Synthetic Gravity Wave Analyses for New Exploitation of Satellite Data (SWANS)

Abstract:

Small-scale gravity waves (GWs) are vital to the dynamics of the Earth's atmosphere, but are difficult to simulate accurately in weather and climate models. While major advances have been made in recent years in our ability to observe GWs from space, translating these advances to model development is complicated by the fragmentary view these observations provide.

In SWANS, our International Team will combine space-based observations and high-resolution simulations to demonstrate a novel pathway to better representation of GWs and their effects in next-generation models. We will do this by adapting a widely-used satellite development technique, the Observing System Simulation Experiment, to the problem of the effectively-fixed GW observing system. This will allow us to produce detailed information on how current instruments 'see' GWs when their sensing parameters are reproduced in state-of-the-art high-resolution atmospheric models.

This approach will allow us to both identify deficiencies in the current GW observational constellation and improved ways to observationally constrain GW parameterisations in next-generation weather and climate models. We will promote these results via our membership in international projects within the World Climate and World Weather Research Programmes (WCRP and WWRP), ensuring broad dissemination and a pathway to real-world impact on numerical weather prediction and climate modelling.

A Scientific Rationale

A.1 Gravity Waves - What Are They and Why Do They Matter?

Atmospheric **gravity waves** (GWs) are small waves with big impacts. Typically hundreds of metres to kilometres in vertical wavelength and tens to hundreds of kilometres in the horizontal, these waves are too small to be fully resolved in weather and climate models and are highly challenging to observe from space, but are critical to the dynamics of the atmospheric system.

GWs have important impacts on the atmosphere at nearly all spatiotemporal scales and levels. In particular, they act as a control on most major atmospheric circulations above the tropopause, including the jet streams, the Brewer-Dobson circulation, the quasi-biennial oscillation (QBO), and the summer-to-winter mesospheric residual circulation (Fritts, 1984; Haynes et al., 1991; Baldwin et al., 2001; Fritts and Alexander, 2003; Ineson and Scaife, 2009). These circulations in turn affect surface weather and climate, particularly at subseasonal to interannual timescales, via a diverse range of downward coupling mechanisms (Alexander and Rosenlof, 2003; Alexander et al., 2010; Richter et al., 2020). GWs also have strong direct effects on local atmospheric conditions: they are involved in ozone depletion, cause flight turbulence affecting aircraft, affect cloud formation in the upper troposphere, and couple into the ionosphere to affect GPS and radio (Whiteway et al., 1997; Carslaw et al., 1998; McCann, 2001; Kim and Alexander, 2015; Hoffmann et al., 2017; Wright and Banyard, 2020; Bramberger et al., 2022).

However, GWs are still poorly-simulated by even state-of-the-art climate and weather models. This is partly due to the issues inherent in accurately simulating small-scale processes in models which are by definition

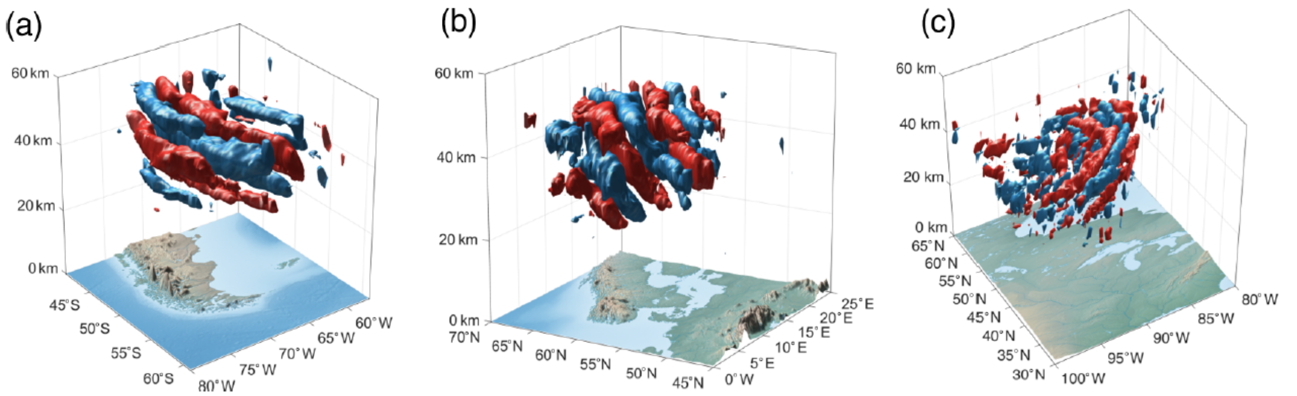

Figure 1: *Gravity waves in data from NASA's AIRS instrument, observed over (a) the Andes mountains, (b) Scandinavia and (c) a large convective storm in North America. Reproduced from Wright et al. (2021).*

limited in spatiotemporal resolution, and partly due to a limited knowledge of GW source mechanisms and propagation characteristics in the real atmosphere.

This is a major problem in particular for the development of subseasonal- and seasonal-timescale forecasting systems, which require most GWs to be *parameterised*, i.e. their effects accounted for in bulk at the scale of a model grid too coarse to directly resolve the waves. For such systems, GW-driven features such as the QBO and Brewer-Dobson circulation are key sources of predictability (Ineson and Scaife, 2009; Vitart and Robertson, 2018). It also imposes important limits on our ability to simulate how atmospheric dynamics will evolve as our climate changes (Butchart et al., 2020; Richter et al., 2020).

A.2 Bridging the Divide - Observations and Models

Due to their importance, it is vital that GW effects are accurately represented in atmospheric models. This is true at all simulated time and space scales, from the high-resolution numerical weather prediction (NWP) models used in daily weather forecasting, which directly resolve a large fraction of the GW spectrum, all the way through to the coarse-resolution climate models which simulate timescales of decades and longer using GW parameterisations. However, accurately constraining how these models represent GWs for future development is complicated by two great technical challenges: (i) **observing GWs in global satellite datasets** and (ii) **fair comparisons between how GWs are seen in observations and GW-resolving models**.

