological characteristics of the gravity wave activities are studied using temperature profiles obtained from Rayleigh lidar located at Reunion Island (20.8°S, 55°E) over a period of ~14 years (1994-2007). Gravity wave (GW) study has been performed over the height range from 30 to 65 km. The present study documents the GW characteristics in terms of time (frequency), height (wave number) and GW associated Potential Energy and their seasonal dependences. Generally, the temporal evolution of temperature profile illustrates the downward phase propagation indicating that the energy is propagating upward. The wave activity is clearly visible with the wave periods ranging from 260 min to 32 min. The dominant components have vertical wavelengths in the range of about ~4 km to 35 km. The potential energy over the height region from 30 km to 65 km are calculated and presented. It is found that the seasonal variation of potential energy is maximum during summer in the upper stratosphere and lower mesosphere. A semiannual variation is seen in the gravity wave activity over all height ranges in the months of February and August.

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Final ID: W-11

Gravity Wave-induced Variations in Exothermic Heating in the MLT region

T. Huang; [1];

1. Penn State Lehigh Valley, Center Valley, PA, United States.

Body: Chemical heating plays a significant role in the energy budget in the MLT region. The reactants in these exothermic reactions are oftentimes modulated in the passage of wave motion, which would lead to variations in the chemical heating rates. We investigate gravity wave-induced variations in the exothermic heating in the MLT region at latitude 18 in the northern and southern hemispheres. A 2D OH chemistry model with wave fields from a spectral full-wave model is used for such investigation in which energy lost by OH nightglow emission is taken into account. Our results show that the peak values of the mean wave-induced total exothermic heating rates are substantial, ~10.5 K/day and 14.5 K/day for 18 S and 18 N, respectively. The major contributors to heating rates are the three-body recombination O+O+M and the H+O3 reaction. The hemispheric asymmetry in the heating rates is due to the different atmospheric conditions at 18 N/S since same wave fields are used in the numerical simulations.

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Final ID: W-12

Case study of a mesospheric wall wave event

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1. Equatorial Geophysical Research Laboratory, Indian Institute of Geomagnetism, Tirunelveli, Tamilnadu, India.
2. Radar Observatory, Indian Institute of Geomagnetism, Shivaji University Campus, Kolhapur, Maharashtra, India.

Body: Intense frontal features associated with gravity waves accompanying intensity variations in the airglow images were observed in the past and explained on the basis of mesospheric bore theory or wall wave theory. Most of such observational features were explained as mesospheric bores while wall wave interpretations are rare. On the night of Februay 2, 2008, airglow imaging observations made from Panhala (17°N, 74.2°E) showed signature of an intense gravity wave in OH, Na and OI green line emissions. Observations revealed passage of four frontal systems separated by ~325 km with an approximate time gap of ~100 minutes between passage of alternate bright and dark features. The intensity variations were nearly in phase between OH and Na images while out of phase with OI green line images. The first three fronts had horizontal extent covering entire field of view while the fourth one was relatively weaker and curved. The bright fronts (in OH and Na) showed evolution of phase locked trailing wave crests with ~15 to 25 km wavelength while the dark fronts (in OH and Na) were devoid of such features. The alternating bright and dark phases of the fronts appear to indicate the crests and troughs of a long period large amplitude gravity wave which might have given rise to evolution of short scale phase locked crests in certain occasions. Thus, this observation suggests possible generation of bores by means of wall wave perturbations. In this work we have discussed the characteristics of the event with background wind data from co-located MF radar and snapshot temperature measurements made by SABER instrument on board TIMED satellite. Also discussion on the probable source of the observed wave is made.

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Final ID: W-12

Atmospheric Gravity Wave Activity over a Sub-tropical and Tropical Indian Locations

S. Sharma; [1]; *S. Sridharan;* [2]; *H. Chandra;* [1]; *S. Lal;* [1]; *Y. Acharya;* [1];

1. Physical Research Laboratory, Ahmedabad, Gujarat, India.
2. National Atmospheric Research Laboratory, Gadanki, A. P., India.

Body: Gravity Waves (GWs) play an important role in energy and momentum transport from troposphere to the upper atmosphere. Nd: YAG laser based Rayleigh lidars are in operation at Mount Abu, (24.5o N, 76.2o E) a sub-tropical site and at Gadanki (13.5o N, 79.2o E) a tropical site, in India. Strong convective activity over tropical and sub-tropical regions plays an important role for the generation of GWs. Mt. Abu (24.5°N, 72.7 °E) is located in sub-tropical, hilly region where a large number of convective phenomena occur. The gravity wave characteristics are presented in terms of vertical wave number and frequency spectra, along with the estimated potential energy for the winter and summer. The GWs study at Mt. Abu may contribute to a better understanding of middle atmosphere on seasonal and long term scales and in delineating vertical coupling between lower, middle and upper atmosphere. Rayleigh lidar is in operation at Mt. Abu since 1997. We make use of ~11 years (1997-2008) of high resolution Rayleigh lidar measurements for the present study. Temperature profiles are derived from raw data (photon count profiles) in the height range of 30-65 km with a vertical resolution of ~480 m. Temperature profiles are further analyzed to extract and delineate the GWs features. The present study is focused on the GWs characteristics in terms of time (frequency) and height (wave-number), associated Potential Energy (P.E.) and their seasonal dependences. The frequency and wave-number spectra are obtained for about 250 days where continuous data sets of ~4 hours are available. Generally, the temporal evolution of temperature profile illustrates the downward phase propagation indicating that the energy is propagating upward. The dominant time period of GW is found to be greater than 2.3 hours in the mesosphere at the 60-65 km height region. The lower periodicity of less than ~2 hours are found in the upper stratosphere (30-45 km). The P.E. for 3 different height regions (35-40 km, 45-50 km and 55-60 km) are calculated and analyzed. The seasonal variation of GWs characteristics and associated P.E. has also been investigated. It shows two distinguished maxima during May and November months. The obtained results are compared with results obtained from tropical station. Furthermore, Lidars at Mt. Abu and Gadanki were operated simultaneously in coordinated fashion during the months of March, April and May. Significant differences are found in the day to day GW characteristics over sub-tropical and tropical locations. Detailed results will be presented and discussed.

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Final ID: W-13

Gravity waves emitted from jets: lessons from idealized simulations

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2. National Center for Atmospheric Research, Boulder, CO, United States.

Body: A longstanding problem in the description of gravity wave sources concerns waves emitted from jets and fronts. Theoretical studies of mechanisms of spontaneous generation suggest that the emission is expected to be exponentially weak in Rossby number, yet the mechanisms described (e.g. mixed instabilities involving baanced and unbalanced motions) do not seem to explain the emission observed and simulated near jets.

From observations, it has been known for some time that jet exit regions often exhibit intense inertia-gravity waves, suggesting generation there. Simulations of idealized baroclinic life cycles have confirmed the specific role of these jet exit regions and shown that specific processes for propagation (i.e. 'wave capture') play an important role there. The generation and subsequent propagation of waves at the front of upper-tropospheric jet streaks has been shown to be analogous to what happens in a dipole, yet the latter is, attractively, much simpler and allows a detailled understanding of the generation mechanism. This poster will focus on recent advances on wave excitation in a dipole and in nine baroclinic life cycles.

The generation of inertia-gravity waves in the front of a dipole has been explained as the linear response, within a balanced background dipole flow, to the small discrepancies between the balanced and the full tendencies for wind and potential temperature. It is worth emphasizing that it is crucial to linearize around a background dipole flow, as the structure of the waves that are generated (i.e. concentration in the jet exit region, phase lines transverse to the flow there, small horizontal scales) comes almost entirely from the resulting non-trivial, non-constant coefficient linear operator.

Past studies have seeked to isolate a diagnostic from the large-scale flow that could be indicative of the location and intensity with which gravity waves are generated (e.g. Lagrangian Rossby numbers, residual of the Nonlinear Balance Equation). The relevance of these diagnostics is tested in both dipole and idealized baroclinic wave simulations. Regarding location, they are not always found to indicate the dynamically significant regions of the flow. An indicator such as the Okubo-Weiss parameter, which highlights regions of strong strain without vorticity, is found to better isolate jet exit regions where waves tend to be captured. Regarding amplitudes, such indicators are by construction linear or quadratic in the dipole strength or as the square of the dipole strength. The emission was not found to follow such a simple scaling law. On the contrary, it rather seems to 'turn on' at a certain finite Rossby number, as could appear if waves are exponentially small in Rossby number. This behavior can be explained if we take into account the advection by the flow past the forcing term. As the dipole strength increases, it is not only the intensity of the forcing which increases, but also the advection past this forcing. As a result, a larger part of the spectrum contributes to wave generation. A nonlinear dependence of wave amplitude on the intensity of the dipole is thus obtained, qualitatively similar to what was found in simulations.

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Final ID: W-14

Momentum Fluxes of Gravity Waves Generated by Variable Froude Number Flow over Idealized and Realistic Three-Dimensional Orography

S. D. Eckermann; [1]; *J. Lindeman;* [2]; *D. Broutman;* [3]; *J. Ma;* [3]; *Z. Boybeyi;* [2];

1. Space Science Division, Naval Research Laboratory, Washington, DC, United States.
2. College of Science, George Mason University, Fairfax, VA, United States.
3. Computational Physics, Inc., Springfield, VA, United States.

Body: Fully nonlinear mesoscale model simulations are used to investigate the momentum fluxes of gravity waves that emerge at a "far-field" height of 6 km from steady unsheared flow over both idealized and realistic three-dimensional orography.

In the idealized experiments, we model flow over both axisymmetric and elliptical obstacles for nondimensional mountain heights $\hat{h}_m = Fr^{-1}$ in the range 0.1–5, where *Fr* is the surface Froude number. Fourier- and Hilbert-transform diagnostics of model output yield local estimates of phase-averaged wave momentum flux, while area integrals of momentum flux quantify the amount of surface pressure drag that translates into far-field gravity waves, referred to here as the "wave drag" component. Estimates of surface and wave drag are compared to parameterization predictions and theory. Surface dynamics transition from linear to high-drag (wave-breaking) states at critical inverse Froude numbers Fr_c^{-1} predicted to within 10% by transform relations. Wave drag peaks at $Fr_c^{-1} < \hat{h}_m < 2$, where for the elliptical obstacle both surface and wave drag vacillate owing to cyclical buildup and breakdown of waves. For the axisymmetric obstacle, this occurs only at $\hat{h}_m = 1.2$. At $\hat{h}_m > 2–3$ vacillation abates and normalized pressure drag assumes a common normalized form for both obstacles that varies approximately as $\hat{h}_m^{-1.3}$. Wave drag in this range asymptotes to a constant absolute value that, despite its theoretical shortcomings, is predicted to within 10%–40% by an analytical relation based on linear clipped-obstacle drag for a Sheppard-based prediction of dividing streamline height. Constant wave drag at $\hat{h}_m$ ~2–5 arises despite large variations with $\hat{h}_m$ in the three-dimensional morphology of the local wave momentum fluxes.

