Evaluating the Climate Sensitivity of Dissipative Subgrid-Scale Mixing Processes and Variable Resolution in NCAR's Community Earth System Model

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Title: Evaluating the Climate Sensitivity of Dissipative Subgrid-Scale Mixing Processes and Variable Resolution in NCAR's Community Earth System Model

SC Division: Office of Biological and Environmental Research (BER)
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Senior personnel:
Dr. Christiane Jablonowski (PI)
Dr. Richard Rood (Co-PI)

The following UM postdoctoral researchers contributed to this DoE project:
Dr. James Kent
Dr. Paul Ullrich

The following UM students contributed to this DoE project:
Kevin Reed
Diana Thatcher
Jared Whitehead
Weiye Yao
M. Soner Yorgun
Colin Zarzycki

Unfunded external collaborators:

Sandia National Laboratories (SNL):
Mark A. Taylor (Community Atmosphere Model (CAM) Spectral Element (SE) Model, variable-resolution, DCMIP-2012)

National Center for Atmospheric Research (NCAR):
Peter H. Lauritzen (advection test cases, DCMIP-2012)

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1) Executive Summary

The goals of this project were to (1) assess and quantify the sensitivity and scale-dependency of unresolved subgrid-scale mixing processes in NCAR's Community Earth System Model (CESM), and (2) to improve the accuracy and skill of forthcoming CESM configurations on modern cubed-sphere and variable-resolution computational grids. The research thereby contributed to the description and quantification of uncertainties in CESM's dynamical cores and their physics-dynamics interactions.

All dynamical cores of atmospheric General Circulation Models (GCMs) need some form of subgrid-scale dissipation, either explicitly specified or inherent in the chosen numerical schemes. The representation of the subgrid scale in GCMs is complex. Besides physical processes to be represented, numerical errors manifest themselves as subgrid-scale diffusion and ad-hoc mixing is used to assure numerical stability and to compensate for numerical dispersion errors. The impact of such mixing processes triggered by the dynamical core and its tracer advection scheme on climate simulations is poorly understood. The research isolated and quantified such signals in idealized climate studies, and shed light on the nonlinear interactions between the dynamical core, tracer transport processes and the physical parameterizations. This was done via a hierarchy of CESM simulations that ranged from dry dynamical core assessments, simulations with simplified moisture processes to full-physics experiments in aqua-planet and full-complexity mode. We utilized selected process studies which included the study of idealized and real tropical cyclones at moderate to extreme (12 km) resolutions, the study of CESM's tracer transport algorithms and their tracer-tracer correlations, the study of stratospheric flow regimes in the tropics and polar regions, and evaluations of the physics-dynamics coupling and the "believable scales or effective-resolutions" of numerical schemes. This research project also contributed to the two-week Dynamical Core Model Intercomparison Project (DCMIP) and summer school in the summer of 2012. In particular, it supported the definition of new dynamical core test cases that were used both for this research project and the DCMIP-2012 event. Furthermore, DCMIP-2012 allowed the comparison of our research results to other dynamical cores, such as NCAR/DoE's *Model for Prediction Across Scales* (MPAS), the cubed-sphere Finite-Volume model FV3 from NOAA's Geophysical Fluid Dynamics Laboratory (GFDL) and the University of Michigan's dynamical core MCORE.

The research has been built upon the four CESM dynamical cores which are the Eulerian (EUL) and semi-Lagrangian (SLD) spectral transform dynamical cores, the Finite-Volume (FV) dynamical core on the regular latitude-longitude grid, and the Spectral Element (SE) dynamical core which has become the most recent default in the Community Atmosphere Model (CAM) of CESM. CAM-SE utilizes a cubed-sphere grid and supports variable-resolution configurations since 2012. In close collaboration with CAM-SE developer and collaborator Mark Taylor (Sandia National Laboratories) the University of Michigan team became the first group that provided an in-depth analysis of CAM-SE's variable-resolution capabilities and its grid imprinting characteristics. The research thereby assessed multi-scale interactions, evaluated dissipative and wave reflection properties in refined domains, and shed light on scale-aware physics interactions in order to prepare pathways for future variable-resolution and adaptive mesh refinement capabilities in GCMs. The research was built upon a strong partnership between the University of Michigan, DoE's Sandia National Laboratories (Dr. Mark Taylor) and the National Center for Atmospheric Research (Dr. Peter Lauritzen) as reflected by the choice of the external collaborators. Furthermore, we collaborated with Dr. Jared Whitehead (Los Alamos National Laboratory on subgrid-scale diffusion aspects and the consistency between dynamical cores and tracer advection algorithms, and Dr. Hui Wan (Pacific Northwest Natonal Laboratory) on physics-dynamics coupling issues.

We worked on all aspects of the original research proposal, had extended the suggested assessments of stratospheric tracer transport to an assessment of stratospheric circulations and added an object-based research theme. The project was highly successful and productive.

2 Final Scientific Report: Summary and Highlights of the Accomplishments

2.1 Research Team at the University of Michigan (partly involved in this research project) and their Careers

The following Ph.D. students and postdoctoral researcher were contributed to this research grant. Their graduation dates are listed and additional information about their current careers is provided. This grant thereby enabled the PI to support and mentor an exemplary group of young scientists.

Postdoctoral Researchers:

Dr. James Kent	University of Michigan, May 2010 – December 2014.
Contributions:	*subgrid-scale processes and mixing, effective resolution of GCMs, advection, dynamical core test cases, sensitivity to model resolutions, DCMIP-2012*
since 1/2015:	Lecturer - Mathematics, Faculty of Computing, Engineering and Science, University of South Wales, U.K.