Over the last decade, significant advances have been made in response to the first of these challenges. New computational techniques have revolutionised our ability to retrieve, detect and characterise GWs in the very large volumes of data provided by the constellation of satellite instruments in low Earth orbit (e.g. Figure 1), which has facilitated the production of GW climatologies with significant scientific utility (e.g. Ern et al., 2018; Hindley et al., 2020, Figure 2). Several members of the proposed Team (*Alexander, Ern, Hindley, Hoffmann, Holt, Wright*) have been heavily involved in these efforts, and previous ISSI International Team Projects have proven critical to the global integration needed for this work.

However, **without a solution to the second problem, fair comparisons, the utility of these datasets is limited**. Current satellite GW observational datasets, like those described by *Ern et al* and *Hindley et al*, cover only specific fragments of the GW spectrum. Therefore, directly comparing these observations to GWs in high-resolution convection-permitting GW-resolving models (Putman and Suarez, 2011; van Niekerk et al., 2018; Stephan et al., 2019; Polichtchouk et al., 2022) is highly challenging, as we are not comparing like with like.

Consequently, there remains an important mismatch between the observational and modelling communities. While many researchers do work across this divide, the fragmentary view of the true state that we have makes it exceptionally challenging to directly compare GW models and observations, both to improve how resolved GWs are simulated and to advance parameterisations. This divide inhibits use of the observationally-driven advances that have led and continue to lead to major advances in other areas of earth-system science.

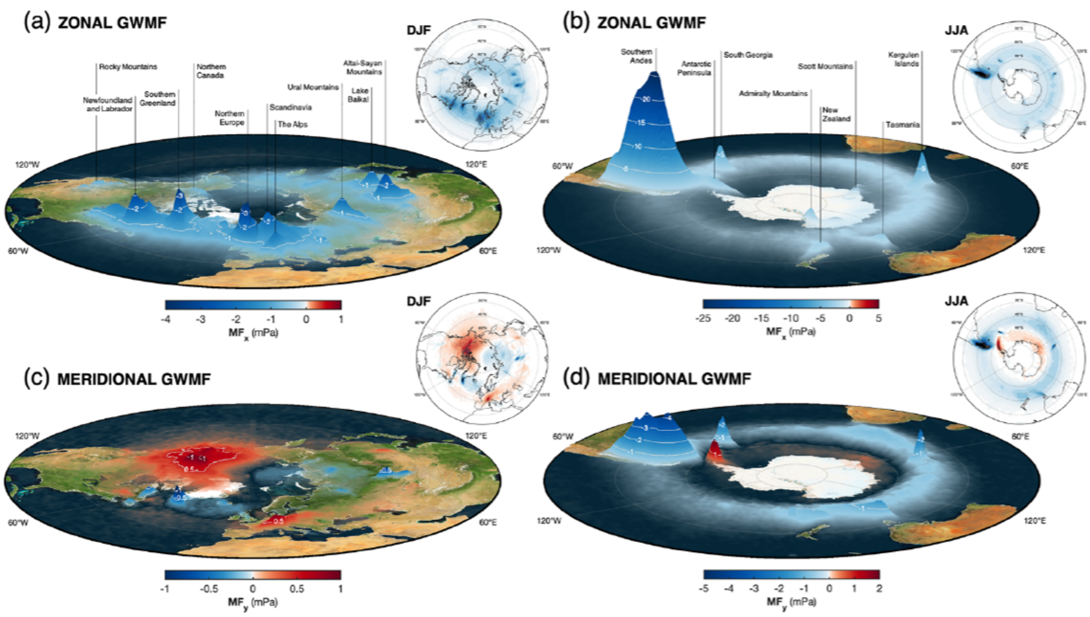

Figure 2: *GW momentum flux estimates derived from NASA's AIRS instrument, in the (top row) eastward (bottom row) northward direction, for (left) boreal (right) austral winter. Reproduced from Hindley et al. (2020).*

A.3 Our Proposed Approach: a Modified OSSE

Our International Team will build on new developments in this fast-evolving field (Wright and Hindley, 2018; Stephan et al., 2019; Wedi et al., 2020; Hindley et al., 2021; Kruse et al., 2022) to directly address the problems that limit the use of satellite data to enhance the modelling of GWs and their effects.

> In SWANS, we will use an approach analogous to the Observing System Simulation Experiments of satellite mission development to make fair comparisons between GW observations and atmospheric models. This data-synthesis approach will support major advances in GW research, with broad implications for fundamental atmospheric dynamics and for the development of next-generation NWP & climate models.

Observing System Simulation Experiments (OSSEs) are a technique widely used in the development of new satellite missions. In an OSSE, output from a high-resolution simulation (often called a 'nature run') is sampled using the resolution and noise characteristics of a proposed instrument design. These synthetic data are then processed to assess their quality, with this latter step often done by assimilating the data into a broader observing *system* of other satellites and models, hence the term O*S*SE. Based on these results, the design of the proposed satellite is then modified to improve the final products and overall utility of the system.

We will modify this traditional OSSE loop (Figure 3) to instead target improvements in GW modelling and in GW detection and characterisation (i.e. data analysis) techniques. **Rather than assessing how a varying observing system will see the atmosphere given a fixed model and fixed data processing chain, we will instead assess how models and the data processing chain can be modified to better interpret the data supplied by a fixed observing system.** This modified OSSE is a useful approach in the GW case for two reasons:

1. While our limited understanding of GWs is widely recognised as an urgent problem which needs to be addressed as weather models approach kilometre-scale resolutions (Stevens et al., 2019; Wedi et al., 2020; Stephan et al., 2022), due to satellite design and launch timescales suitable observing instruments are very unlikely to come on-stream until the 2030s (Sinnhuber et al., 2021).
2. This approach will unlock the door to the reinterpretation of decades of existing GW-resolving satellite data. It thus has significant potential to help understand how GWs interact with, control and amplify the dynamical effects of long-term Earth-system processes, including the impacts of the 11-year solar cycle on the atmosphere and changes to the structure of the jet streams as our climate changes.

Such an approach will require the combined input of *modellers* able to provide the simulation-system knowledge needed to understand and improve atmospheric models, *retrieval scientists* able to explain and reproduce the ways in which existing satellites measure the atmosphere, *remote sensing experts* experienced with the methods currently used to characterise GWs in these observations, and *theorists* with the knowledge and mathematical skill needed to contextualise the novel information our approach will produce. **Our International Team will bring specialists in all these areas together** to generate the knowledge needed for a step change in our ability to characterise and simulate GWs in the terrestrial atmosphere.