We then progress to simulations of representative trade winds ($\hat{h}_m$=5) impinging upon the Big Island of Hawaii. We find that the wave momentum fluxes are dominated by forcing from subsidiary topographic peaks, with the broader island topography controlling flow splitting and lee vortex generation. Waves also arise at the far northern and southern extremities of the island by acceleration of split flow. The strength of the local momentum fluxes proves to be sensitive to a small change in the incident flow direction. Areally integrated fluxes (wave drag) align closely with the incident flow direction and are an order of magnitude smaller than linear predictions and an order of magnitude larger than corresponding dividing streamline predictions.

Specific implications of these results for the parameterization of subgrid-scale orographic drag in global climate and weather models are discussed.

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Final ID: W-15

Influence of Vertically Propagating Gravity Waves on the Atmosphere of Mars

A. S. Medvedev; [1]; *E. Yigit;* [2]; *P. Hartogh;* [1];

1. Max Planck Institute for Solar System Research, Katlenburg-Lindau, Germany.
2. Atmospheric, Oceanic and Space Sciences, University of Michigan, Ann Arbor, MI, United States.

Body: Observations and theoretical considerations point out to much stronger than on Earth generation of gravity waves (GWs) in the troposphere of Mars due to instabilities of weather systems, volatile convection, and flow over the rugged topography. Disturbances attributed to GWs have amplitudes several times larger than on Earth in both Martian lower and upper atmospheres. However, unlike on Earth, the significance of these vertically propagating waves is not yet well established. General circulation models (GCMs) are apparently able to reproduce the observed circulation patterns without parameterized GWs, at least up to 80-100 km. The submission addresses the fundamental gap in the knowledge of the momentum budget in the Martian upper atmosphere. Using our recently developed GW parameterization suitable for thermospheres [1] and a Martian GCM, we quantify for the first time the GW momentum deposition at thermospheric heights. It is shown [2] that GW drag plays a role similar to the one in the terrestrial lower thermosphere but somewhat higher, at 110-130 km, at altitudes where the recently observed temperature deviates significantly from model simulations [3].The reason for the difference lies in stronger than on Earth EP flux divergence due to resolved waves, and the pecularities of GW propagation.

1. Yigit, E., A.D. Aylward, A.S. Medvedev, J.Geophys. Res., 113, D19106, doi:10.1029/2008JD010135, 2008.
2. Medvedev, A.S., E. Yigit, P. Hartogh, Icarus, 2010, in press.
3. Forget, F. et al. J. Geophys. Res., 114, E01004, doi10.1029/2008JE003086, 2009

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Final ID:

Global Distributions of Gravity Wave Momentum Flux Measured by Satellites: Some Implications for the Dynamics of the Strato- and Mesosphere (*INVITED*)

M. Ern; [1]; *P. Preusse;* [1]; *S. Kalisch;* [1];
1. Institute for Energy and Climate Research - Stratosphere (IEK-7), Forschungszentrum Juelich, Juelich, Germany.

Body: The satellite instruments HIRDLS and SABER both provide long-term high spatial resolution data sets of temperature altitude profiles that allow gravity wave (GW) parameters like wave amplitudes, horizontal and vertical wavelengths, and, consequently, also absolute values of GW momentum flux to be determined. HIRDLS covers the years 2005-2007 and SABER the years 2002-2010 (almost a whole 11-year solar cycle). We present estimates of GW momentum flux from both instruments. Seasonal, interannual, and spatial variations, as well as implications for GW parameterizations will be discussed. For the first time global distributions of GW momentum flux in the mesosphere are derived from SABER measurements. Results show that non-vertical propagation of GWs is a significant effect. In particular, GW momentum flux originating from convective sources in the subtropics during the monsoon seasons is the main contribution of GW momentum flux at midlatitudes in the summer hemisphere around 70 km altitude. This means that GWs generated in the subtropics likely contribute significantly to the reversal of the summertime mesospheric jet.

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Estimation of Optimal Gravity Wave Parameters for Climate Models using a Hybrid Genetic-Variational Technique (*INVITED*)

M. Pulido; [1];

1. Department of Physics, Universidad Nacional del Nordeste, Corrientes, Corrientes, Argentina.

Body: There is a current need to constrain the parameters of gravity wave drag schemes of climate models using observational information instead of tuning them arbitrarily. An inverse technique is presented to estimate parameters from gravity wave schemes. We define a cost function that measures the differences between the zonal and meridional components of the 'observed' gravity wave drag field and the gravity wave drag calculated with a scheme.

The proposed inverse technique is composed by a genetic algorithm and a variational assimilation technique based on conjugate gradients. The first is used to estimate a close enough first guess and then conjugate gradients is applied. It is concluded that the parameter estimation using this hybrid technique is robust over a broad range of prescribed 'true' parameters. Estimations using 'observed' gravity wave drag from Pulido and Thuburn (2008) are performed, the gravity wave drag given by the parameterization for an optimal set of global parameters does not reproduce the observed features. On the other hand, if the parameters are allowed to vary with the latitude, a good fit of the observed gravity wave drag is obtained, except at the tropical lower stratosphere. In this region some relaxations of the parameterization are proposed in order to have a better agreement with the forcing needed to drive the QBO. Simulations with the dynamical stratosphere model using the optimal parameters are performed, an important reduction of the model error is obtained.

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Final ID:

Balloon-Borne Observations of Gravity-Wave Momentum Fluxes over Antarctica and Surrounding Areas (*INVITED*)

A. Hertzog; [1]; *R. Vincent;* [2]; *G. Boccara;* [1]; *F. Vial;* [1];

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2. University of Adelaide, Adelaide, SA, Australia.

Body: Gravity waves (together with planetary-scale Rossby waves) drive the global scale Brewer-Dobson circulation in the middle atmosphere. In the descending branch of this circulation, i.e., over the winter polar and sub-polar area, air is adiabatically compressed, resulting in a middle atmosphere significantly warmer than it would have been under pure radiative equilibrium. The role of gravity waves is even more important to this respect in the Southern Hemisphere, since the activity of larger scale Rossby waves is less there than in the Northern Hemisphere.
Beside their pure dynamical effects, gravity waves also indirectly impact the chemistry and physics of the Southern polar vortex. For instance, the temperature field inside the vortex will control many aspects of processes involved in ozone depletion (like the occurence and composition of polar stratospheric clouds or chemical reaction rates) in the coming years, as long as the decline of ozone-depleting substances will not be significant. Hence, for a number of reasons, an accurate parameterization of gravity-waves effect in (chemistry-)climate models is needed to predict the evolution of the Southern Hemisphere stratosphere.

Such an accurate parameterization critically relies on global observations of gravity-wave momentum fluxes. While such observations have historically been very difficult (or even impossible) to collect, new techniques have recently emerged, which enable us to diagnose this quantity at global scale. Estimation of gravity-waves momentum fluxes under long-duration balloons, able to fly for several months in the lower stratosphere on constant-density surfaces, is one of these techniques. Among the main
assets of balloon-borne momentum-flux estimations are the ability of providing directional momentum fluxes and the fact that the whole gravity-wave spectrum can be observed.

The presentation will recall the methodology used to estimate gravity-wave momentum fluxes from observations collected during long-duration balloon flights. Results based on two campaigns (Vorcore 2005 and Concordiasi 2010) performed over Antarctica will be presented. The respective role of orographic and non-orographic waves, as well as the observed intermittency of gravity waves will be discussed.

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Mountain Wave Momentum Fluxes in the Southern Hemisphere from Satellite Measurements

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2. LMD, Paris, France.

Body: Accurate representation of stratospheric winds in the Southern Hemisphere in climate models depends on the parameterization of gravity wave drag. Parameterization of orographic wave drag is widely considered to be insufficient in these models, and additional drag from non-orographic waves is very important. Previous work has shown the stratospheric circulation affects both the seasonal development of the ozone hole, and predicted changes in 21st century Southern Hemisphere climate. Recent observational evidence suggests that small islands in the Southern Ocean may be important sources of orographic wave drag that is currently missing in existing parameterizations. Latitudinal and downstream propagation of Andean mountain waves has also been demonstrated in recent model studies. We provide observational estimates of momentum flux carried by Southern Hemisphere mountain waves as derived from Atmospheric Infrared Sounder (AIRS) observations from the Aqua satellite. The fluxes from these sources will be shown to cover a much broader range of longitudes and latitudes than current orographic parameterizations predict. The analysis reveals errors in the existing parameterizations due to missing island sources and due to the assumption that the orographic drag only affects the column of air directly above the topography. Our results provide some quantitative guidance for future improvements in orographic gravity wave drag parameterizations.

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Final ID:

Analysis of spatial structure of gravity waves using GPS occultation data (*INVITED*)

T. Horinouchi; [1];
1. Hokkaido University, Sapporo, Japan.

Body: It is found that the GPS radio occultation events obtained over about an hour by the COSMIC/FORMOSAT-3 satellites are frequently aligned horizontally in linear shapes especially in the first year since their launch. This feature gives an opportunity to study almost instantaneous features of gravity waves (GWs) in vertical cross sections, where clear GW features are frequently found. It is indicated from a statistics that horizontal wavelengths of GWs in the northern hemisphere in winter time are generally smaller than those in the equatorial region or in the other hemisphere. A positive skewness is found in the probability distribution of GW amplitude in mid-to-high latitudes, while it is not skewed in low latitudes. Analysis of GW propagations relative to background winds are also conducted.

Further analysis is made to study three-dimensional atmospheric features in high latitudes using the COSMIC/FORMOSAT-3 data. Sharp frontal features were frequently found at the polar vortex edge during stratospheric sudden warmings. These features should be isolated to study GWs. The analyses is also used to study GWs.

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Final ID:

Detailed Analysis of Horizontal Wave Parameters using Radio Occultation Data

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2. Facultad de Ingeniería, Universidad Austral, Buenos Aires, Argentina.
3. Institude for Space Sciences, Freie Universität Berlin, Berlin, Germany.