Dr. Paul Ullrich	University of Michigan, May 2011 – August 2012.
Contributions:	*dynamical core test cases, DCMIP-2012, intercomparisons to the dynamical core MCORE*
since 9/2012:	Assistant Professor, Department of Land, Air and Water Resources, University of California, Davis, CA

Graduate Students (in both the PI's and Co-PI's research groups)

Kevin Reed	Ph.D. in Atmospheric and Space Science, Graduate Certificate in Public Policy, University of Michigan, graduation in January 2012
Contributions:	*tropical cyclone test cases and uncertainty quantification, simplified physics processes, DCMIP-2012*
5/2012-8/2012:	Postdoctoral researcher, University of Michigan
9/2012-8/2013:	AGU Congressional Science Fellow in Washington, D.C.
9/2013-12/2014:	Postdoctoral Fellowship Holder, Advanced Study Program (ASP) and Climate and Global Dynamics Division (CGD), NCAR
since 1/2015:	Assistant Professor, School of Marine and Atmospheric Sciences, Stony Brook University, NY

Diana Thatcher	Ph.D. Candidate, University of Michigan
Contributions:	*moist idealized dynamical core test cases, variable-resolution modeling with CAM-SE, dynamical core intercomparisons*

Jared Whitehead	Ph.D. in Mathematics, University of Michigan, Department of Mathematics, Program in Applied and Interdisciplinary Mathematics (AIM), graduation in Dec. 2011, (co-advised by Dr. Rood and Dr. Jablonowski)
Contributions:	*subgrid-scale diffusion processes, consistency between dynamical cores and tracer advection schemes, dynamical core intercomparisons*
2/2012-10/2013:	Postdoctoral Research Associate, Los Alamos National Laboratory
since 11/2013:	Assistant Professor, Department of Mathematics, Brigham Young University, Utah

Weiye Yao	Ph.D. in Atmospheric and Space Science and Scientific Computing, University of Michigan, graduation in December 2014
Contributions:	*idealized dynamical core simulations over decadal time scales, impact of dynamical cores on stratospheric dynamics and waves with foci on the Quasi-Biennial Oscillation (QBO) and Sudden Stratospheric Warmings (SSW), diffusion in dynamical cores, gravity wave drag*
since 1/2015:	Postdoctoral Fellow, Geophysical Fluid Dynamics Laboratory (GFDL), Princeton, NJ

M. Soner Yorgun	Ph.D. in Atmospheric and Space Science, University of Michigan, graduation in August 2014, (advised by Dr. Rood)
Contributions:	*idealized moist dynamical core simulations, impact of orography on precipitation, statistical tools for evaluating the performance and validation of models, object-based approaches*
since 4/2015:	Postdoctoral Fellow, NOAA Earth System Research Laboratory Global Systems Division, Boulder

Colin Zarzycki	Ph.D. in Atmospheric and Space Science, Graduate Certificate in Computational Discovery and Engineering, University of Michigan, graduation in May 2014
Contributions:	*variable-resolution modeling in aqua-planet and full-complexity mode, tropical cyclone modeling with CAM-SE*
6/2014-8/2014:	Postdoctoral researcher, University of Michigan
since 9/2014:	Postdoctoral Fellowship Holder, Advanced Study Program (ASP) and Climate and Global Dynamics Division (CGD), NCAR

2.2 Summary of the Research Products by the PI's Research Team

The following list provides a high-level overview of the research products that are an outcome of this research grant. All details are listed below.

- # Journal Articles: 31 published plus 2 papers currently in review, 1 in preparation
- # Edited Books and Book Chapters: 1 edited book, 2 book chapters
- # Conference Proceedings Papers: 1 (AMS Hurricanes Conference)
- # Technical Reports: 1 (DCMIP Test Case Descriptions)
- # Conference and Seminar Presentations: 88
- # Ph.D. Theses, related to this project, University of Michigan: 5 completed, 1 in progress

  Dr. Kevin Reed
  An Exploration of Tropical Cyclone Simulations in NCAR's Community Atmosphere Model, 2012

  Diana R. Thatcher
  Scale-Interactions in Variable-Resolution General Circulation Models, in progress

Dr. Jared Whitehead
Topics in Geophysical Fluid Dynamics, 2011

Dr. Weiye Yao
An Assessment of the Quasi-Biennial Oscillation (QBO) and Sudden Stratospheric Warmings (SSWs) with Idealized General Circulation Models, 2014

Dr. M. Soner Yorgun
An Object-based Approach for Quantification of GCM Biases in the Simulation of Orographic Precipitation, 2014

Dr. Colin M. Zarzycki
Variable-resolution frameworks for the simulation of tropical cyclones in global atmospheric general circulation models, 2014

2.3 Organized Events related to this Research Project

- PI: Co-organizer of the workshop `Physics-Dynamics coupling in geophysical models – Bridging the gap', in Ensenada, Baja California, Mexico, December 2-4, 2014, in collaboration with M. Gross (CICESE, Centro de Investigación Científica y de Educación Superior de Ensenada), N. Wood (U.K. Met Office) and S. Malardel (ECMWF)
- PI: Co-convener of the session 'Numerical methods of the atmosphere and ocean (including composition and boundary layer at all latitudes)' at the World Weather Open Science Conference (WWOSC) 2014 in Montreal, Canada, in collaboration with Dr. Jean Côté, August 16-21, 2014
- PI: Co-convener of the session 'Recent developments in numerical Earth System Modelling' at the European Geosciences Union (EGU) General Assembly 2014 in Vienna, Austria, in collaboration with Dr. James Kent, Colin Zarzycki, Eigil Kaas, Brian Sorensen, Peter H. Lauritzen, April 27 – May 2, 2014
- James Kent (University of Michigan) and Jared P. Whitehead (LANL):
  Organizer of the Minisymposium MS82 'Using Test Cases in the Development of Dynamical Cores' at the 2013 SIAM Conference on Mathematical & Computational Issues in the Geosciences, Padova, Italy, June 17-20, 2013
- PI: Lead-organizer of the Dynamical Core Model Intercomparison Project (DCMIP) and 2-week summer school on `Future-Generation Non-Hydrostatic Weather and Climate Models, NCAR, Boulder, CO, 7/30-8/10/2012
- PI: Session chair at the 30th AMS Conference on Hurricanes and Tropical Meteorology, Ponte Vedra Beach, FL, USA, April 15-20, 2012