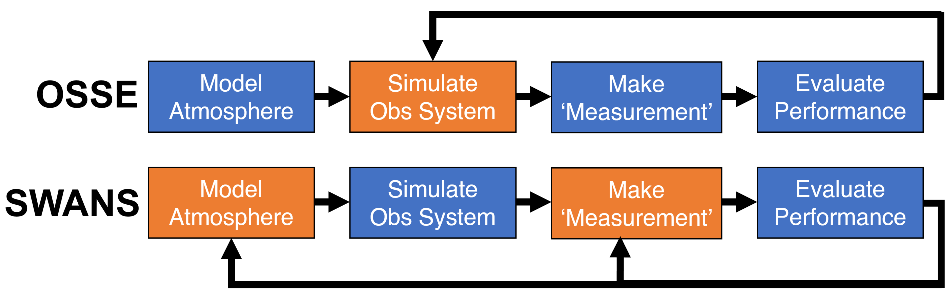

Figure 3: *Schematic showing the approach we will take in SWANS. The upper row shows the operational flow for a satellite-design OSSE: a fixed model atmosphere is sampled using the proposed system, then the extracted data is processed, the results evaluated, and the observing system modified. In our project, we will instead assume a fixed observing system and modify the model and processing chain to better reproduce real GW observations. For each row, orange boxes indicate elements that are modified and blue elements that stay constant.*

B Objectives and Work Plan

B.1 Objectives

Our primary goal is to advance weather and climate science by providing the data, models and tools needed to improve our knowledge of small-scale gravity waves and their role in the atmospheric system.

To achieve this goal, we will

- generate synthetic measurements representative of current satellite- and selected non-satellite systems, by applying novel sampling and analysis techniques to state-of-the-art high-resolution weather forecast models (advancing upon the work of Wright and Hindley (2018) and Kruse et al. (2022)).
- apply advanced detection and characterisation techniques to these synthetic data to produce equivalent synthetic GW measurements (using methods described by Alexander et al., 2008; Lehmann et al., 2012; Ern et al., 2017; Wright et al., 2017, 2021, amongst others; see also Figure 2).
- compare the GWs observed in these synthetic measurements to those present in the original model fields, then use our Team's detailed knowledge of instrument characteristics and GW theory to identify which differences arise due to measurement limitations and model inaccuracies respectively.

The very-high resolution model runs we will use already exist as part of other projects we are individually involved in, including INCITE 1 km runs of the ECMWF IFS (Polichtchouk et al., 2022), high-resolution runs in multiple models carried out as part of the DYAMOND project (Stevens et al., 2019), and Nature Runs for satellite OSSEs carried out in the GEOS model (Holt et al., 2017). We will have the opportunity to feed back modifications into new iterations of these models between the two in-person SWANS workshops, and will devote time at our first meeting to detailed planning of how to effectively exploit these large-volume datasets.

These comparisons will provide the evidence base to improve both (i) simulation of GWs by atmospheric models and (ii) measurement techniques used to characterise GWs in observations, allowing our Team to

1. quantify the strengths and limitations of the current GW-resolving observational constellation
2. validate high-resolution convection-permitting global GW simulations of the type that will form the dynamical basis of next-generation weather forecasting systems, and
3. identify and highlight the key gaps in current observational techniques, at an early enough stage to be integrated into the design of next-generation GW-resolving satellite instruments.

Targets 1 and 3 are particularly timely in the context of current development of Cairt, a candidate ESA Earth Explorer 11 mission intended to resolve fine-scale atmosphere dynamics which will launch in $\sim$2032 if selected.

B.2 Schedule

We plan two five-day in-person and three two-day virtual meetings, to be attended by all team members. The first meeting will be in-person, to provide the best environment for encouraging positive inter-personal team building and collaboration between all Team members. Beforehand, participants will prepare brief summaries of available resources, including model output and GW detection software. At the meeting we will discuss these inputs, develop a detailed action plan, and identify targets and progress milestones. We will also select an individual leader for each output (see below), in order to maintain focus.

We will hold two virtual meetings between the in-person meetings, spaced evenly across this period. At these meetings, we will discuss results achieved to date and retarget our work on this basis. This will include designing new model runs, modifications to our sampling techniques, and changes to our GW detection methods.

At the second in-person meeting we will discuss our results, and refine them into clearly-structured manuscripts. These manuscripts will distill the new information we generate for the broader community, including specific recommendations for future development of models, instruments and software techniques. A follow-up virtual meeting around a month after the in-person meeting will be used to steer the manuscripts towards final submission. Finally, we will seek a final meeting of opportunity (not funded by ISSI) at a conference attended by researchers in our field, where we can present our final results and link them to their broader scientific context.

B.3 Planned Outputs

We plan to produce 2-4 influential publications on GW observational tests of weather and climate model data, to be completed by the end of the 2-year project. The exact details of these publications will be determined at the first in-person meeting, but are likely to be selected from the following topics:

- quantification of the uncertainties in existing GW observational analyses, both from instrument sampling and data analysis techniques.

- case studies examining the roles of GWs at different lengthscales and from different sources, to inform seamless parameterisations operating across the 'grey zone' of partially-resolved GWs (Vosper et al., 2016).
- a detailed review of existing observational capabilities and knowledge, including details of the 'missing' observations needed to address current and near-future modelling needs, acting as an update of the most recent major review of the field (Alexander et al., 2010).
- quantitative constraints for GW parameterisation schemes that account for the fragmentary spectral coverage of the input observations

Completing manuscripts which address all of these topics is unlikely within the two-year window, but our Team will start from a strong position given that the model output and data processing software needed for the first phase of our work are already available, with only the sampling step required to produce the products needed for our first pass through the OSSE operational loop. Based on past experiences of Team members with ISSI International Teams, it is likely that the materials collected and collaborations forged during the project will lead to further publications. We also hope to publish a global GW climatology as a data product that can be accessed by other model groups for future validation efforts, merging the best features of and improving upon the Ern et al. (2017) and Hindley et al. (2020) climatologies using the new knowledge our project generates.

We will ensure acknowledgement of ISSI's role in all publications and products.