Body: Ern et al. (2004) introduced a method to derive horizontal wave parameters along the adjacent line of two vertical temperature profiles. The horizontal wavenumber (k_h) is given by the ratio of the phase shift (Φ) and the spatail distance dx between the regarded profiles at one altitude $k_h = \Delta\Phi/\Delta x$. We apply this method to GPS radio occultation (RO) profiles from the six-satellites constellation COSMIC/FORMOSAT-3, delivering approximately 2500 temperature profiles daily. The RO technique is a limb sounding method that is sensitive to gravity waves with small ratios of vertical to horizontal wavelength. To extract the real horizontal wavelength, a third measurement is needed. In the early mission months (April to December 2006) several triads of RO profiles are found, due to the close flying arrangement of the satellites. Before we apply this method to our dataset, a theoretical analysis is made. A sensitivity study of the Ern method shows, that the results for the horizontal wavenumber and therefore all follow up products (like wavelength or momentum flux) have a high dependency on the horizontal distances of the measured profiles. Therefore the phase shift must have a lower limit, which raises with increasing distance between the profiles. Another restrain is, that the regarded profiles must be within one pi-phase for the Ern method to deliver the real horizontal wavelength, once the regarded profiles are further apart, the results for horizontal wavelength will represent an upper boundary of the wavelength. Restrictions like the dominant vertical wavelength and a phase shift and the wavenumber comparision will be discussed. Additionally a case study in the Andes mountains is presented, delivering wavelength between 30 and 300 km for altitudes from 20 to 27 km. These results are verified using the Weather and Forecast model (WRF). From global analysis for August and December 2006, results for the horizontal wavelength of several hunderd up to 2500 km are derived.

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Final ID:

Measuring gravity wave intermittency and propagation directions from satellite observations

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2. CIRES, University of Colorado, Boulder, CO, United States.

Body: It is well known that satellite observations of the Earth's atmosphere have the potential to provide global-scale constraints for gravity wave parameterizations. Initial satellite-based analyses focused on gravity waves examined the climatological features of wave activity. More recently developed processing schemes which derive horizontal and vertical information using paired satellite observations have improved the amount of gravity wave information that can be obtained (e.g. momentum fluxes). But, the uncertainties on these measurements can not be quantified and are large based on theory. The problems associated with the different 'observational filters' of different observing systems provides another difficultly in interpreting satellite observations.

In this study, we primarily examine the possibility of deriving information on the intermittency and propagation direction of gravity waves using data from the COSMIC constellation. This observing system uses the GPS radio occultation methodology on data from six near-identical observing satellites to produce extremely accurate and precise high resolution measurements of atmospheric temperature between approximately 10 and 40 km. These characteristics allow us to make measurements of small-scale waves. However, the configuration of the satellites' orbits in the constellation means that the spatial and temporal distribution of observations is not uniform and analysis shows that 'clusters' of observations occur relatively often.

The occasional dense sampling of a region, characterized by several measurements made within a 250 km radius of each other and separated by less than one hour, offers the opportunity to explore:

a.the spatial variability of measures of gravity wave activity

b.the coherence between the gravity waves observed in profiles separated by a range of small distances.

c.the uncertainty of satellite observations of wave activity

d.the observational filter of the Radio occultation measurements.

e.Intermittency of gravity waves

f.Propagation directions of waves

This presentation explores these possibilities and follows-on from previous work discussed in Horinouci and Tsuda (2009) and McDonald et al. (2010).

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Final ID:

Long-term global GW activity in lower and middle atmosphere from CHAMP, GRACE and COSMIC radio occultation data between 2001 and 2010.

P. Llamedo Soria; [1]; *A. de la Torre;* [1]; *P. Alexander;* [2]; *R. Hierro;* [1]; *T. Schmidt;* [3]; *J. Wickert;* [3]; *A. Haser;* [3];
1. Universidad Austral, Buenos Aires, Argentina.
2. Universidad de Buenos Aires, Buenos Aires, Argentina.
3. Geoforschungs Zentrum, Potsdam, Germany.

Body: We discuss the long-term global tropospheric-stratospheric gravity wave (GW) activity expressed by the specific potential energy derived from GPS radio occultation data, as retrieved by CHAMP, GRACE and COSMIC Low Earth Orbit (LEO) satellites between 2001 and 2010. Systematic annual and interannual features as a function of longitude, latitude and time are shown, extending and/or modifying results and features pointed out in previous climatologies. Possible over/under estimations due to the data processing are also remarked. The GW analysis is based on the correct extraction of the perturbation component of the individual measured temperature profiles by applying different filtering techniques. We test a new filtering procedure that considerably reduces the usually observed wave activity enhancement at the tropopause. After applying a bandpass filter, the perturbation component is detrended again to force a zero mean. For reference, we create known synthetic perturbation components added to background temperature profiles to compare the ability of the different filtering methods. This filtering procedure considerably reduces a systematic over estimation of the wave activity observed in previous climatologies, mainly at tropopause regions.

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Final ID:

Global observations of stratospheric gravity waves made with COSMIC GPS-RO and comparisons with an atmospheric general circulation model

S. Alexander; [1]; *T. Tsuda;* [2]; *Y. Kawatani;* [3]; *M. Takahashi;* [4]; *K. Sato;* [5]; *A. Klekociuk;* [1];

1. Australian Antarctic Division, Kingston, TAS, Australia.
2. Research Center for Sustainable Humanosphere, Kyoto University, Uji, Japan.
3. Frontier Research Center for Global Change, Japan Agency for Marine-Earth Science and Technology, Yokohama, Japan.
4. Atmosphere and Ocean Research Institute, University of Tokyo, Kashiwa, Japan.
5. Department of Earth and Planetary Science, University of Tokyo, Tokyo, Japan.

Body: The launch of the six Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) satellites in 2006 and resultant ~2000 daily profiles of temperature below 40km altitude have provided a rich dataset for the analysis of mesoscale gravity waves. We will discuss some of the highlights of our research over the last few years, including comparisons between observed and modelled gravity-wave activity. Gravity wave and equatorial wave-mean flow interaction is clearly apparent in the COSMIC results. Tropical stratospheric gravity waves observed with COSMIC are seen above regions of active convection. Kelvin waves and mixed Rossby-gravity waves with zonal wavenumbers < 9 are observed intermittently throughout the equatorial upper troposphere and lower stratosphere. A T106L60 atmospheric general circulation model is used to examine the same part of the gravity-wave spectrum seen by COSMIC, with good agreement in wave activity noted between observations and model. Large gravity-wave activity occurs around and above the winter sub-tropical jet, which decreases with altitude but increases poleward and upward as these waves are focussed into the polar night jets. Gravity waves seen by COSMIC in the polar regions capture the very large but intermittent nature of orographic waves forced by surface topography. The descending nature of the austral springtime enhanced gravity-wave activity will also be discussed, along with Doppler-shifting by the strong vortex winds.

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Final ID:

Gravity wave signatures in AIRS radiances: Can AIRS observe wave scales shorter than its weighting function thickness?

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1. Aerosol and Cloud Group, Jet Propulsion Laboratory, La Canada Flintridge, CA, United States.
2. Middle Atmosphere Dynamics, Naval Research Laboratory, Washington,DC, DC, United States.

Body: Gravity wave (GW) variances and preferred zonal propagation directions are investigated using Atmospheric Infrared Sounder (AIRS) radiances at pressure altitudes of 2 - 100 hPa using 50 CO_2 channels. From the 90 AIRS cross-track field-of-view (FOV) measurements, we are able to accurately derive measurement noises, high-frequency internal GWs, and low-frequency inertial GWs. Even though the vertical wavelengths of inertial GWs are shorter than the thickness of AIRS weighting functions, the non-uniform vertical distribution of wave amplitudes produce a measurable variance that has unique FOV dependence. Since the AIRS scanning is perpendicular to the polar orbiting tracks, the preferred zonal component of GW propagation can be inferred by differencing the variances derived between the leftmost and the rightmost scan angles at most latitudes. Monthly mean AIRS GW variances show large enhancements over meridionally-oriented mountain ranges and islands at wintertime high latitudes, where GWs have predominant westward propagation. Enhanced wave activities are also found above tropical deep convection regions with preferred eastward phase propagation. Annual cycle dominates both variables for almost all latitudes, with modulation of weak quasi-biennial oscillation (QBO) in the tropical lower stratosphere. Simulations with idealized GWs support the AIRS sensitivity to GWs with low inertia frequencies in the tropical lower stratosphere. Characterization of these low frequency GWs has important implications for constraining the GW drag parameterization schemes in general circulation models and for understanding formation and distribution of tropical cirrus clouds.

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Final ID:

Rayleigh lidar observations of gravity wave seasonal variability over a tropical site

A. Guharay; [1];

1. Space and Atmospheric Sciences Division, Physical Research Laboratory, Ahmedabad, Gujarat, India.

Body: Extensive study of middle atmospheric gravity waves (GWs) has been carried out to characterize seasonal variability of wave associated potential energy, vertical component of horizontal momentum flux and mean flow acceleration with long term database (1998-2008) over Gadanki (13.5N, 79.2E), India. GWs are observed to transport significant energy and momentum flux with considerable variability throughout the seasons. Dominant annual oscillation (AO) is observed in the energy and momentum flux pattern in the middle atmosphere. Mean flow acceleration due to GW divergence is found to be very high in the mesosphere. Power spectral density of the vertical wavenumber spectra of normalized temperature derived for the upper stratosphere and mesosphere exhibit resemblance in the saturated region. Logarithmic slope of vertical wavenumber spectra reveals more negative value in the upper stratosphere (~ -2.83) than the mesosphere (~ -2.43) as well as higher magnitude during solstices and lower during equinoxes.

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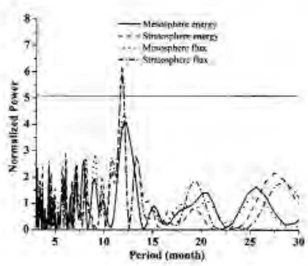
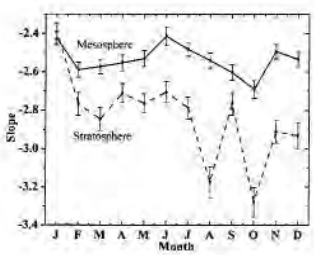


Lomb-Scargle periodogram of normalized power for the mesosphere and upper stratosphere energy and momentum flux over 130 months (Mar-1998 to Dec-2008).



Logarithmic slope of the vertical wavenumber spectra for all the months of the year for the stratosphere and mesosphere.