2.4 Leadership Positions the PI acquired during the Funding Period

- Co-Chair of the CESM Atmospheric Model Working Group (AMWG), responsible for the future direction of the Community Atmosphere Model (CAM) which is the atmospheric component of the NCAR/DoE Community Earth System Model (CESM) (since 11/2014)
- Member of the Climate Change Science Institute Science Advisory Board at the Department of Energy's (DoE) Oak Ridge National Laboratory (2014-2017)
- Member of the advisory committee for the Computer Science and Mathematics Division at Oak Ridge National Laboratory (2015 onwards)

2.5 Awards won by the PI during the award period

- Presidential Early Career Award for Scientists and Engineers (PECASE), Oct. 2011

2.6 Related Research Awards won by the PI's and co-PI's team during the award period

Graduate Visitor Fellowship, National Center for Atmospheric Research — Feb-Aug. 2015
NCAR Advanced Study Program (ASP)
Diana Thatcher

People's Choice Award (Poster competition) — Nov. 6, 2014
Michigan Institute for Computational Discovery and Engineering (MICDE)
Fall 2014 Research Computing Symposium
Diana Thatcher
poster: Diana R. Thatcher and Christiane Jablonowski, *Intercomparison of numerical methods in climate simulations with idealized moisture parameterization*

AGU Newsletter "AGUniverse" Publication Highlight — Nov. 6, 2014
Authors: Colin Zarzycki and Christiane Jablonowski
Paper: "A multidecadal simulation of Atlantic tropical cyclones using a variable-resolution global atmospheric general circulation model"
in the AGU journal "Journal of Advances in Modeling Earth Systems" (JAMES)

NCAR Postdoctoral Fellowship, Advanced Study Program (ASP) — 9/2014-8/2016
National Center for Atmospheric Research, Boulder, CO
Colin Zarzycki

Graduate Visitor Fellowship, National Center for Atmospheric Research — May-Jul. 2014
Weiye Yao

AOSS Finalist for the Richard and Eleanor Towner Prize for Outstanding Ph.D. Research, UM 2013 CoE Engineering Graduate Symposium, — Nov. 15, 2013
Weiye Yao

1st place at the UM 2013 College of Engineering Graduate Symposium (EGS) — Nov. 15, 2013
Ann Arbor, MI, category *Atmospheric and Climate Sciences*
Diana Thatcher
poster: Thatcher, D. and C. Jablonowski, *Comparison of a moist idealized test case and aquaplanet simulations in an atmospheric general circulation model*

AGU Travel Award, Fall 2013 meeting — Sep. 5, 2013
Diana Thatcher

1st place: Michigan Geophysical Union (MGU) Student Research Symposium and winner of the Student Choice Award — Apr. 3, 2013
Ann Arbor, MI, category *Climate and Meteorology*
Weiye Yao
poster: Weiye Yao and Christiane Jablonowski, *The influence of convection in idealized simulations of the Quasi-biennial Oscillation with different dynamical cores*

Rackham Predoctoral Fellowship, University of Michigan — 5/2013-4/2014
Colin Zarzycki

Honorable Mention Award in the University of Michigan — Feb. 2013
2012 Rackham Proquest Distinguished Dissertation Award Competition
Kevin Reed
10 awardees, and 11 honorable mention awardees were honored out of all 750 Ph.D. dissertations at UM in 2012

American Meteorological Society (AMS) Honorable Mention Award — Jan. 30, 2013
93rd Annual AMS Meeting: 11th Conference on Artificial and Computational Intelligence and its Applications to the Environmental Sciences, Austin, TX
M. Soner Yorgun, presentation:
Yorgun, M. S. and R. B. Rood: *Quantifying the Relationship between Dynamical Cores and Physical Parameterizations by Object-Based Methods*

American Meteorological Society (AMS) Best Oral Presentation Award — Jan. 30, 2013
93rd Annual AMS Meeting: Weather Analysis and Forecasting Symposium, Austin, TX
Colin Zarzycki, presentation:
Zarzycki, C. M., C. Jablonowski, M. A. Taylor: *Assessing the Ability of Variable-Resolution Global Models to Forecast Tropical Cyclones*

NCAR Postdoctoral Fellowship, Advanced Study Program (ASP) — 9/2013-12/2014
National Center for Atmospheric Research, Boulder, CO
Kevin Reed

1st place at the UM 2012 College of Engineering Graduate Symposium (EGS) — Nov. 2, 2012
Ann Arbor, MI, category *Earth Sciences and Remote Sensing*
Colin Zarzycki
poster: Zarzycki, C. M. and C. Jablonowski, *Improving weather prediction and regional climate modeling through the use of variable-resolution global atmospheric models*

Rackham Merit Fellowship, University of Michigan — 9/2012-4/2014
Diana Thatcher

AGU Congressional Science Fellowship, Washington D.C. — 9/2012-8/2013
Kevin Reed

Isaac Newton Institute for Mathematical Sciences, Cambridge, U.K. — Sep.-Oct., 2012
Invited long-term participant of the program
Multiscale Numerics for the Atmosphere and Ocean
Colin Zarzycki

NCAR Advanced Study Program Summer Colloquium — Jun. 4-22, 2012
The Weather-Climate Intersection: Advances and Challenges, Boulder, CO, USA
Invited Participant: Weiye Yao

Travel award: 23rd AMS Conference on Climate Variability and Change — 1/22-26/2012
New Orleans, LA, USA
Kevin Reed

2.7 Selected Highlights

a) Advancing the frontiers of variable-resolution modeling with the Spectral Element (SE) version of the DoE/NCAR Community Atmosphere Model (CAM-SE): Tropical cyclone examples

A statically-nested, variable-mesh option has been introduced into CAM-SE version 5.3. In close collaboration with Mark Taylor (SNL) we conducted a series of tests with increasing complexity. These highlight the use of variable-resolution grids in CAM-SE to improve the representation of tropical cyclones by dynamically resolving storms without requiring the computational demand of a global high-resolution grid. We show that no numerical distortions or wave reflections are observed in the grid transition regions. Figure 1 shows an example of a variable-resolution grid that is based upon CAM-SE's cubed-sphere grid geometry. Figure 2 displays snapshots of the 850 hPa wind speed and 500 hPa relative vorticity of an idealized tropical cyclone that smoothly moves through the grid transition region over the course of several days.