B.4 Timeliness

SWANS is a highly timely project. It builds upon very recent modelling and methodological advances, including new kilometre-scale global weather simulations (Stephan et al., 2019; Wedi et al., 2020; Polichtchouk et al., 2022; Stephan et al., 2022), new techniques able to extract much more precise measurements of GW properties from observations than previous methods (Hindley et al., 2020; Wright et al., 2021) and novel approaches for comparing modelled and observed GWs (Wright and Hindley, 2018; Kruse et al., 2022).

At an output level, in addition to supporting plans for Cairt (discussed above), our work will fill a large need for observational constraints on subseasonal to decadal weather models. It will also provide an important opportunity to collectively produce an up-to-date review of work in the field - the most recent major such review was in 2010 (Alexander et al., 2010), over a decade ago.

B.5 Why ISSI?

ISSI support of this project will allow our diverse team of scientists to meet and work towards our scientific objectives. An ISSI International Team makes focused, in-depth discussions possible, rather than merely presenting work as at a scientific conference.

This project builds upon the recent *New Quantitative Constraints on Orographic Gravity Wave Stress and Drag* International Team which ran from 2019-2021, with several shared members, and therefore we are highly familiar with the benefits ISSI offers. The first meeting of this Team was a valuable opportunity to meet informally and work as a group, which allowed us to build a team spirit which sustained the group through the pandemic-related cancellation of the second planned meeting while still producing useful output, culminating in a detailed publication which we expect to have significant impact on the field (Kruse et al., 2022).

The project is closely aligned with ISSI's remit to support research that uses space data and applying theory with direct application to satellite data.

B.6 The Team

The Team will consist of the following 12 members: Joan Alexander *(NWRA, USA)*, Manfred Ern *(FZ Jülich, Germany)*, Neil Hindley *(University of Bath, UK)*, Lars Hoffmann *(FZ Jülich, Germany)*, Laura Holt *(NWRA, USA)*, Chris Kruse *(NWRA, USA)*, Annelize van Niekerk *(Met Office, UK)*, Riwal Plougonven *(École Polytechnique, France)*, Inna Polichtchouk *(ECMWF, UK)*, Bill Putman *(NASA, USA)*, Claudia Stephan *(MPI für Meteorologie, Germany)* and Corwin Wright *(Team Leader, University of Bath, UK)*.

Our team has a balanced gender representation (5 female members, 7 male), a mix of seniority levels (3 senior, 3 mid-career and 6 early-career scientists), and represents a broad disciplinary mix incorporating observationalists, modellers, and theorists. All team members commit to attending all meetings.

B.7 Financial Support Requested

We request hotel and per-diem support for the twelve team members and for two additional scientists at a career stage earlier than two years post-PhD, who will be selected at a later date in accordance with ISSI guidelines. We also request financial support for the Team Leader's travel to Bern.

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Wright, C. J., N. P. Hindley, L. Hoffmann, M. J. Alexander, and N. J. Mitchell, 2017: Exploring gravity wave characteristics in 3-D using a novel S-transform technique: AIRS/Aqua measurements over the Southern Andes and Drake Passage. *Atmospheric Chemistry and Physics*, **17**, 8553–8575, doi:10.5194/acp-17-8553-2017.

Team Membership

Team Leader:
Corwin Wright
University of Bath
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Team Members:

M. Joan Alexander
Northwest Research Associates
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NASA
william.m.putman@nasa.gov

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Max-Planck-Institut fuer Meteorologie
claudia.stephan@mpimet.mpg.de

WRIGHT, Corwin

Affiliation:
University of Bath, Bath, UK

Role in the project:
Team Leader and specialist in observational gravity wave detection and characterization techniques

Current position:
Senior Research Fellow and Royal Society University Research Fellow (URF)
[Independent post equivalent to US Associate Professor or UK Senior Lecturer]

Former Positions:
Research Fellow and Royal Society URF at University of Bath, UK (2017-2019)
Research Officer at University of Bath, UK (2013-2017)
Postdoctoral Researcher at National Center for Atmospheric Research, USA (2010-2011,2012-2013)
Postdoctoral Researcher at University of Western Brittany, France (2011-2012)

Education:
DPhil Atmospheric Physics, University of Oxford, 2010
MSc Photonics, University of St Andrews & Heriot-Watt University, 2006
MSci Physics, University of Durham, 2005

Service in National and/or International Committees:
2022-date: Co-Chair, SPARC Gravity Waves Activity
2019-date: Lead Convenor, AGU Fall Meeting Gravity Waves Session
2019-2022: Chair, Royal Society Research Fellows' Network
2019-2021: Member, ISSI International Team *(Constraints on Orographic Waves)*
2009-2011: Member, ISSI International Team *(The Gravity Wave Project)*

Plus grant selection panels for: British Council (UK), EASME (EU), Horizon 2020 (EU), and NASA (USA)

Honors:
2017 Royal Society University Research Fellowship

Invited talks at major conferences including the American Meteorological Society Annual Meeting, American Geophysical Union Fall Meeting, Canadian Division of Atmospheric and Space Physics Spring Meeting, and the Chapman Conference on Gravity Waves

Journal Highlight citations for three papers in EGU journals (2016, 2017,2018)

Selected Publications:

1. Tonga eruption triggered waves propagating globally from surface to edge of space
CJ Wright, NP Hindley, MJ Alexander, M Barlow, L Hoffmann, CN Mitchell, F Prata, M Bouillon, JA Carstens, C Clerbaux, SM Osprey, N Powell, CE Randall, and J Yue
Preprint available on ESSOAr, doi:10.1002/essoar.10510674.1 (2022)

2. Quantifying the global impact of tropical cyclone-associated gravity waves using HIRDLS, MLS, SABER and IBTrACS
CJ Wright
Quarterly Journal of the Royal Meteorological Society, doi:10.1002/qj.3602 (2019)

3. How well do stratospheric reanalyses reproduce high-resolution satellite temperature measurements?
CJ Wright and NP Hindley
Atmospheric Chemistry and Physics, doi:10.5194/acp-18-13703-2018 (2018)

4. Exploring gravity wave characteristics in 3-D using a novel S-transform technique: AIRS/Aqua measurements over the Southern Andes and Drake Passage
CJ Wright, NP Hindley, L Hoffmann, MJ Alexander and NJ Mitchell
Atmospheric Chemistry and Physics, doi:10.5194/acp-17-8553-2017 (2017)