Final ID:

Investigations On Gravity Wave Potential Energy Seen By Different Satellites And Ground Based Techniques

S. R. John; [1]; *K. K. Kumar;* [1];
1. ISRO, Trivandrum, Kerala, India.

Body: Gravity waves fall in a wide spectrum of frequencies. Depending on the technique, different instruments see different regions of the gravity wave spectrum. To parameterize gravity waves in the atmosphere, a complete understanding of the parts of the spectrum that each technique can capture is essential. In this study, a uniform method is used to extract gravity wave induced fluctuations in temperature after removing 0-6 zonal wave number contributions. Gravity wave potential energy is then calculated using 4 satellite based instruments, SABER, a limb viewer, HIRDLS, a limb viewer with better horizontal resolution, COSMIC, using GPS radio occultation, AIRS, a nadir viewing satellite, and ground based instruments like Lidar over Gadanki (13.5 N, 79.2 E) and Meteor Wind Radar over Thumba (8.5 N, 77 E). Global maps of potential energy for Stratosphere (20-40 km) are derived which show astounding similarities among the limb viewing and radio occultation techniques. Fig 1 is the global potential energy map derived from SABER during winter which shows polar highs. Fig 2 shows global winds from ERA-40 which shows strong polar jets that cause enhancement of wave activity. Further, SABER potential energy maps are calculated upto the Mesosphere-Lower Thermosphere (MLT). With increasing altitude, the potential energy highs shift equatorward from poles and at the MLT region, we find highest potential energies at the tropics in all seasons. This is due to Doppler shifting of wave frequency and observational filtering effect. Wyoming Radiosonde wind data is used for hodograph analysis and this gives an estimation of prominent wave characteristics.

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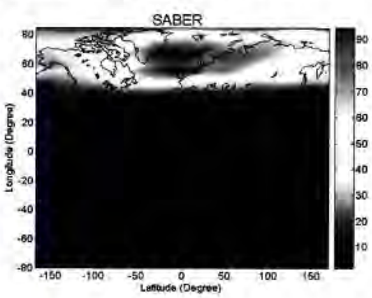

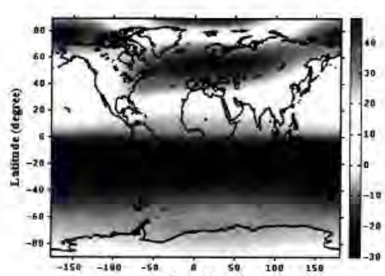

Final ID:

Characteristics of high frequency gravity waves in the upper mesosphere observed in OH nightglow over low latitude Indian sector during 2007

V. L. Narayanan; [1]; *S. Gurubaran;* [1];

1. Equatorial Geophysical Research Laboratory, Indian Institute of Geomagnetism, Tirunelveli, Tamilnadu, India.

Body: Small scale high frequency gravity waves are believed to play a vital role in the upper mesospheric region by means of wave breaking and their interactions with other waves and background mean flow. They are known to propagate large distances from their source regions by means of ducting which makes identification of their source distribution a challenging task. Further, their global distribution is not yet well known. In this work we have studied the characteristics of such high frequency waves observed in OH Meinel band emissions over Tirunelveli (8.7°N, 77.8°E) during the year 2007. The study reveals predominance of meridionally propagating waves, possibly indicating the wind filtering effects in the lower atmosphere. During summer period, waves propagating towards south and south-west were observed much more frequently. The apparent phase velocities of the waves are higher during equinox periods followed by summer and winter solstices respectively. There was no significant variation in the wavelength range of the observed waves. Detailed discussion on the characteristics of the observed waves and possible source distributions around this site during different seasons are made in this study.

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Frequency dependence of gravity wave energy and momentum flux estimates in the lower atmosphere using Gadanki MST radar observations

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2. Physics, Vanajari Seethaiah Memorial College of Engg.,, Hyderabad, Andhara Pradesh, India.

Body: It is now well established that internal gravity waves play a significant role in the momentum and energy budgets of the lower and middle atmosphere. The interaction between vertical flux of horizontal momentum carried by these waves with the mean winds are of great importance. But the relative contribution of different frequencies of gravity waves to the total flux has not been investigated thoroughly and still remains controversial. In fact measurements of the frequency dependence of flux estimates are almost non-existent in the tropical middle atmosphere. This paper presents results of kinetic energy and momentum flux estimates obtained with Mesosphere Stratosphere Troposphere (MST) radar data of Gadanki, India. The radar was operated continuously on four different days (15-16 July, 2004; 18-19 April, 2005; 10-11 December, 2005; 12-13 February, 2006) continuously for 24 hours and more to measure horizontal and vertical winds with very short data gaps ranging between 1.5 to 3.5 minutes and height resolution of 150 m. Altitude profiles of kinetic energy and momentum flux were obtained using these data in two period bands (<2 h and 2 - 8 h). Energy and momentum flux estimates of inertia gravity wave (IGW) were obtained using wind data between 13 and 17 July, 2004 with a data gap of 3 h. Comparisons of simultaneous measurements of kinetic energy and momentum fluxes in different period bands reveal that the shortest period (<2 h) gravity waves transport maximum energy and momentum fluxes in the upper troposphere and lower stratosphere over this tropical station. Oscillations between 60 – 100 minutes are found to be stronger and carry most of the flux estimates whereas for periods <1 h, the flux is more isotropic and contribute little to the mean momentum fluxes. In the 2 – 8 h period band, prominent oscillations between 2.5 – 6 h are found to be isotropic in nature leading to lesser mean flux estimates in the stratosphere. Simultaneous data to study IGW was available only for July 2004 case which shows that the energy and momentum transported by this longest period gravity wave was minimum. Wavelet transforms showed significant variability and localization of the flux estimates with time. The dominant gravity wave momentum fluxes were found to arise from discrete and localized wave packets in frequency and time.

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Final ID:

Topographic Drag in Ultra-Fine Resolution Global Simulations

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1. IPRC, University of Hawaii, Honolulu, HI, United States.
2. Japan Agency for Marine-Earth Science and Technology, Yokohama, Japan.
3. AORI, University of Tokyo, Tokyo, Japan.

Body: The drag due to the pressure gradient across topographic features is computed for high resolution global simulations performed with the Atmospheric GCM for the Earth Simulator (AFES) and the Nonhydrostatic ICosahedral Atmospheric Model (NICAM). The results are compared with those obtained when the full topography and pressure fields are smoothed, resulting in a determination of drag as a function of horizontal scale. The implications for parameterizing the surface drag in moderate-resolution GCMs is examined, and comparisons of the explicit results with the predictions of current parameterization schemes may be presented. An attempt will also be made to use the explicit simulations to determine the component of the surface drag associated with gravity waves that propagate away from the surface.

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Final ID:

Brief History of Ultra-High Resolution Global Model Studies and Future Plans (*INVITED*)

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1. IPCC/JAMSTEC, Yokohama, Kanagawa, Japan.
2. IPRC/University of Hawaii, Honolulu, HI, United States.

Body: Besides the development of high-resolution global numerical weather prediction (NWP) models, e.g. at ECMWF, free-running high-resolution general circulation models (GCMs) have been used to study dynamics of the middle atmosphere (MA). The GFDL SKYHI GCM has the longest history of this research area. It was the first high-top (~80 km) GCM with 40 vertical layers without gravity wave (GW) parameterization. The horizontal resolution (HR) has increased with time; N30 (1980), N90 (1986), N150 (1997), and N270 (1999). (The number following N means model's grid points between the equator and pole.) One of the most important outcomes was that reality of the MA simulations continuously improved with increasing HR, as resolved spectra of GWs increased. A cold pole bias within the austral winter polar vortex was about -70 K and -35 K in N30L40 and N90L40, while it was nearly eliminated in N270L40 (Hamilton et al., 1995 and 1999). The N270L40 also simulated realistic GW horizontal-wavenumber (k-) spectra (Koshyk et al., 1999). The MACCM2 at NCAR also obtained similar results to SKYHI that HR of T106 (~N80) was insufficient to eliminate the cold pole bias in the polar vortex (Boville, 1997). It was the late 1990's during which several types of non-orographic GW parameterizations were developed, and were generally implemented to lower-HR high-top GCMs (e.g., McLandress, 1998).

In Japan, the University of Tokyo (CCSR) group cooperated with NIES has developed high vertical resolution (VR) GCMs. The T21L60 GCM with ~500 m VR firstly succeeded to simulate the equatorial quasi-biennial oscillation (Takahashi, 1996). Pioneered by T106L53 aqua planet GCM of Sato et al. (1999), this Japanese group intensively studied gravity waves in ~50 km-top T106 GCMs with high VR (500-600 m) (e.g., Kawatani et al. 2003). After the appearance of the Earth Simulator in 2002, a high-top (85 km) and high VR (300 m) T213L256 GCM was developed for the KANTO project to study GWs and their roles in MA (see Kawatani et al. 2010 and references therein), as well as the extratropical tropopause region (Miyazaki et al. 2010). The 150 km-top T213L270 JAGUAR was also developed combining the KANTO GCM and the Kyushu-GCM, and used to study interactions between tides and GWs (Watanabe and Miyahara, 2009).

The Japanese modeling group (CCSR/NIES/JAMSTEC/Kyushu Univ.) is currently planning modeling activity in next 5 years in conjunction with operations of the Antarctic PANSY radar. They would increase HR of JAGUAR to T639 that would likely bridge hydrostatic GCMs and a non-hydrostatic global cloud resolving model, i.e., vertical extension of 7 km-NICAM is also planned. However, there could be several options other than using the free-running JAGUAR to study GWs appearing in near real-time observations. For detailed generation and propagation of GWs, it would be more straightforward to use finer-resolution mesoscale models being nested onto

high-top NWP models that assimilate observations (e.g. ECMWF and NOGAPS-ALPHA). There are also issues in the dissipation due to sub-grid processes and secondary generation of GWs near the mesopause, which cannot be represented by hydrostatic GCMs. We would like to openly discuss about these issues in this conference.

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Final ID:

A new estimation method of the momentum fluxes associated with gravity waves: An application to gravity-wave-resolving general circulation model data

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1. Department of Earth and Planetary Science, Graduate School of Science, University of Tokyo, Tokyo, Japan.
2. Frontier Research Center for Global Change, Japan Agency for Marine-Earth Science and Technology, Yokohama, Japan.