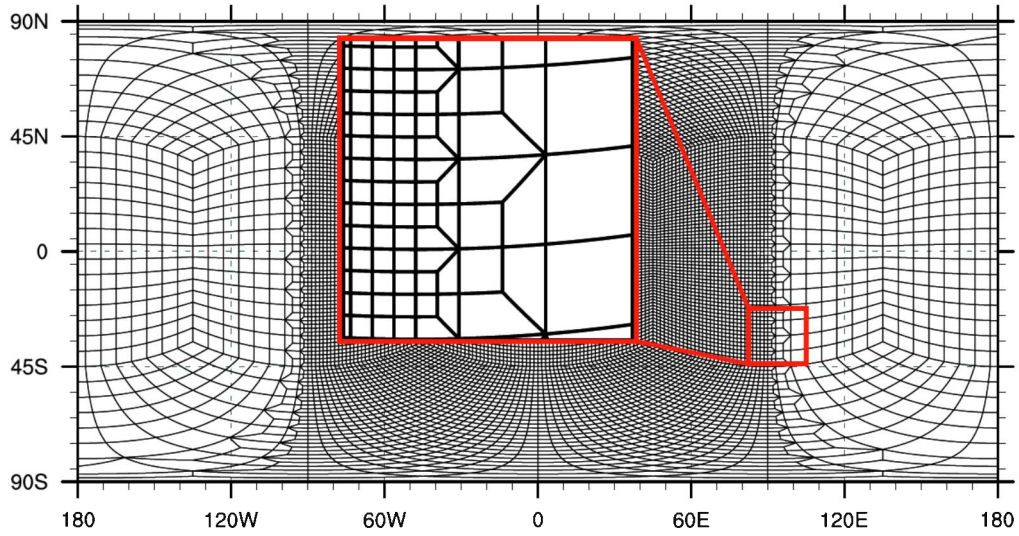

Figure 1: Zoom of CAM-SE transition region for variable resolution grid refined over one hemisphere.

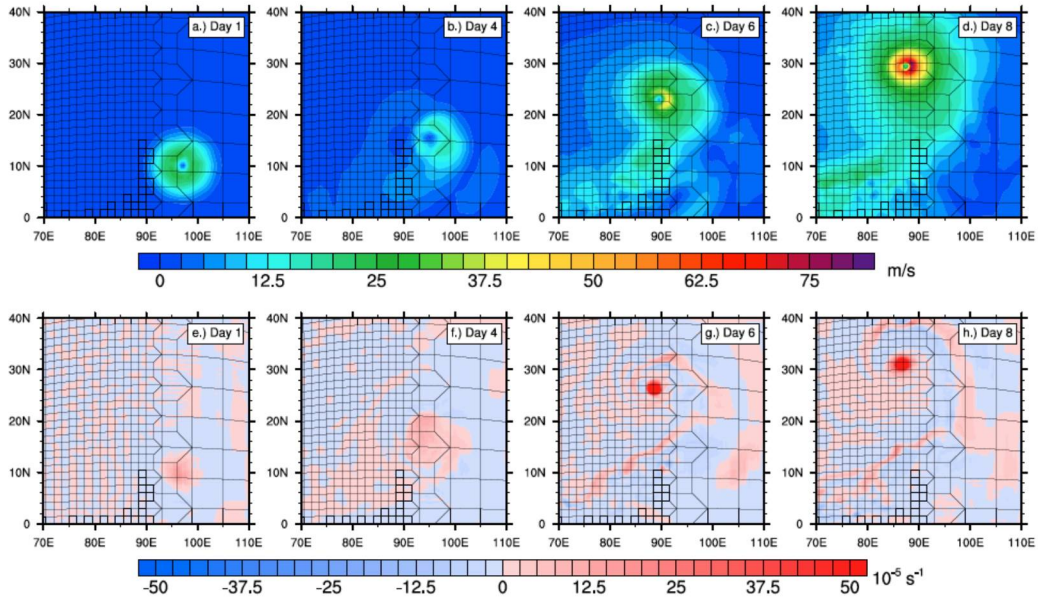

Figure 2: Snapshots of the 850 hPa horizontal wind speed (top) and 500 hPa relative vorticity (bottom) of an idealized tropical cyclone as it moves through the grid transition region.

b) The Dynamical Core Model Intercomparison Project (DCMIP-2012) and new dynamical core test cases

The PI was the lead organizer of the Dynamical Core Model Intercomparison Project (DCMIP) and 2-week summer school on 'Future-Generation Non-Hydrostatic Weather and Climate Models' that took place at the National Center for Atmospheric Research (NCAR) in August 2012. We taught over 38 multi-disciplinary students and researchers how today's and future non-hydrostatic atmospheric models are or need to be designed and built, hosted 18 dynamical core modeling groups at NCAR for a hands-on student-run model intercomparison project, established new non-hydrostatic dynamical core and tropical cyclone test cases in the community, and learned from keynote speakers about modern numerical techniques, uncertainty quantification, the physics-dynamics coupling, simple moisture feedbacks, and innovative computational aspects such as variable-resolution grids. DCMIP was supported by new cyberinfrastructure tools: http://earthsystemcog.org/projects/dcmip-2012/. Figure 3 displays snapshots of the DCMIP intercomparison. The test describes a 3D advection experiment and exposes the diffusive and numerical characteristics (e.g. undershoots) of the tracer advection schemes in the dynamical cores.
DCMIP was jointly funded by DoE, NSF, NOAA, NCAR and the University of Michigan, and was endorsed by the World Meteorological Organization (WMO) Working Group on Numerical Experimentation (WGNE).