5. Combining AIRS and MLS Observations for Three-Dimensional Gravity Wave Measurement
CJ Wright, NP Hindley and NJ Mitchell
Geophysical Research Letters, doi:10.1002/2015GL067233 (2016)

6. Multi-instrument gravity-wave measurements over Tierra del Fuego and the Drake Passage – Part 1: Potential energies and vertical wavelengths from AIRS, COSMIC, HIRDLS, MLS-Aura, SAAMER, SABER and radiosondes
CJ Wright, NP Hindley, AC Moss, DC Fritts, D Janches and NJ Mitchell
Atmospheric Measurement Techniques, doi:10.5194/amt-9-877-2016 (2016)

7. The Southern Stratospheric Gravity Wave Hotspot: Individual Waves and Momentum Flux Estimates from COSMIC GPS-RO
NP Hindley, CJ Wright and NJ Mitchell
Atmospheric Chemistry and Physics, doi:10.5194/acp-15-7797-2015 (2015)

8. Global observations of gravity wave intermittency and its impact on the momentum flux morphology
CJ Wright, SM Osprey and JC Gille
Journal of Geophysical Research (Atmospheres), doi:10.1002/jgrd.50869 (2013)

9. Intercomparisons of HIRDLS, COSMIC and SABER for the detection of stratospheric gravity waves
CJ Wright, M Belmonte Rivas and JC Gille
Atmospheric Measurement Techniques, doi:10.5194/amt-4-1581-2011 (2011)

10. HIRDLS Measurements of gravity wave activity in the 2006 Arctic stratosphere
CJ Wright, SM Osprey, JJ Barnett, LJ Gray and JC Gille
Journal of Geophysical Research, doi:10.1029/2009JD011858 (2010)

ALEXANDER, M. Joan

Affiliation:
NorthWest Research Associates (NWRA), Boulder, CO, USA

Role in the project:

Team Participant with expertise in both limb and nadir-viewing satellite observations of atmospheric gravity waves

Current position:
Senior Research Scientist, Vice President, and Director at NWRA-Boulder
Affiliate Professor, University of Colorado

Former Positions:
1994-1998: Research Assistant Professor, University of Washington
1992-1994: Postdoctoral Scientist, Univ. of Washington, Seattle

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

Service in National and/or International Committees:

Currently serves on Council of the American Meteorological Society (AMS). Past appointments include President of the American Geophysical Union (AGU) Atmospheric Sciences Section, Chair of the WCRP SPARC Project, and member of the Board on Atmospheric Science and Climate for the US National Academy of Sciences.

Honors:
Elected Fellow of the AMS in 2006 and Fellow of the AGU in 2017.

Publications:
Alexander, M. J., C. C. Liu, J. Bacmeister, M. Bramberger, A. Hertzog, J. H. Richter, 2021: Observational validation of parameterized gravity waves from tropical convection in the Whole Atmosphere Community Climate Model (WACCM). J. Geophys. Res.—Atmos., 126, doi: 10.1029/2020JD033954

Vincent, R. A., and M. J. Alexander, 2020: Balloon-borne observations of short vertical wavelength gravity waves and interaction with QBO winds. J. Geophys. Res.—Atmos., 125, e2020JD032779, doi: 10.1029/2020JD032779.

Alexander, M. J. 2015: Global and seasonal variations in three-dimensional gravity wave momentum flux from satellite limb sounding temperatures. Geophys. Res. Lett., 42, doi:10.1002/2015GL065234.

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

ERN, Manfred

Affiliation: Institute of Energy and Climate Research – Stratosphere (IEK-7), Forschungszentrum Juelich, Juelich, Germany

Role in the project: International Team Member, role in applying specialized methods to detect gravity waves in satellite data of limb and nadir sounders

Current position: 2002-present: Research Scientist at Forschungszentrum Juelich

Former Position(s): 2000-2002: Post-Doc Scientist at Wuppertal University

Education:

1987 – 1993	University of Wuppertal, Germany (Physics)
1993	Diploma (M. Sc.) in Physics
2000	Ph.D. in Physics (magna cum laude), University of Wuppertal

Services in National and/or International Committees (most recent nominations):

- Member of the SPARC gravity wave initiative (since 2007)

Honors:

1995: DARA (German Space Agency) award (for the CRISTA-SPAS satellite team)
2013: Certificate of Excellence in Reviewing by J. Atmos. Solar-Terr. Phys.
2014: AGU Editor's Citation for Excellence in Reviewing

Selected Publications:

(1) Ern, M., M. Diallo, P. Preusse, M. G. Mlynczak, M. J. Schwartz, Q. Wu, and M. Riese (2021), The semiannual oscillation (SAO) in the tropical middle atmosphere and its gravity wave driving in reanalyses and satellite observations, Atmos. Chem. Phys., 21, 13763–13795, https://doi.org/10.5194/acp-21-13763-2021.

(2) Ern, M., Q. T. Trinh, P. Preusse, J. C. Gille, M. G. Mlynczak, J. M. Russell III, and M. Riese (2018), GRACILE: a comprehensive climatology of atmospheric gravity wave parameters based on satellite limb soundings, Earth Syst. Sci. Data, 10, 857–892.

(3) Ern, M., L. Hoffmann, and P. Preusse (2017), Directional gravity wave momentum fluxes in the stratosphere derived from high-resolution AIRS temperature data, Geophys. Res. Lett., 44, 475–485, doi:10.1002/2016GL072007.

(4) Ern, M., et al. (2011), Implications for atmospheric dynamics derived from global observations of gravity wave momentum flux in stratosphere and mesosphere, J. Geophys. Res., 115, D19107, doi:10.1029/2011JD015821.

(5) Ern, M., P. Preusse, M. J. Alexander, and C. D. Warner (2004), Absolute values of gravity wave momentum flux derived from satellite data, J. Geophys. Res., 109, D20103, doi:10.1029/2004JD004752.