Body: The momentum flux associated with gravity waves is an important quantity to evaluate their effects on global circulations. As the gravity waves have various sources, it is likely that multiple gravity waves propagating in different directions are usually superposed. In such situation, even if all physical quantities are available, it is difficult to estimate the total momentum flux of gravity waves (i.e., a sum of absolute values of momentum fluxes of respective waves). In the present study, a new formula was derived to estimate the total momentum fluxes. This theoretical formula contains variances of three dimensional wind and temperature fluctuations and includes neither wavenumbers nor frequencies explicitly. This formula requires that wave fields are decomposed into monochromatic waves. The momentum fluxes were estimated by applying this formula to a gravity-wave resolving general circulation model data. The model has T213 spectral horizontal resolution and 256 vertical levels extending from the surface to a height of 85 km with a uniform vertical spacing of 300 m in the middle atmosphere (Watanabe et al., JGR, 2008). As no gravity wave parameterization is used, all gravity waves in the model are spontaneously emitted from sources (convections, topographies, instabilities, jet imbalances, etc). Watanabe et al. showed that the model represents realistic general circulation and thermal structure in the middle atmosphere. Disturbances whose horizontal wavenumbers are greater than 26 are defined as gravity waves. Estimation was made for the following 3 cases whose degree of monochromatic wave assumption at each grid is different: 1) The fluctuations are assumed to be due to a monochromatic gravity wave. 2) The fluctuations can be decomposed only by vertical wavenumbers. 3) The fluctuations can be decomposed by both vertical wavenumbers and frequencies. The resultant momentum fluxes from 2) and 3) are similar, while those from 1) and 2) are largely different, suggesting that gravity waves could be decomposed into monochromatic waves only by vertical wavenumbers. Moreover, following previous studies such as super pressure balloon observations (such as VORCORE), the vertical and time average of the product of horizontal and vertical wind fluctuation components was calculated and compared with the estimate from the new formula. The result accords well with those from 2) and 3). This means that this simple method used in the previous studies gives reasonable results. Furthermore, the absolute momentum fluxes were divided into components in 4 directions and the geographic distributions were examined. The result is shown in the table,which is consistent with the result of net momentum fluxes distributions shown by Sato et al. (GRL, 2009).

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Contribution of respective components to the total momentum fluxes				
region	northward (%)	westward (%)	southward (%)	eastward (%)
Indian monsoon	22	10	24	43

the subtropical jet region of the Southern Hemisphere	20	37	27	16
South Andes	15	51	22	12

Final ID:

Universal frequency spectra of the short period fluctuations

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1. Dept. Earth and Planetary Sci., the Univ. of Tokyo, Tokyo, Japan.
2. Japan Agency For Marine-Earth Science And Technology, Yokohama, Japan.
3. Atmosphere and Ocean Research Institute, the Univ. of Tokyo, Tokyo, Japan.

Body: It is known that in the free atmosphere, wavenumber (frequency) spectra have power law (e.g. VanZandt 1982) due to gravity waves (Smith et al. 1987; Sato and Yamada 1994). This study focuses on the frequency spectra especially at the surface because of long-term accumulation of short-time interval observations. According to Sato and Hirasawa (2007) using hourly surface data over 50 years in the Antarctic, the frequency spectra have a characteristic shape proportional to different powers of the frequency with a transition frequency of (several days)$^{-1}$. In order to confirm the universality of the characteristic spectra, hourly surface data, including surface temperature, sea level pressure (SLP), and zonal and meridional winds collected over 45 years at in Japan, were analyzed. Similar spectral shapes are obtained for any physical quantities at all stations. The spectral slopes clearly depend on the latitude, particularly for SLP, which is larger at higher latitudes (see the figure). The analysis was extended using realistic simulation data over a month (Miura et al. 2007; Noda et al. 2010) with a nonhydrostatic general circulation model (NICAM; Nonhydrostatic ICosahedral Atmospheric Model; Satoh et al. 2008). It is confirmed that the model spectra accord well with the 138 observations in Japan and Syowa Station in the Antarctic. The spectral slopes are largely dependent on the latitude, i.e., shallow in the low latitudes, and steep in the middle and high latitudes for all physical quantities. The latitudinal change of the spectral slope is severe around 30°, which may be due to the dynamical transition from nongeostrophy to geostrophy. The longitudinal variations are also observed according to geography. The variance is large in the storm track region for the pressure, on the continents for the temperature, and in the rainy regions in the tropics and in the storm track regions over the oceans for the winds.

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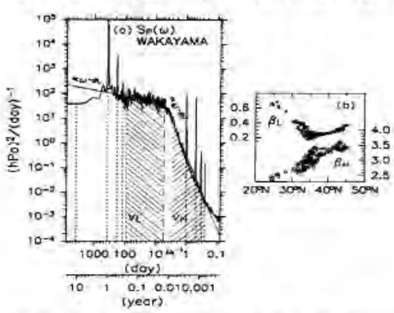

(a) Frequency spectra of the SLP and their shape paramters at Wakayama. (b) Spectral slopes in the low and high frequency range β_L (cross marks) and β_H (circles) as a function of the latitude.

Final ID:

Transport and mixing in the extratropical tropopause region in a high vertical resolution GCM

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4. National Institute of Polar Research, Tokyo, Japan.

Body:

A high-vertical resolution general circulation model (GCM) output has been analyzed to clarify transport and mixing processes in the extratropical tropopause region. The high-resolution GCM, with a vertical resolution of about 300 m above the extratropical upper troposphere, allows simulation of fine atmospheric structures near the tropopause, such as the extratropical tropopause transition layer (ExTL) and the tropopause inversion layer (TIL). The high-resolution GCM realistically simulates fine thermal and dynamic structures in the extratropical tropopause region. The high-resolution output was analyzed using a zonal mean potential vorticity (PV) equation to identify dominant transport processes in the extratropical tropopause region. In the northern hemisphere extratropics during winter, mean downward advection sharpens the PV gradient between the tropopause and 20 K below it, whereas latitudinal variation in isentropic mixing sharpens the vertical PV gradient between the tropopause and 10 K above it. During summer, vertical mixing substantially sharpens the vertical PV gradient at 10-25 K above the tropopause. These sharpening effects may be strongly related to the formation mechanisms of strong concentration gradients of chemical tracers around the ExTL. Mechanisms of evolution of the TIL are also discussed by analyzing a thermodynamic equation. Downward heat advection and radiation processes primarily determine the seasonality of the TIL. The analysis results suggest that the locations of the TIL and the ExTL can be similar because of common dynamic processes and interactions between constituent distributions and thermal structure.

The relative roles of atmospheric motions on various scales, from meso-wave scale to planetary scale, in transport and mixing in the extratropical tropopause region are also investigated. A downward control calculation shows that the E-P flux of the gravity waves diverges and induces a mean equatorward flow in the extratropical tropopause region, which differs from the mean poleward flow induced by the convergence of large-scale E-P fluxes. The diffusion coefficients estimated from the eddy potential vorticity flux in tropopause-based coordinates reveal that isentropic motions diffuse air between 20 K below and 10 K above the tropopause from late autumn to early spring, while vertical mixing is strongly suppressed at around 10–15 K above the tropopause throughout the year. The isentropic mixing is mainly caused by planetary- and synoptic-scale motions, while small-scale motions with a horizontal scale of less than a few thousand kilometer largely affect the three-dimensional mixing just above the tropopause. Analysis of the gravity wave energy and atmospheric instability implies that the small-scale dynamics associated with the dissipation and saturation of gravity waves are a significant cause of the three-dimensional mixing just above the tropopause. A rapid increase in the static stability in the tropopause inversion layer is considered to play an important role in controlling the gravity wave activity around the tropopause.

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Final ID:

Gravity Wave Sources in Tropospheric Weather Systems (*INVITED*)

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2. Department of Meteorology, The Pennsylvania State University , State College, PA, United States.

Body: Gravity waves are one of the most fundamental dynamical processes in the atmosphere. They are closely associated with a wide variety of atmospheric processes ranging from micro-scale to global-scale dynamical phenomena. A better knowledge of these processes demands a complete understanding of source mechanisms by which they are generated. In this talk, we focus on gravity wave sources within tropospheric weather systems, including atmospheric convection, upper tropospheric jets and surface fronts. In particular, we review recent developments in the understanding of source mechanisms of gravity wave from upper tropospheric jets. Two types of idealized atmospheric jets will be discussed: vortex dipole jets and baroclinic jets. Recent studies have demonstrated that wave generation from quasi-balanced dipole-jets can be considered as forced linear responses in a linear framework. In this talk, we will present further evidence that gravity waves from a highly transient baroclinic jet follows similar linear dynamics.

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Final ID:

Aircraft Measurements And Numerical Simulations Of Gravity Waves In The Extratropical UTLS Region During The START08 Field Campaign

J. Wei; [1]; *F. Zhang;* [1]; *M. Zhang;* [1]; *K. Bowman;* [2]; *L. Pan;* [3]; *E. Atlas;* [4];

1. Department of Meteorology, Pennsylvania State University, State College, PA, United States.
2. Department of Atmospheric Sciences, Texas A&M University, College Station, TX, United States.
3. National Center for Atmospheric Research, Boulder, CO, United States.
4. Rosenstiel School of Marine and Atmospheric Science, The University of Miami, Miami, FL, United States.

Body: Gravity waves are one of the key dynamical processes contributing to the structure and composition of the extratropical upper-tropospheric and lower-stratospheric (UTLS) region. Previous field campaign mainly focuses on terrain-induced gravity wave, but the generation and maintenance of mesoscale gravity waves in a jet-front system is still not clear. One of the primary objectives of the START08 (Stratosphere-Troposphere Analyses of Regional Transport Experiment 2008) field experiment is to characterize the source and impact of these waves with the comparison between high-resolution aircraft measurements and mesoscale models.

Preliminary analyses have been conducted to examine the GV aircraft flight-level observations to extract gravity wave information and to explore the spectral distributions of different variables in the lower stratosphere during the START08 mission. One of the research mission flights, RF02, was dedicated for the first time to probing mesoscale gravity waves associated with strong upper-tropospheric jet-front systems. It is shown by spectral analysis that clear signals of significant waves with wavelengths ranging from 10 to 300 km present in almost every leg of the 8-hour flight sampled by the aircraft, mostly in the lower stratosphere. Strong localized variations of the wave signals can be observed with wavelet analysis, over the area of background flow conditions covered by near-jet core, jet over the high mountains and the exit region of the jet. In order to testify the physical reliability of such localized wave signals, the phase and amplitude relation of linear theory is studied based on wavelet-filtered observational data. The mesoscale component of the gravity waves measured has some qualitative similarity to those predicted by a real-time mesoscale forecast model with horizontal grid spacing of 15 km and a cloud-resolving hindcast simulation. However, one of the most noticeable disagreements between simulation and observation lies in the small-scale component of vertical velocity. We will continue to examine how well the current generation of mesoscale models predicts the excitation and characteristics of the gravity waves, how they contribute to understanding the dynamics and impacts of these waves in the UTLS region, how surface fronts and moist convection impact upper-level gravity waves during the life cycle of baroclinic waves, and the reliability of aircraft measurement and high-resolution numerical simulations.