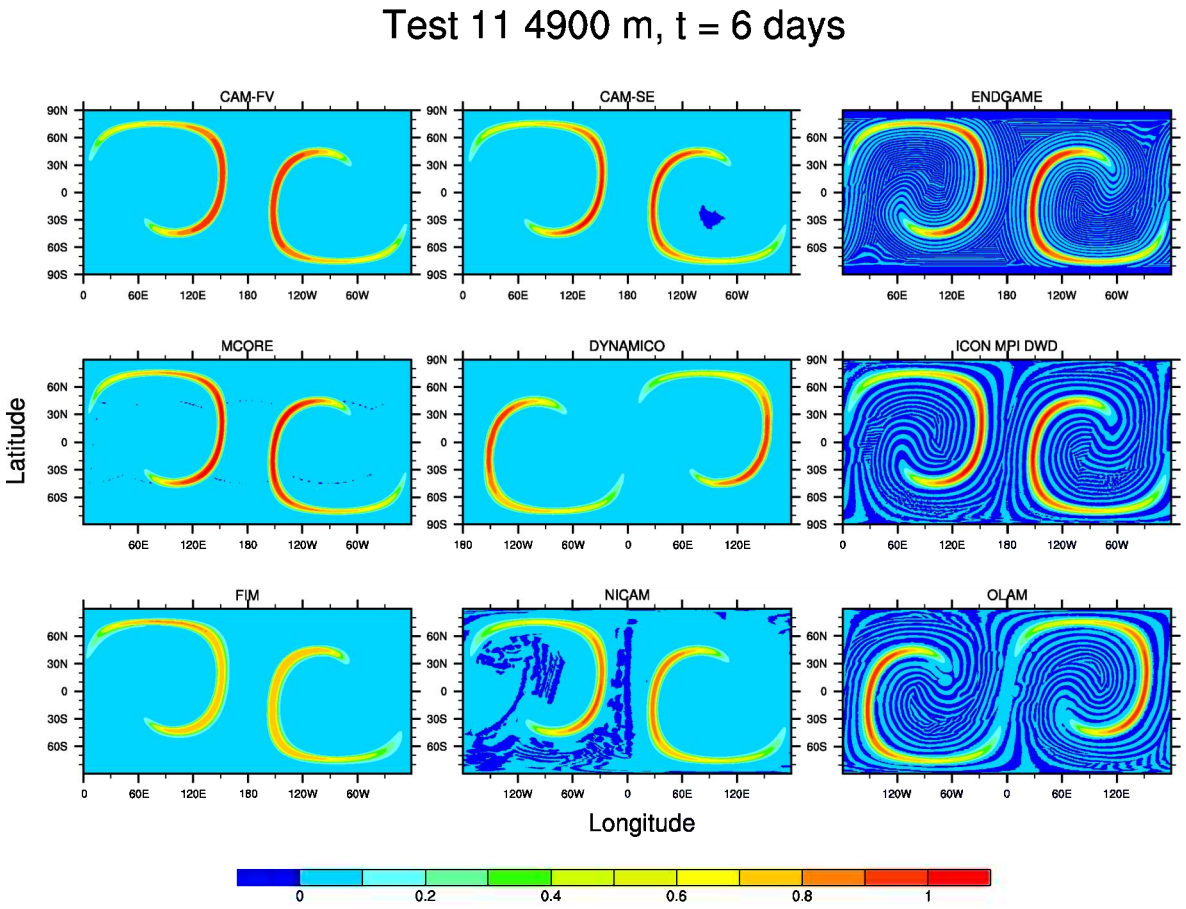

Figure 3: Selected results of the DCMIP test case 1-1 from 9 different dynamical cores which conduct a 3D tracer advection experiment. The tracer q1 at 4900 m at day 6 is shown when it is stretched the most. The model names are denoted in the titles. The DYNAMICO and OLAM results are visually shifted by 180°. The dark blue areas denote undershoots.

c) **Examples of subgrid-scale mixing processes in GCMs: Understanding and improving advection algorithms**

Advection schemes are at the heart of a dynamical core and one of the keys to analyzing and quantifying the discrepancies among models. We have provided insight into the subgrid-scale mixing characteristics of all four CAM5 advection algorithms, and determined their dependence on both the horizontal and vertical resolutions. The mixing processes in the advection schemes have direct implications for short-term and long-term climate assessments since they provide non-linear interactions with the resolved scales. Figure 4 presents tracer advection results that reflect four variants of the CAM-FV (finite-volume) advection algorithm. The FV advection process introduces nonlinear numerical diffusion via the choice of the numerical scheme (first-, second- (van Leer) or third-order (PPM) and its limiters (default PPM or the newly introduced Colella-Sekora limiter). The transported slotted cylinder in this 2D advection experiment shows various degrees of deformation after one revolution around the sphere, including numerical under- and overshoots in b), c) and d).