HINDLEY, Neil

Affiliation:	University of Bath, Bath, UK
Role in the project:	Team Member focusing on observations and analysis of atmospheric gravity waves
Current position:	Postdoctoral Research Associate (2017-2022)
Former Position(s):	Research Fellow, University of Leeds, UK (2017) Defence Science and Technology Laboratory, UK (2016-2017)
Education:	PhD in Atmospheric Physics, University of Bath, UK (2012-2016) MPhys in Astrophysics, Cardiff University, UK (2007-2011)

Selected Publications:

Stratospheric gravity-waves over the island of South Georgia: testing a high-resolution dynamical model with 3-D satellite observations and radiosondes
N. P. Hindley, C. J. Wright, A. M. Gadian, L. Hoffmann, J. K. Hughes, D. R. Jackson, J. C. King, T. Moffat-Griffin, A. C. Moss, S. B. Vosper, A. N. Ross and N. J. Mitchell
Atmospheric Chemistry and Physics (2021), doi:10.5194/acp-21-7695-2021.

An 18-year climatology of directional stratospheric gravity wave momentum flux from 3-D satellite observations
N. P. Hindley, C. J. Wright, L. Hoffmann, T. Moffat-Griffin, and N. J. Mitchell
Geophysical Research Letters (2020), doi:10.1029/2020gl089557.

Gravity waves in the winter stratosphere over the Southern Ocean: high-resolution satellite observations and 3-D spectral analysis
N. P. Hindley, N. D. Smith, C. J. Wright, L. Hoffmann, L. A. Holt, M. J. Alexander, T. Moffat-Griffin and N. J. Mitchell
Atmospheric Chemistry and Physics (2019), doi:10.5194/acp-2019-371.

A two-dimensional Stockwell transform for gravity wave analysis of AIRS measurements
N. P. Hindley, N. D. Smith, C. J. Wright, D. A. S. Rees and N. J. Mitchell
Atmospheric Measurement Techniques (2016), doi:10.5194/amt-9-2545-2016.

The southern stratospheric gravity-wave hot spot: individual waves and momentum fluxes measured by COSMIC GPS-RO
N. P. Hindley, C. J. Wright, N. D. Smith and N. J. Mitchell
Atmospheric Chemistry and Physics (2015), doi:10.5194/acp-15-7797-2015.

HOFFMANN, Lars

Affiliation: Jülich Supercomputing Centre (JSC), Forschungszentrum Jülich, Jülich, Germany

Role in the project: Dr. Hoffmann has 20 years of experience in remote sensing, atmospheric science, and high performance computing. He will provide expertise on analyzing infrared sounder observations of stratospheric gravity waves, in particular for NASA's Atmospheric Infrared Sounder (AIRS). Dr. Hoffmann's team at JSC has developed dedicated AIRS data products for gravity wave research such as full-resolution stratospheric temperature retrievals and brightness temperature data sets. The team will provide the AIRS gravity wave data products for the time period from 2002 to present to the ISSI project. In addition, Dr. Hoffmann's team has expertise in high-resolution atmospheric modeling using the German numerical weather prediction and climate model ICON, which will be applied for modeling case studies by the ISSI team.

Current and former positions:
since 2022: senior scientist, designated co-lead of
Division HPC in Applied Sciences and Engineering at JSC
2010-2021: research scientist, team leader of Simulation and Data Laboratory Climate Science at JSC
2008-2009: Postdoc at Institute of Energy and Climate Research,
Forschungszentrum Jülich
2007: visiting scientist at NorthWest Research Associates
and research scholar at University of Colorado, Boulder

Education:
2004-2006: PhD student, Institute of Chemistry and Dynamics of the Geosphere, Forschungszentrum Jülich
1998-2003: physics student, University of Wuppertal

Selected Publications:

Lars Hoffmann co-authored more than 90 peer-reviewed publications, see https://scholar.google.de/citations?user=dNfR0lgAAAAJ.

Hoffmann, L., Xue, X., and Alexander, M. J. (2013), A global view of stratospheric gravity wave hotspots located with Atmospheric Infrared Sounder observations, *J. Geophys. Res. Atmos.*, 118, 416– 434, doi:10.1029/2012JD018658.

Hoffmann, L., and Alexander, M. J. (2009), Retrieval of stratospheric temperatures from Atmospheric Infrared Sounder radiance measurements for gravity wave studies, *J. Geophys. Res.*, 114, D07105, doi:10.1029/2008JD011241.

HOLT, Laura

Affiliation: NorthWest Research Associates, Boulder, CO, USA

Role in the project: Expertise in high-resolution, global modeling of gravity waves

Current position:
2016-Present: Research Scientist, NorthWest Research Associates, Boulder, CO.

Former Position(s):
2014—2016: Postdoctoral Research Scientist, NorthWest Research Associates, Boulder, CO.
2013—2014: Postdoctoral Research Scientist, University of Colorado Boulder / Laboratory for Atmospheric and Space Physics, Boulder, CO.
2007—2013: Graduate Research Assistant, University of Colorado Boulder / Laboratory for Atmospheric and Space Physics, Boulder, CO.

Education:
Bachelor of Arts, St. Cloud State University, 2005, Mathematics.
Bachelor of Science, St. Cloud State University, 2005, Physics.
Doctor of Philosophy, University of Colorado Boulder. 2013, Atmospheric Science.

Services in National and/or International Committees (last ones):
2020—Present: Co-lead of the SPARC GW Activity
2018—Present: Member of the American Meteorological Society Middle Atmosphere Committee

Honors:
IAGA Young Scientist Award 2013
Best student poster, 2012 ATOC Student Poster Conference
Best student paper, 2011 3rd Annual International HEPPA Workshop

Selected Publications:
Laura A. Holt et al., An evaluation of tropical waves and wave forcing of t QBO in the QBOi models. Quart. J. Roy. Meteor. Soc., 2020. https://doi.org/10.1002/qj.3827.

Laura A. Holt, et al., An evaluation of gravity waves and gravity wave sources in the Southern Hemisphere in a 7-km global climate simulation. Quart. J. Roy. Met. Soc., 143:2481–2495, 2017. https://doi:10.1002/qj.3101.

Laura A. Holt, et al., Tropical waves and the quasi-biennial oscillation in a 7-km global climate simulation. J. Atmos. Sci., 73:3771–3783, 2016. https://doi:10.1175/JAS-D-15-0350.1.

KRUSE, Christopher

Affiliation:
NorthWest Research Associates (NWRA), Boulder, CO, USA

Role in the project:
Numerical modeling, and model/satellite observation comparisons

Current position:
2021-Present: Research Scientist, NorthWest Research Associates, Boulder, CO.