URL: http://www.met.psu.edu/people/jzw158

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Final ID:

Spontaneous gravity wave radiation from unsteady rotational flows in a rotating shallow water system

N. Sugimoto;[1]; *H. Kobayashi;*[1]; *Y. Shimomura;*[1]; *K. Ishioka;*[2];

1. Keio University, Yokohama, Japan.
2. Kyoto University, Kyoto, Japan.

Body: Spontaneous gravity wave radiation from unsteady rotational flows is investigated in a rotating shallow water system. It is well known that gravity waves play very important roles on the middle atmosphere. They propagate far away from the source region of the troposphere to the middle atmosphere and drive global material circulation of the middle atmosphere by putting significant amount of energy and momentum flux. Recent observational studies suggested that gravity waves are radiated from strong rotational flows, such as polar night jet, sub-tropical jet, and typhoon. This radiation process is called as a spontaneous gravity wave radiation, since gravity waves are spontaneously radiated from initially balanced rotational flows. Although there are several numerical studies, this process has not been fully understood.

In the previous studies, we investigated spontaneous gravity wave radiation from unsteady jet flow in the most simplified system of shallow water that includes both rotational flows and gravity waves. Figure 1 shows a snapshot of the spontaneous gravity wave radiation from unsteady jet flow in a shallow water system on a rotating sphere. The key point was that only gravity waves having higher frequency than the inertial cut-off frequency are spontaneously radiated from higher frequency tails of unsteady rotational flows. Therefore, the effect of the Earth's rotation greatly affects spontaneous gravity wave radiation and propagation.

In the present study, we investigate spontaneous gravity wave radiation from co-rotating vortex pair in an f-plane shallow water system. By this simple setting, we can derive analytical estimation for the far-field of spontaneous gravity wave radiation, using the theory of the vortex sound (Lighthill theory). In addition, we also perform numerical simulation of this setting (Fig.2). We use a new spectral model in the unbounded domain by projection from plane to sphere. Then there is no reflection of radiated gravity waves at the boundary. This model allows us to estimate gravity wave amplitude with high accuracy. We check both accuracies of the numerical model and the analytical estimation. The dependencies of parameters, such as Rossby and Froude numbers, on spontaneous gravity wave radiation will be discussed.

URL: http://web.hc.keio.ac.jp/~nori/title-eg-k.htm

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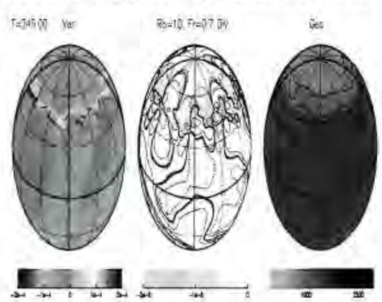
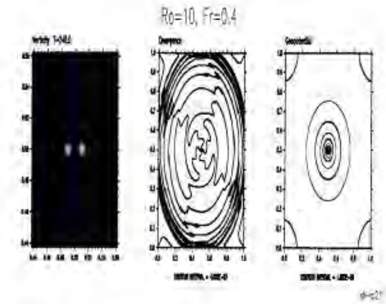


Fig.1 A snapshot of flow field in a shallow water system on a rotating sphere.

Fig.2 A snapshot of flow field in an f-plane shallow water system.



Final ID:

Gravity Waves in the Laboratory: Mechanisms, Properties, and Impacts

P. D. Williams; [1];

1. Department of Meteorology, University of Reading, UK, Reading, United Kingdom.

Body: I will describe a series of laboratory experiments in which gravity waves are generated ubiquitously. The apparatus employed is the rotating annulus, which has been used for decades to study large-scale mid-latitude atmospheric flows. I will discuss the following aspects of the gravity waves: their generation mechanisms; their properties; and their impacts on the large-scale flow.

The evidence suggests that the gravity waves are generated as spontaneous-adjustment emission through loss of balance in the large-scale flow. Therefore, these experiments provide perhaps the first direct experimental evidence that all evolving balanced flows will tend to emit gravity waves, in accordance with theoretical expectations. The experiments imply an inevitable emission of gravity waves at Rossby numbers similar to those of the large-scale atmospheric and oceanic flow.

The amplitude of the emitted gravity waves varies linearly with Rossby number, at constant Burger number (or rotational Froude number). This linear scaling challenges the notion, suggested by several dynamical theories, that gravity waves generated by balanced motion will be exponentially small. It is estimated that the balanced flow leaks roughly 1% of its energy each rotation period into the gravity waves, at the peak of their generation.

The impact of the gravity waves on the large-scale flow is generally small. However, there are circumstances in which the gravity waves trigger rapid regime transitions between different large-scale flow patterns. Motivated by this finding, it has recently been suggested that stratospheric polar vortex splits may in principle be triggered by gravity-wave noise.

URL: http://www.met.reading.ac.uk/~williams/

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The view of the rotating annulus from above, showing trains of gravity waves in the troughs of the large-scale flow pattern. A color movie showing the evolving flow can be viewed at http://www.youtube.com/RotatingAnnulus .

Final ID:

Dynamics and Impacts of Gravity Waves in the Baroclinic Jet-Front Systems with Moist Convection (*INVITED*)

F. Zhang; [1]; *J. Wei;* [1];
1. Penn State University, University Park, PA, United States.

Body: This study explores the dynamics and impacts of the gravity waves generated by the tropospheric baroclinic jet-front systems with moist convection. We performed high-resolution convective-resolving simulations of idealized moist baroclinic waves with multiply-nested mesoscale models initialize with a balanced unstable baroclinic jet in a mesoscale model with modest convective instability. With the inclusion of moist convection, the background baroclinic wave intensifies faster and stronger, resulting in stronger and higher-frequency gravity waves in the jet-exit-region through balanced adjustment as in the dry simulations. Moreover, there are even smaller-scale (<100km) large-amplitude gravity waves apparently generated from and/or coupled with individual convective cells and associated vigorous diabatic heating within the moist baroclinic waves. Given most strong midaltitude baroclinic waves are often associated with strong convection, the changes in gravity wave characteristics and intensity in the moist environment can have profound impacts on the the momentum and energy fluxes by these waves, and subsequently their influence on the general circulation.

URL: http://www.met.psu.edu/people/fuz4

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Final ID:

Model study of waves generated by convection with direct validation via satellite

A. W. Grimsdell; [1]; *M. J. Alexander;* [1]; *P. T. May;* [2]; *L. Hoffmann;* [3];

1. NorthWest Research Associates, Colorado Research Associates Division, Boulder, CO, United States.
2. Center for Australian Weather and Climate Research, CSIRO/Bureau of Meteorology, Melbourne, VIC, Australia.
3. Forschungszentrum Juelich, ICG-1, Juelich, Germany.

Body: Atmospheric gravity waves are a common feature of the middle atmosphere, shaping the flow in this region by transporting energy and momentum from the troposphere. In the tropics specifically, gravity waves are believed to contribute to the forcing of the QBO. Gravity waves are generated by a variety of sources and understanding these sources and the generation mechanism of gravity waves is crucial to modelling of the middle atmosphere circulation. Convection is a particularly important source in the tropics due to the deep cumulus convection as well as the lack of topography which precludes any topographic wave generation. In the case of convectively generated waves the source can vary in both time and space, generating waves through a wide range of phase speeds, frequencies and vertical and horizontal scales.

In this research we examine an event on January 12, 2003, when convective waves were clearly generated near Darwin, Australia. Between 1500 UTC and 1700 UTC a line of storms associated with a tropical depression produced heavy rain and flash flooding in the Darwin region. At 1640 UTC the Aqua satellite overflew Darwin and the Atmospheric Infrared Sounder (AIRS) instrument on board provided images of a clear wave pattern generated by this convective event. We modelled the wave generation using a three dimensional, non-linear, non-hydrostatic, cloud resolving model. The model was forced by profiles of latent heating which varied spatially in all three dimensions as well as temporally. The heating profiles were derived from C-band polarimetric radar measurements and were given at each model grid location. The depth of heating was derived directly from the radar reflectivity, while latent heating profiles were derived from the radar column rainfall rates. Since the model was forced with observed precipitation patterns, the generated wave field can be compared directly to observations. This approach, using prescribed heating, gives us both an understanding of the mechanism of wave generation and the means to validate the model results with satellite data.

The results show good agreement between the modelled wave field and that observed by AIRS. The curvature of the wavefronts indicates the latent heating from the convective storm is the major source of forcing for the observed waves. The conversion from reflectivity to heating still requires improvement, which means the wave amplitudes produced by the model are uncertain, but the horizontal and vertical wavelengths as well as the wave pattern are very similar to those observed by AIRS. These results provide a validation of the model method of forcing the waves with a prescribed heating field, and the model method further provides a means of evaluating and improving the parameterizations developed for global model studies.

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Final ID:

Gravity Wave Generation by Tropical Convection and Middle Atmosphere Response (*INVITED*)

R. A. Vincent; [1]; *M. J. Alexander;* [2]; *S. Kovalam;* [1]; *B. Dolman;* [1]; *A. MacKinnon;* [1]; *I. M. Reid;* [1];

1. Physics, University of Adelaide, Adelaide, SA, Australia.
2. Colorado Research Associates, Boulder, CO, United States.

Body: The TWPICE campaign centered on Darwin (12°S, 131°E) in northern Australia in January-February 2006 provided an opportunity to study gravity wave generation by convection and the associated wave propagation and momentum transport. The project used a variety of radars to study the spatial and temporal variability of rainfall and the associated latent heat release during large convective storms. A high-resolution numerical model utilized the latent heat release to compute the spatial and geographic variation of gravity wave generation and propagation into the lower stratosphere. Gravity wave ray-tracing techniques were then used to estimate the wave flux penetrating to heights near 90 km, where the results were compared with direct measurements made using a meteor radar. An analysis of meteor radar (MR) detection techniques is used to assess the reliability of wave fluxes derived from MR observations. It is shown that, provided the meteor rates are high enough, wave energies can be reliably measured. This result is used to 'calibrate' the indirect fluxes from the model, including momentum fluxes and the associated wave drag. It is shown that wave fluxes have a high degree of temporal variability, with consequent variability in momentum flux deposition and wave drag. A number of storm events are studied in detail. Outcomes can be used to help constrain gravity wave parametrization schemes.