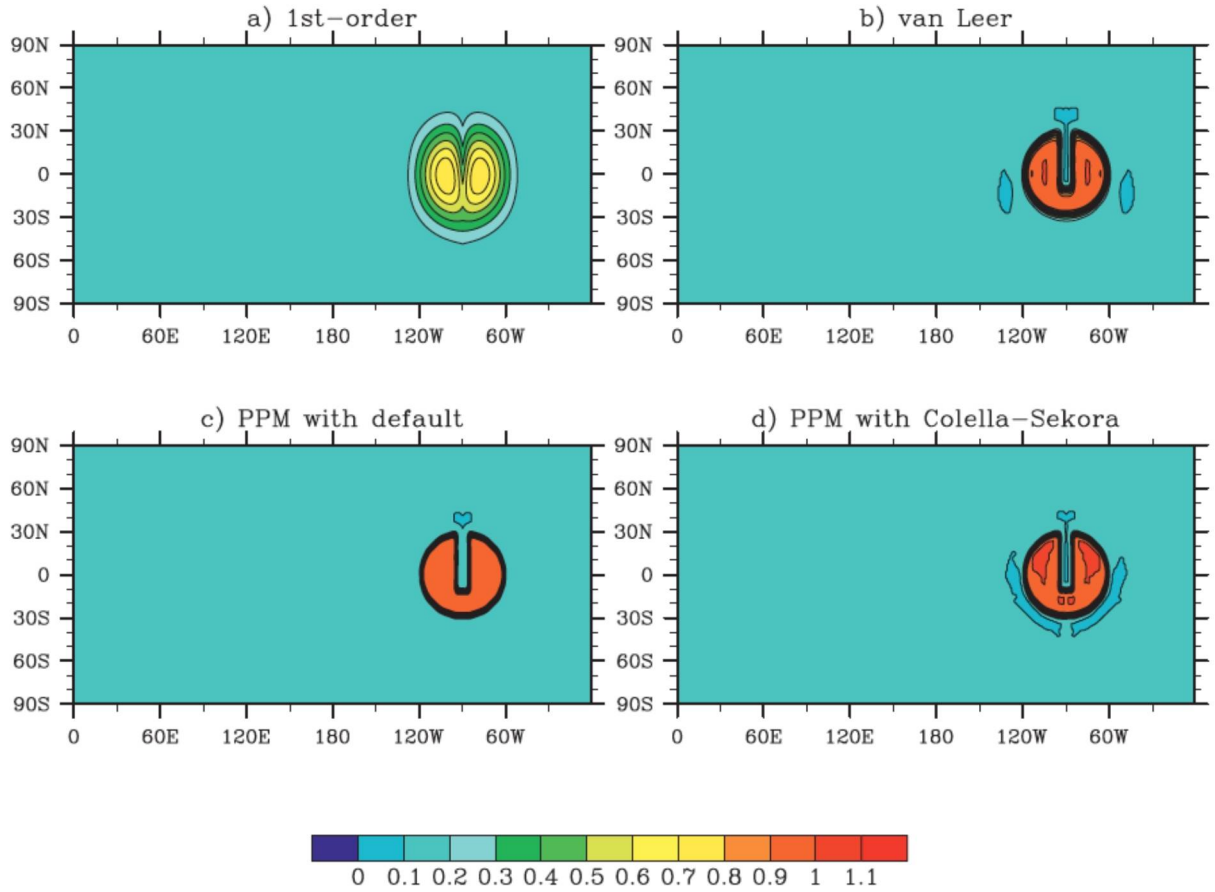

Figure 4: Tracer mixing ratio on the 1°x1° grid after 12 days, using CAM-FV with (a) the first-order scheme, (b) the van Leer scheme, (c) PPM and the default limiter, and (d) PPM with the Colella-Sekora limiter, using slotted cylinder initial conditions. The analytic solution is a slotted cylinder with sharp edges.

3) Extended Summary of the Project Activities (includes points 4, 5, 7 of the reporting requirements)

3.1) Advancing the frontiers of variable-resolution modeling with the Spectral Element (SE) version of the DoE/NCAR Community Atmosphere Model (CAM-SE): Tropical cyclone examples

Modeling of tropical cyclones in General Circulation Models (GCMs) has traditionally proved challenging due to issues such as relatively small storm sizes and intense convective processes. Tropical cyclones are significantly under-resolved, if not completely unresolved, at traditional GCM grid resolutions of 50-300 km. However, recent gains in computational ability and advances in GCM model design now allow for GCM simulations with grid spacings as small as 12-30 km. At these resolutions, models are able to more effectively capture key features of tropical cyclones. Our work explored a novel variable-resolution mesh approach in CAM-SE that allows for high spatial resolutions in areas of interest, such as low-latitude ocean basins where tropical cyclones are prevalent. Such GCM designs with variable-resolution meshes have the potential to become a future tool for regional climate assessments.

The statically-nested, variable-mesh option in CAM-SE first became available in 2012. Our series of tests with increasing complexity highlighted the benefits of the variable-resolution grid in CAM-SE. It greatly improved the representation of tropical cyclones in the refined domain without requiring the computational demands of a global high-resolution grid. As a simplified initial test, we advected a dry vortex through the grid transition regions on an irrotational planet without the CAM subgrid parameterization package. The vortex structure and intensity was only affected by grid resolution and no spurious artifacts in the grid transition regions were observed. CAM-SE model simulations using an idealized tropical cyclone test case on an aqua-planet (with constant sea surface temperature (SST)) showed no numerical distortion or wave reflection when the cyclone interacted with an abrupt transition region. Using the same test case, we demonstrated that a regionally-refined mesh can produce the same local results as a globally-uniform grid with significantly fewer degrees of freedom. Additionally, we analyzed more complex aqua-planet experiments with meridionally-varying SSTs. These experiments were further accompanied by realistic decadal (23-year-long) climate simulations in AMIP mode (prescribed SSTs and sea ice) with a high-resolution area (28 km) over the North Atlantic. The high-resolution domain facilitated tropical cyclogenesis. Tropical cyclones were spontaneously generated whereas the surrounding global grid spacing (110 km) was too coarse to support them in a realistic way. We compared the hurricane and overall climate statistics in refined and uniform-resolution simulations to gain an understanding of the local and global impact of high-resolution domains.