Former Positions:
Project Scientist 1, National Center for Atmospheric Research
Advanced Study Program Fellow, National Center for Atmospheric Research

Education:
Ph.D., Geology and Geophysics, Yale University, 2018
M.Phil., Geology and Geophysics, Yale University, 2016
M.S., Atmospheric Sciences, University of Wyoming, 2013
B.S., Atmospheric Sciences, University of North Dakota, 2011

Service in National and/or International Committees:
American Meteorological Society Committee on Mountain Meteorology
Previous ISSI Team Member

Honors:
2017 Elias Lumis Prize, from the Dept. of Geology and Geophysics at Yale University for excellence in study of the physics of the Earth

Publications:

Kruse, C. G., Alexander, M. J., Hoffmann, L., Niekerk, A. v., Polichtchouk, I., Bacmeister, J. T., Holt, L., Plougonven, R., Šácha, P., Wright, C., Sato, K., Shibuya, R., Gisinger, S., Ern, M., Meyer, C. I., and Stein, O., 2022. Observed and Modeled Mountain Waves from the Surface to the Mesosphere Near the Drake Passage, Journal of the Atmospheric Sciences. DOI: https://doi.org/10.1175/JAS-D-21-0252.1

Kruse, C. G., J. H. Richter, M. J. Alexander, J. T. Bacmeister, C. Heale, and J. Wei: Gravity wave drag parameterizations for Earth's atmosphere. Chapter 11 of AGU Book Titled "Fast physics in large-scale models: parameterization, evaluation, and observations." Accepted 15 Dec 2021 in AGU Books.

Kruse, C. G., 2020. Regional to Global Evolution of Impacts of Parameterized Mountain- Wave Drag in the Lower Stratosphere. Journal of Climate 33, 8, 3093-3106. DOI: https://doi.org/10.1175/JCLI-D-19-0076.1

Kruse, C. G., Julio T. Bacmeister, Colin M. Zarzycki, Vince E. Larson, and Katherine Thayer-Calder, 2022. Do Nudging Tendencies Depend on the Nudging Timescale Chosen in Atmospheric Models? Under review in JAMES.

Kruse, C. G. R. B. and Smith, 2018. Nondissipative and Dissipative Momentum Deposition by Mountain Wave Events in Sheared Environments. Journal of the Atmospheric Sciences 75, 8, 2721-2740, DOI: https://doi.org/10.1175/JAS-D-17-0350.1

VAN NIEKERK, Annelize

Affiliation: Met Office, UK

Role in the project: Team member with expertise in high-resolution model data

Current position: Senior Scientist

Former Position(s):

Education: PhD, Oceans, Atmosphere and climate, University of Reading (2013-2017), MSc, Astrophysics, Queen Mary University of London (2011-2012), BA, Mathematics and Philosophy, University of Liverpool (2007-2010)

Services in National and/or International Committees (most recent nominations): TEAMx Waves and Dynamics working group lead, TEAMx Numerical modelling committee member, GASS/WGNE project lead

Honors: Royal Meteorological Society, L F Richard Prize (2017)

Selected Publications:

van Niekerk, A., and Vosper, S. B. (2021): *Towards a more scale-aware orographic gravity wave drag parametrization: Description and initial testing*. Q.J.R. Meteorol. Soc.

van Niekerk, A., Sandu, I., Zadra, A., Bazile, E., Kanehama, T., Köhler, M., Koo, M., Choi, H., Kuroki, Y., Toy, M. D., Vosper, S. B. and Yudin, V. A. (2020): *COnstraining ORographic Drag Effects (COORDE): A Model Comparison of Resolved and Parametrized Orographic Drag.* **J. Adv. Model. Earth Syst.**

Vosper, S., **van Niekerk, A.**, Elvidge, A., Sandu, I. and Beljaars, A. (2020): *What can we learn about orographic drag parametrisation from high-resolution models? A case study over the Rocky Mountains*. **Q.J.R. Meteorol. Soc**.

van Niekerk, A., Sandu, I. and Vosper, S. B. (2018): *The circulation response to resolved versus parametrized orographic drag over complex mountain terrains.* **J. Adv. Model. Earth Syst.**

van Niekerk, A., Scinocca, J.F. and Shepherd, T.G. (2017): *The modulation of stationary waves, and their response to climate change, by parameterized orographic drag.* J. Atmos. Sci.

van Niekerk, A., Shepherd, T.G., Vosper, S.B. and Webster, S. (2016): *Sensitivity of resolved and parameterized surface drag to changes in resolution and parameterization.* Q.J.R. Meteorol. Soc.

PLOUGONVEN, Riwal

Affiliation: Laboratoire de Météorologie Dynamique (LMD), Ecole Polytechnique, Institut Polytechnique de Paris

Role in the project: Methodology for the comparison of simulations and observations; identification of dynamical issues to be explored in model outputs

Current position: Professor (2012-)

Former Position(s): Lecturer at LMD, Ecole Normale Supérieure (2005-2012); Lecturer in the School of Mathematics and Statistics, St Andrews Uni. (2004-2005)

Education: Bachelor: Classes Préparatoires, Lycée Louis le Grand, Paris (1993-1995); Master of Science: Ecole Polytechnique, Palaiseau, France (1995-1998), and PhD at Université Pierre et Marie Curie (1998-1999)

PhD in Geophysical Fluid Dynamics: Université Pierre et Marie Curie (1999-2002)

Services in National and/or International Committees (most recent nominations): co-lead for the SPARC Gravity Wave activity (2020-); Deputy Director of LMD (2016-); co-convener for the Internal Gravity Waves session at the Europ. Geosc. Union GA since 2006; Associate Editor for *Month. Weath. Rev.* (2016-) and for *J. Atmos. Sci.* (2021-); co-leader of the Research Action on *Energy Assessment and Forecast* within the Energy for Climate (E4C) research center (2020-)

Honors: Advanced Study Program fellowship (2002-2004)

Selected Publications:

Corcos, M., Hertzog, A., **Plougonven, R.**, & Podglajen, A. **(2021)**. Observation of gravity waves at the tropical tropopause using superpressure balloons. *Journal of Geophysical Research: Atmospheres*, 126, e2021JD035165.