Contact Information: Contact Information

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robert.vincent@adelaide.edu.au?subject=agu-cc11gw: Question regarding '>click here to send an email

Final ID:

Concentric gravity waves generated by deep convections in the Great Plain and observed by all-sky airglow imager in the mesopause

J. Yue; [1]; *S. Vadas;* [2]; *T. Nakamura;* [3]; *C. She;* [4]; *W. Lyons;* [5]; *H. Liu;* [1];

1. High Altitude Observatory, National Center for Atmospheric Research, Boulder, CO, United States.
2. NorthWest Research Associates, Boulder, CO, United States.
3. National Institute for Polar Research, Tokyo, Japan.
4. Physics, Colorado State University, Fort Collins, CO, United States.
5. FMA, Fort Collins, CO, United States.

Body: Expanding concentric rings of gravity waves were observed on 9 nights near equinoxes by the all-sky OH imager at Yucca Ridge Field Station (40.7N, 104.9W) near Fort Collins, Colorado. The pattern on 11 May 2004 was observed for about 1.5 hours, with the rings encompassing nearly 360 for the first 30 minutes. The centers of the rings were observed at the geographic locations of two convective plumes. We measure the horizontal wavelengths and periods of these gravity waves as functions of both radius and observation time. The observations compare favorably with predictions using the internal gravity wave dispersion relation with assumed zero wind. Furthermore, the event on 8 September 2005 lasted 5 hours and one-on-one correlation between the tropospheric wave source and the corresponding mesospheric gravity waves is evident. Since 9 out of the 10 events of concentric patterns among 760 nights of image were observed in May or late August/early September, we hypothesize that the weak mean background zonal wind near equinoxes is a necessary condition for gravity waves excited from convective overshoots near the tropopause to be observed as concentric rings in the OH layer. Ray tracing program results with the background wind and parameterized plumes will be compared to the observations.

Contact Information: Contact Information

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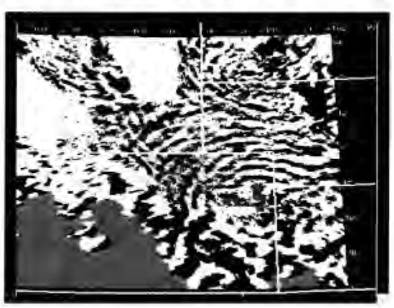

Concentric gravity waves on 8 September 2005 projected on the 800 km^2 geographic coordinate. The centers of the waves are marked by red dots.

Final ID:

Characterization of the sources of Gravity Waves over the Tropical Region, using High Resolution Measurements

D. Nath; [1]; *M. Venkat Ratnam;* [1];

1. National Atmospheric Research Laboratory, Tirupati, India.

Body: An attempt has been made to investigate the dominant source mechanisms for the generation of gravity waves of different scales over a tropical station like Gadanki (13.5oN, 79.2oE) using high-resolution GPS radiosonde measurements for inertia gravity waves. The high pass filtered profiles with a cut off > 3 days are subjected to least square fit to extract the dominant vertical wavelength and then different wave parameters like horizontal wavelength, vertical and horizontal phase speed, vertical and horizontal phase propagation direction etc. are estimated from hodographs. It is well known that convection, wind shear (vertical shear of horizontal wind) and topography are dominant sources for the generation of gravity waves over the tropics. Apart from these, horizontal shear of horizontal wind (i.e. geostropic adjustment/spontaneous imbalance in jets) is also a probable source for Inertia period gravity waves. Lagrangian Rossby Number shows high value over the observational site indicating the role of Geostropic Adjustment for the generation of Inertia Gravity waves. Although Geostropic Adjustment is a frequent phenomenon over midlatitudes, but this is the first time report over the tropical region. During southwest monsoon season (June-August), over Indian region both convection and wind shear co-exists but upper tropospheric wind shear is found responsible for the generation of GWs on various scales, whereas convection mainly generates the high frequency gravity waves. Availability of long term GPS radiosonde data motivated us to study the seasonal characteristics of inertia gravity wave. Clear semi-annual variation in inertia gravity wave energy with maximum during monsoon and winter and minimum during pre- and post-monsoons in the troposphere is noticed during 2006 and 2008 but not clear in 2007. Annual variation is observed in the lower stratosphere with maximum during monsoon (winter enhancement is not significant) season. This kind of winter enhancement in the troposphere is not expected at this tropical site but the contribution of meridional wind to the total kinetic energy is prominent. At the lower stratospheric height waves are propagating mainly eastward, indicates the selective filtering of westward propagating gravity waves due to strong shear. In addition, to understand the spatial characteristics of gravity wave and wave mean flow interaction over the tropical region COSMIC GPS Radio Occultation data are used. Space-time spectra have been constructed from the symmetric and antisymmetric component of temperature perturbations centered on the equator to extract the contribution due to gravity wave. The interaction of background wind shear due to QBO becomes important in the lower stratosphere, which modifies the potential energy (EP) distribution at lower stratosphere. The magnitude of stratospheric EP is ~ 10 J/Kg over Gadanki and is more prominent in the eastward wind phase of QBO, which matches fairly well with ground based observations.

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Final ID:

Convective Gravity Waves and Their Parameterization: Current Status and Issues (*INVITED*)

H. Chun; [1];

1. Dept of Atmospheric Sciences, Yonsei University, Seoul, Korea, Republic of.

Body: Convective gravity waves are the major non-stationary gravity waves with wide spectrum that contribute significantly to the momentum budget in the middle atmosphere when they dissipated. Even for the current high-resolution general circulation models (GCMs), the convective gravity waves and their dissipation process are mostly unresolved, and thus they should be parameterized in the models. During the last twenty years, there have been several efforts to parameterize convective gravity waves for use in GCMs. The main efforts have been made to formulate the cloud-top (launch-level) momentum flux spectrum in the 3-D framework based on the linear theory of internal gravity waves forced by diabatic heating. The cloud-top momentum flux spectrums developed have been validated compared with high-resolution mesoscale simulations that explicitly resolve convective gravity waves. Through the mesoscale simulations of convective storms developed under various basic-state conditions, some free parameters included in the parameterization can be determined. In the propagation process, commonly used columnar method that allows only the vertical propagation within a horizontal grid of GCM has been improved to a ray-based method that allows the three-dimensional propagation following each ray of wave launched at the cloud top. The spatiotemporal variation of convective sources produced from the GCM grids can be accounted in the convective GWD parameterizations developed, although with specified subgrid-scale convective source structure within the GCM grids. The impacts of the convective GWD parameterization in GCMs have been investigated compared with global reanalysis and satellite data-produced gravity wave temperature variances. Due to the limited spectral domains observable for each satellite, only a portion of the parameterized gravity wave spectrum can be compared with satellite observations. The magnitudes of the momentum flux spectrum at the cloud top and above are uncertain, as well as their temporal and spatial variations. How we can constraint those values remains to be a challenging problem, which can be important for realistic reproduction of current climate and climate change simulations using GCMs that include either a part of or the whole middle atmosphere.

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Final ID:

Nonlinear Processes and Their Role in the Generation of Gravity Waves by Convective Clould

M. J. Reeder; [1]; *T. P. Lane;* [2];

1. Monash University, Clayton, VIC, Australia.
2. University of Melbourne, Melbourne, VIC, Australia.

Body: Convective clouds generate gravity waves and these waves are known to have important influences on the momentum budget of the middle atmosphere. Significant advances in our understanding of the wave generation process and the resultant spectrum have been achieved in the last decade using theory, models, and observations. One outcome of this understanding has been the development of a number of new parameterizations of the source spectrum of convectively generated gravity waves for use in general circulation models. These source parameterizations are ultimately based on the linear response to imposed diabatic heating. However, previous studies have shown that nonlinearities within convective clouds play an important role in defining the wave spectrum. In this study, we focus our attention on the characteristics and dynamics of these nonlinearities. In particular, a set of idealized linear and nonlinear models forced by an imposed diabatic heat source are used to explore the role of nonlinearities in the wave generation process. These simulations clearly show that the nonlinearities play the key role in the production of gravity waves that have frequencies close to the Brunt-Väisälä frequency. They also demonstrate that the fully nonlinear wave spectrum is readily reproduced using a weakly nonlinear source formulation. The implications for these results for improving gravity wave source parameterizations will also be presented.

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Final ID:

Observational Constraints on the Spectrum of Gravity Waves Generated by Tropical Convection

P. T. Love; [1];

1. Institute for Terrestrial and Planetary Atmospheres, Stony Brook University, Stony Brook, NY, United States.

Body: Ray-tracing techniques are employed to simulate gravity wave propagation through the equatorial middle atmosphere in the central Pacific. Multiple time-dependent simulations are carried out using a variety of multi-year time-series observations to specify monthly mean background atmospheres with tidal perturbations. Initial gravity wave parameters for simulations are specified from a range of deep convection gravity wave source models. Simulation results are compared to radar observations of middle atmospheric gravity wave activity to infer the most accurate source model and its spectral characteristics. The inferred source spectrum characteristics are analyzed in relation to meteorological conditions during the period of each simulation to assess the consistency with theoretical models of gravity wave excitation by deep convection. Results infer a highly anisotropic source spectrum with peak momentum flux preferentially aligned with tropospheric winds.