We also conducted short-term CAM-SE assessments in 5-day forecast-mode over two hurricane seasons (with 14 km grid spacing over the North Atlantic) to compare the CAM-SE hurricane statistics to hurricane observations. In addition, we evaluated the sensitivity of high-resolution CAM-SE tropical cyclone simulations to the choice of the physics time step when using the CAM5 physics package, and explored the scale-sensitivities of the CAM4 and CAM5 physics packages.

Relevant papers:

Zarzycki, C. M. and C. Jablonowski (2015)
Walsh et al. (2015)
Zarzycki, C. M., C. Jablonowski, D. R. Thatcher and M. A. Taylor (2015)
Wehner et al. (2015)
Zarzycki, C. M. and C. Jablonowski (2014)
Zarzycki, C. M., C. Jablonowski and M. A. Taylor (2014)
Zarzycki, C. M., M. Levy, C. Jablonowski, Taylor, Overfelt and Ullrich (2014)
Zarzycki, C. M. and C. Jablonowski (2012)
Reed, K. A., C. Jablonowski and M. A. Taylor (2012)
Reed, K. A. and C. Jablonowski (2012)

3.2) The Dynamical Core Model Intercomparison Project (DCMIP) and new dynamical core test cases

The PI was the lead organizer of the Dynamical Core Model Intercomparison Project (DCMIP) and 2-week summer school on 'Future-Generation Non-Hydrostatic Weather and Climate Models' that took place at the National Center for Atmospheric Research (NCAR) in August 2012. The co-organizing team included Drs. Paul Ullrich, James Kent and Kevin Reed (University of Michigan), Dr. Mark Taylor (SNL), and Drs. Peter H. Lauritzen and Ram Nair (NCAR).

The objectives of DCMIP and the summer school were (1) to teach a group of about 38 multi-disciplinary students and researchers how today's and future non-hydrostatic atmospheric models are or need to be designed and built, (2) to host about 18 dynamical core modeling groups to NCAR for a hands-on student-run model intercomparison project, (3) to establish new non-hydrostatic dynamical core and tropical cyclone test cases in the community, (4) to invite keynote speakers to NCAR that give lectures on modern numerical techniques, uncertainty quantification, the physics-dynamics coupling, simple moisture feedbacks, and innovative computational aspects such as variable-resolution grids, and (5) to establish DCMIP as a community resource that is supported by cyberinfrastructure tools. The website is http://earthsystemcog.org/projects/dcmip-2012/

The summer school included morning lectures and afternoon hands-on model intercomparison sessions in partnership with a modeling mentor. The latter enabled the students to gain an in-depth understanding of the modeling choices available to them in one particular model. These small-team sessions were lively, exciting and relevant, and guaranteed the direct scientific feedback about the model results. The students and mentors shared and discussed the results immediately through a novel interactive website that is Wiki-driven and hosts the model data, metadata and online visualization capabilities. DCMIP was jointly funded by DoE, NSF, NOAA, NCAR and the University of Michigan, and was endorsed by the World Meteorological Organization (WMO) Working Group on Numerical Experimentation (WGNE). DCMIP established a series of new dynamical core test cases. In particular, we utilized a small-Earth environment to expose non-hydrostatic effects at cheap computational costs.

Several new dry and idealized moist dynamical core test case were developed, such as a moist variant of the Held-Suarez (BAMS, 1994) test which extends the popular test for dry dynamical cores. Other test cases include two new baroclinic wave tests (both on the sphere and in a Cartesian channel), 2D and 3D advection tests, mountain wave tests, gravity wave tests, and new variants of the tropical cyclone test with background flows.

Relevant papers:

Hall, D. M., P. A. Ullrich, K. A. Reed, C. Jablonowski and H. Tufo (2015)
Ullrich, P. A., K. A. Reed and C. Jablonowski (2015)
Thatcher, D. R. and C. Jablonowski (2015)
He, F., D. J. Posselt, C. M. Zarzycki and C. Jablonowski (2015)
Ullrich, P. A., T. Melvin, C. Jablonowski and A. Staniforth (2014)
Lauritzen et al. (2014)
Kent, J., P. A. Ullrich and C. Jablonowski, C. (2013)
Kent, J., C. Jablonowski, J. P. Whitehead and R. B. Rood (2012)
Reed, K. A. and C. Jablonowski (2012)
Reed, K. A. and C. Jablonowski (2011a)
Reed, K. A. and C. Jablonowski (2011b)
Reed, K. A. and C. Jablonowski (2011c)

3.3) Subgrid-scale mixing in GCMs: 4 focus areas

a) Impact of limiters, the vertical resolution and energy backscatter algorithms

Modeling the transport of trace gases is an essential part of any atmospheric model. The tracer transport scheme in the Community Atmosphere Model finite-volume dynamical core (CAM-FV), which is part of the NCAR's Community Earth System Model (CESM1), was investigated using multidimensional idealized advection tests. CAM-FV's tracer transport algorithm makes use of one-dimensional monotonic limiters. The Colella–Sekora limiter, which is applied to increase accuracy where the data are smooth, is implemented into the CAM-FV framework, and compared with the more traditional monotonic limiter of the piecewise parabolic method (the default limiter). For 2D flow, CAM-FV splits dimensions, allowing overshoots and undershoots, with the Colella–Sekora limiter producing larger overshoots than the default limiter.

The impact of vertical resolution has also been explored. A vertical Lagrangian coordinate is used in CAM-FV, and is periodically remapped back to a fixed Eulerian grid. For purely vertical motion, it is found that less frequent remapping of the Lagrangian coordinate in CAM-FV improves results. For full 3D tests, the vertical component of the tracer transport dominates the error and limits the overall accuracy. If the vertical resolution is inadequate, increasing the horizontal resolution has almost no effect on accuracy. This is because the vertical resolution currently used in CAM version 5 may not be sufficiently fine enough to resolve some atmospheric tracers and provide accurate vertical advection. Idealized tests using tracers in a gravity wave agree with these results.