R. Plougonven, A. de la Cámara, A. Hertzog & F. Lott. (**2020)** How does knowledge of atmospheric gravity waves guide their parameterizations? *QJR Meteorol Soc.*, 115, doi:10.1002/qj.3732

R. Plougonven, A. de la Camara, V. Jewtoukoff, A. Hertzog and F. Lott (**2017**). On the relation between gravity wave and wind speed in the lower stratosphere. *J. Atmos. Sci.*, 74, p1075-1093, 10.1175/JAS-D-16-0096.1

R. Plougonven & F. Zhang **(2014)**. Internal gravity waves from atmospheric jets and fronts, *Reviews of Geophysics*, 52, doi:10.1002/2012RG000419.

R. Plougonven, A. Hertzog & L. Guez. **(2013)** Simulations of gravity waves above Antartica and the Southern Ocean and comparisons to balloon observations. *Quart. J. Roy. Meteor. Soc.*, DOI:10.1002/qj.1965.

POLICHTCHOUK, Inna

Affiliation: European Center for Medium Range weather forecasts (ECMWF)

Role in the project: Generate very high resolution global model simulations with ECMWF IFS model. Provide modelling support for the project and analyze and interpret high-resolution global simulations.

Current position: Scientist in the Numerical Methods Team

Former Position(s): Post doctorate research Associate, University of Reading, UK

Education: 2010-2014: PhD, School of Physics and Astronomy, Queen Mary, University of London, UK, Thesis: Baroclinic Jets on "Other" Jupiters and Earths

2006-2010: MSci in Mathematics with Statistics, Queen Mary, University of London, UK

Services in National and/or International Committees (most recent nominations):

2021-present: MAG Member for ESA Earth-Explorer-11 mission CAIRT

2020-present: Member of the Expert Network of the new WMO Technical Commissions: INFCOM and SERCOM

Selected Publications:

[1] I. Polichtchouk, N. Wedi & Kim Y.-H., 2021, Resolved gravity waves in the tropical stratosphere: Impact of horizontal resolution and deep convection parametrization. *Q J R Meteorol Soc*, 148(742), 233– 251.

[2] I. Polichtchouk & R. K. Scott, 2020, Spontaneous inertia-gravity wave emission from a nonlinear critical layer in the stratosphere, QJRMS, 146(728), 1516–1528

[3] I. Polichtchouk, T. G. Shepherd & N. J. Byrne, 2018 Impact of Parametrized Nonorographic Gravity Wave Drag on Stratosphere-Troposphere Coupling in the Northern and Southern Hemispheres, GRL, 45(16), 8612–8618

[4] I. Polichtchouk, T. G. Shepherd, R. J. Hogan & P. Bechtold, 2018 Sensitivity of the Brewer-Dobson circulation and polar vortex variability to parametrized nonorographic gravity-wave drag in a high-resolution atmospheric model, JAS, 75(5), 1525–1543

[5] I. Polichtchouk & T. G. Shepherd, 2016 Zonal-mean circulation response to reduced air-sea momentum roughness, QJRMS, 142, 2611–2622

PUTMAN, William

Affiliation: *NASA, Goddard Space Flight Center, Global Model and Assimilation Office*

Role in the project: Team Member with expertise in NASA GEOS global gravity wave resolving modeling.

Current position:

- **03/2010 to present:** Associate Chief (2021-) and Research Meteorologist – Global Model and Assimilation Office, NASA, Goddard Space Flight Center, Greenbelt, MD

Former Position(s):

- **05/2008 to 03/2010:** Group Lead – Advanced Software Technology Group, NASA, Goddard Space Flight Center, Greenbelt, MD
- **05/2004 to 05/2008**: Computer Scientist, NASA, Goddard Space Flight Center, Greenbelt, MD
- **08/2001-04/2004**: Senior Software Engineer, Science Applications International Corporation – Data Assimilation Office / Global Modeling and Assimilation Office

Education:

- PhD., 06/2007: Meteorology - Florida State University, Tallahassee, FL
- M.S., 08/1998: Meteorology - Florida State University, Tallahassee, FL
- B.S., 05/1996: Computer, Mathematical, and Physical Science - University of Maryland, College Park, MD

Services in National and/or International Committees (most recent nominations):

- NOAA Strategic Implementation Plan: Convection Allowing Modeling and Dynamics working groups
- NOAA Next Generation Global Prediction System (NGGPS): convection allowing modeling and non-hydrostatic dynamical core

Honors:

- **2016 NASA Honor Award - Exceptional Scientific Achievement Medal.** For the design and execution of the 7-km GEOS-5 Nature Run for OSSEs.
- **2010 Robert H Goddard Exceptional Achievement Award.** Science Team award for exceptional achievement enabling advances in earth climate simulations.

Selected Publications:

- Stephan C., J. Duras, L. Harris, D. Klocke0 W. Putman, M. Taylor, N. Wedi, N. Žagar, F. Ziemen, 2022: Atmospheric energy spectra in global kilometre-scale models. Tellus, submitted.
- Arnold, N. P., W. M. Putman and S. R. Freitas, 2020. Impact of resolution and parameterized convection on the diurnal cycle of precipitation in a global nonhydrostatic model. J. Meteorol. Soc. Jpn., 98, 6, 1279-1304. doi: 10.2151/jmsj.2020-066.
- Satoh, M., B. Stevens, F. Judt, M. Khairoutdinov, S.-J. Lin, W. M. Putman, and P. Duben, 2019. Global Cloud-Resolving Models. Curr. Clim. Chan. Rep., 5, 172-184. doi:10.1007/s40641-019-00131-0
- Freitas, S. R., G. A. Grell, A. Molod, M. A. Thompson, W. M. Putman, C. M. Santos e Silva, and E. P. Souza, 2018. Assessing the Grell-Freitas Convection Parameterization in the NASA GEOS Modeling System. J. Adv. Model. Earth Sys, 10, 1266-1289. doi: 10.1029/2017MS001251
- Putman, W. M., and M. Suarez (2011), Cloud-system resolving simulations with the NASA Goddard Earth Observing System global atmospheric model (GEOS-5), *Geophys. Res. Lett.*, *38*, L16809, doi:10.1029/2011GL048438.

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