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Peter T. Love, Stony Brook, New York, USA, 11790, click here to send an email

Final ID:

Momentum Flux Spectrum of Convective Gravity Waves:

Impacts of an Updated Parameterization in a GCM

H. Choi; [1]; *H. Chun;* [1];

1. Dept of Atmospheric Sciences, Yonsei University, Seoul, Korea, Republic of.

Body: The reference-level (cloud-top) momentum flux spectrum of convective gravity wave drag (GWDC) parameterization by Song and Chun (2005) is updated by determining two free parameters, the moving speed of the convective source and wave-propagation direction, using mesoscale simulations that explicitly resolve the convective GWs under various storm environments. In the updated GWDC parameterization, the moving speed of the convective source is determined by the basic-state wind averaged below 700 hPa. For the wave-propagation direction, a directional pair of 45° (northeast and southwest) and 135° (northwest and southeast) is considered as the best choice for computational efficiency. The ray-based GWDC parameterization by Song and Chun (2008) with the updated cloud-top momentum flux spectrum is implemented in the Whole Atmosphere Community Climate Model version 1b (WACCM1b) in addition to two existing GWD parameterizations: mountain GWD (GWDM) and background GWD (GWDB). The impacts of the updated parameterization in WACCM1b are investigated in terms of zonal-mean zonal wind and temperature, wave-induced forcing, meridional circulations, and tropical middle-atmosphere variabilities. The results are also compared with those of the original ray-based GWDC parameterization (RayC simulation).
When both of the two update factors are included (RayDCQ simulation), the zonal-mean zonal wind in January and July are significantly improved compared with the RayC simulation, especially in the polar night jet regions, equatorial upper stratosphere to subtropical summer mesosphere, and polar summer mesosphere. The improvements in the polar night jet regions (equatorial upper stratosphere to subtropical summer mesosphere) are due mainly by the GWDC and GWDB changes (GWDC change). The improvements in the polar summer mesosphere are due to the EP flux divergence and GWDB that are changed indirectly by updating the GWDC parameterization. The temperature is also improved in the RayDCQ simulation in January and July, especially in mid- to high-latitudes and the polar night jet regions in the both hemispheres. These are due to the changes in meridional circulations by additional GWDC forcing and other wave forcing terms that are modulated by the GWDC forcing. Finally, it is found that the interannual variabilities in the tropical stratosphere related to the quasi-biennial oscillations (QBO) are enhanced in the RayDCQ simulation. The enhancements are mainly by the resolve wave forcing that is enhanced by including the updated GWDC parameterization, while contributions by GWDB are reduced.

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Final ID:

Effects of the Convective Gravity-Wave Drag Parameterization in the Global Forecast System of the Met Office Unified Model in Korea

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Body: The spectral convective gravity-wave drag (CGWD) parameterization by Song and Chun (2005) is implemented to the operational version of UK Met Office Unified Model (UM) 6.6 in Korea to investigate the effects of CGWD in the medium-range global forecast system. We performed one-month experiments of the five-day forecasts at every 00/12 UTC for the January 2010 and July 2009 initialized from 6-hr 4DVAR data assimilation cycle with (GWDC experiment) and without (CTL experiment) the CGWD parameterization. The parameterization represents well the spatial and temporal variability of the cloud-top gravity-wave momentum flux: the maximum eastward momentum flux occurs in the tropical region, whereas the maximum westward flux exists on the oceans in midlatitudes of the winter hemisphere along the storm tracks. CGWD modulates the equatorial zonal winds with wave-like vertical structures and decelerates winds in mid- to high-latitudes of the winter hemisphere in the stratosphere. By CGWD, the mean zonal and meridional circulations are modified, in addition to the changes in other forcing terms (e.g. the resolved-wave forcing, Coriolis force, non-orographic gravity-wave forcing). The tropical stratospheric wind biases for both months in the CTL experiment are reduced by 10 – 20% in the GWDC experiment: the excessive easterly in the mid-stratosphere is weakened, and the positive and negative biases of the near-zero winds in the upper and lower stratosphere, respectively, are reduced. The cold pole bias and westerly biases in midlatitudes of the winter stratosphere are also alleviated by ~10%. In the troposphere, the tropical circulation is significantly modified, and this modulates rainfalls so that the precipitation errors are reduced, particularly in the January 2010. Based on the skill scores of 5-day forecasts, mid-tropospheric geopotential heights and lower tropospheric temperatures in the tropics are forecasted better in the GWDC experiments. The root-mean-square errors (RMSE) of the 500-hPa geopotential heights are reduced by 5 – 10% for the both months, and those of the 850-hPa temperatures by ~5% for the July 2009.

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Gravity wave forcing and its effects in entire middle atmosphere: Study under Atmospheric Forcing and Responses (SAFAR), a major NARL campaign (*INVITED*)

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Body: Study of Atmospheric Forcing and Responses (SAFAR) is a five year (2009–2014) research programme specifically to address the responses of the earth's atmosphere to both natural and anthropogenic forcings using a host of collocated instruments operational at the National Atmospheric Research Laboratory, Gadanki (13.5oN, 79.2o E), India from a unified viewpoint of studying the vertical coupling between the forcings and responses from surface layer to the ionosphere. As a prelude to the main program a pilot campaign was conducted at Gadanki during May–November 2008 using collocated observations from the MST radar, Rayleigh lidar, GPS balloonsonde, and instruments measuring aerosol, radiation and precipitation, and supporting satellite data and extended with full pledged campaign since January 2009. Present study focuses on study of the upward traveling waves in the middle atmosphere coupling the lower atmosphere with the upper atmosphere, their manifestation in the mesospheric temperature structure and inversion layers, the mesopause height extending up to 100 km, and the electro-dynamical coupling between mesosphere and the ionosphere which causes irregularities in the ionospheric F-region.

Main mechanisms for the generation of gravity waves (GWs) are convection, wind shear (vertical shear of horizontal wind and/or geostropic adjustment i.e., spontaneous imbalance in jets) and topography over Indian region. During south-west monsoon season (June-August) over Indian region both convection and wind shear co-exists. In order to understand which mechanism dominates for generating the GWs few special experiments has been conducted with MST radar under theme 3 of SAFAR. MST Radar was operated continuously for 72 hours to capture high frequency GWs followed by every six hours observations for capturing medium scale to inertial period waves in different seasons. During this time, radiosonde has been released for every six hours in addition to the regular (daily once) launch throughout the season. These two data sets are utilized effectively to characterize the jet stream and associated GWs. Although two major sources, that is, strong convection and wind shears coexist during monsoon season, wind shear (both vertical shear of horizontal wind and geostropic adjustment) is found responsible for the generation of GWs on various scales. This raises the question, what happened to the waves generated due to convection?

The purpose of this presentation is not only to share the knowledge that we gained from the SAFAR pilot campaign, but also to inform the international atmospheric science community about the SAFAR program as well as to extend our invitation to join in our study.

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Gravity waves and cloud structures: AIRS observations

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Body: Interactions between wave dynamics and humidity form clouds at wide spatial scales. On one hand, wave perturbations can enhance cirrus formation in the upper troposphere, regulating cloud and water vapor distributions and feedbacks on climate. On the other hand, energy exchanges and perturbations from organized cloud systems act as a source of new wave generation, which may affect general circulation in the middle and upper atmosphere. In this study we analyze organized cloud structures using AIRS radiances from the 90 view angles, each of which has a beamwidth of ~13 km, to characterize how clouds are modulated by gravity waves. We focus on five tropical convective regions and compiled eight-year (2003 - 2010) statistics of cloud-induced radiances. The ensemble of AIRS cloud radiances suggests that more or stronger anvil clouds are observed near the local noon (13:30 LST) from east view angles of the AIRS scans, whereas the cloud amounts from east and west views are roughly equal at midnight (01:30 LST). Oblique view angles are generally more sensitive to anvil clouds than the nadir views. However, the sensitivity is reversed for deep convective clouds. The east-view preference of AIRS cloud radiances is slightly larger over lands than over oceans, which can be explained by gravity-wave-induced structures embedded in anvil clouds. The wave-induced bands appear to be closely associated with the upper troposphere wind shear at noon when convection is initiated, but it may not be the case at midnight when convection is at its mature or decay stage. These results have important implications for gravity wave spectra launched from the clouds in the upper troposphere, which will affect wave momentum budgets in the middle and upper atmosphere.

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Sources of Gravity Waves in Hurricanes

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Body: The hurricane affords a unique dynamical environment in which the time scale of vortical processes is accelerated to become comparable with that of buoyant processes. Consequently we expect unique interactions between the slow and fast manifolds. The circular geometry of the storm and nonlinear modifications of primary and secondary circulation, owing to the strength of the latter, provide several unique mechanisms for gravity-wave excitation. Twelve such sources have been identified in the literature. Our talk focuses on four of these: fluctuations of interior heating in the eyewall, inertially neutral or unstable outflow aloft, pulsating radial inflow and the associated corner flow in the hurricane boundary layer under the eyewall, and the role of coherent polygonal deformations of the eyewall (associated with moist convective mesovortices) in organizing the envelope of gravity-wave activity on intermediate and short scales. The fourth mechanism illustrates the conditional nature of convective heating, implying that gravity wave packets remain coherent with their eyewall mesovortex source in the near field of the storm. This aspect is demonstrated with a high-resolution numerical simulation of Katrina (2005). A discrete vortical-convective mode with radiating structure in the far field is also identified in the simulation.

Some comments are made, based on geostationary satellite imagery, concerning the "hyper-fast" nature of convective triggering in the proto-hurricane environment and in tropical easterly waves.

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Influence of gravity waves generated by typhoon on the typhoon development

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Body: Gravity waves generated by typhoons have been examined observationally and numerically. Previous studies of typhoon-generated gravity waves (TGWs) have focused on their characteristics and influence on the background flow, in particular in the stratosphere. However, to date there have been no studies of the feedback from TGWs to the typhoon. Numerical-modeling studies have shown significant momentum deposition in the upper troposphere and lower stratosphere by TGWs, and this momentum deposition can modify the background flow. Thus, TGWs are expected to affect their source given that the environmental flow around a typhoon is a major factor determining the typhoon's evolutionary processes, along with a typhoon's internal dynamics and energy from the ocean. This study examines the impact of TGWs on typhoon development. We simulate Typhoon Saomai, which formed in the western Pacific in August 2006, and examine the background-flow changes induced by TGWs at z = 12-17 km by calculating the momentum flux of TGWs. Then, we investigate their possible influences on typhoon development by considering the environment conditions, including the vertical wind shear and divergence filed. Numerical simulations are performed using Weather Research and Forecasting (WRF-ARW) model in three domains with horizontal grid spacings of 27 km, 9 km, and 3 km. Three domains are nested with a two-way interaction, and the innermost domain with a grid spacing of 3 km is designed to move following the typhoon center. The momentum flux of TGWs and its vertical divergence/convergence are larger in the developing stage than in the mature and decaying stages of the typhoon. In the developing and mature stages of the typhoon, TGWs are found to act to decrease the vertical wind shear, which is one of the inhibiting factors in a typhoon's intensification. On the other hand, TGWs act to increase the vertical wind shear in the decaying stage of the typhoon. This means that TGWs can contribute to favorable vertical wind shear conditions for the typhoon's developing and mature stages. Once typhoon intensity begins to decrease, however, TGWs can help a typhoon decay. Horizontal divergence also varies depending on the typhoon's evolution. Upper-level divergence, which is positively correlated with the typhoon intensity, is found to be related significantly to the activity of TGWs.

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