In addition, we developed a novel energy backscatter scheme and implemented it in a 2D shallow water model on the sphere. Energy that is dissipated by the numerical scheme can thereby be added back as a flow dependent quantity instead of a global correction. We detect the regions where energy loss was greatest and use the resulting patterns for a selective backscatter of kinetic and potential energy. We showed that this technique leads to improved error norms. The total energy is conserved over long time scales without adversely affecting any flow characteristics.

Relevant paper: Whitehead, J., C. Jablonowski, R. B. Rood and P. H. Lauritzen (2011)
Kent, J., C. Jablonowski, J. P. Whitehead and R. B. Rood (2012a)
Kent, J., C. Jablonowski, J. Thuburn and N. Wood (2015)

b) Downscale cascades

The accurate modeling of cascades to unresolved scales is an important part of the tracer transport component of dynamical cores of weather and climate models. Our work investigated the ability of the advection schemes in CAM5 to model this cascade. In order to quantify the effects of the different advection schemes in CAM5, four two-dimensional tracer transport test cases were developed. Three of the tests stretch the tracer below the scale of coarse resolution grids to ensure the downscale cascade of tracer variance. These results were compared with a high-resolution reference solution, which was simulated on a resolution fine enough to resolve the tracer during the test. The fourth test had two separate flow cells, and was designed so that any tracer in the western hemisphere should not pass into the eastern hemisphere. This is to test whether the diffusion in transport schemes, often in the form of explicit hyper-diffusion terms or implicit through monotonic limiters, contains unphysical mixing.

An intercomparison of three of the CAM5 dynamical cores was performed. The results show that the finite-volume (CAM-FV) and spectral element (CAM-SE) dynamical cores model the downscale cascade of tracer variance better than the semi-Lagrangian transport scheme of the Eulerian spectral transform core (CAM-EUL). Each scheme tested produces unphysical mass in the eastern hemisphere of the separate cells test.

Relevant paper: Kent, J., C. Jablonowski, J. P. Whitehead and R. B. Rood (2012b)

c) Consistency

Maintaining functional relationships between tracers and the dynamical wind and temperature fields with which they interact is a desirable trait of atmospheric General Circulation Models (GCMs). A systematic, explicit test was developed to measure the consistency between a dynamical core's integration of the equations of motion, and its tracer transport algorithm. Ertel's potential vorticity (PV) is used as a diagnostic tool allowing a direct comparison between the treatment of PV in the dynamics and the integration of PV as a passive tracer. We suggested several quantitative and qualitative metrics to measure this consistency including grid-independent probability density functions. Comparisons between the four dynamical cores of the Community Atmosphere Model version 5.1 (CAM) have been conducted. It was found that the numerical designs of the finite-volume (CAM-FV) and spectral-element (CAM-SE) dynamical cores lead to an improved consistency between the dynamic PV and passively transported PV fields in comparison to CAM's spectral-transform Eulerian (CAM-EUL) and semi-Lagrangian (CAM-SLD) dynamical cores in the presence of a breaking baroclinic wave.

Relevant paper: Whitehead, J. P., C. Jablonowski, J. Kent and R. B. Rood (2015)

d) Effective resolution (believable scales)

The effective resolution of a numerical scheme describes the smallest spatial scale (largest wavenumber) that is completely resolved by that scheme. Investigating the dispersive and dissipative properties of a numerical scheme for the advection equation allows the effective resolution to be calculated. The advection equation is a fundamental building block of dynamical cores of atmospheric and ocean models, and this analysis provides an indication of the effective resolution of the numerical methods used by dynamical cores. Using a variety of finite-difference schemes, the effect on effective resolution of using explicit diffusion and hyper-diffusion terms has been examined. The choice of order-of-accuracy, and the time-stepping of the numerical scheme has also been investigated with regards to effective resolution. In addition, we applied this analysis to methods that are commonly used in dynamical cores of atmospheric general circulation models, namely semi-Lagrangian and finite-volume methods.

Relevant papers: Kent, J., J. P. Whitehead, C. Jablonowski and R. B. Rood (2014)
Kent, J., C. Jablonowski, J. P. Whitehead, and R. B. Rood (2014)

3.4) Quasi-Biennial-Oscillation (QBO)-like oscillations and Sudden Stratospheric Warmings (SSWs) in the dynamical cores of atmospheric general circulation models

The ability of General Circulation Models to simulate the tropical QBO and the polar SSWs are an important model characteristic. Typically, it is believed that the moist convective parameterization is the key GCM component that acts as the triggering mechanism for tropical waves, thereby forcing wave-mean flow interactions within the QBO region. However, we found that QBO-like oscillations and SSWs can also be simulated in a dry dynamical core when driven by the idealized Held-Suarez (BAMS, 1994) forcing or the modified Held-Suarez-Williamson forcing (Williamson, Olson and Boville, MWR 1998). We intercompare the QBO, SSW and wave climatologies of all four CAM dynamical cores EUL, SLD, FV and SE. This gives information about the wave generation and diffusion properties of the numerical schemes.

We found that the semi-Lagrangian spectral-transform dynamical core (SLD) leads to the most distinct QBO- and SSW-like.phenomena. Its QBO-like signal has a long period between 42-45 months and occurs in the upper stratosphere, which is somewhat different than observations. However, the amplitudes, asymmetries and meridional extent closely resemble the observed QBO. Wave-number frequency analysis shows that resolved equatorially-trapped waves are abundant in SLD despite the absence of

cumulus convection. A Transformed Eulerian Mean analysis suggests that the divergence of the Eliassen-Palm flux and vertical advection provide most of the forcing, counteracted by diffusion. We also found QBO-like oscillations in the dry CAM-SE and CAM-EUL dynamical cores. However, CAM-FV does not exhibit such a QBO-like signal, which might suggest missing wave forcings. Similar findings also apply to the SSW statistics in polar regions. In addition, we have evaluated how simple moist physics processes and a gravity wave drag scheme modify the characteristics of the QBO-like oscillation.

Relevant papers: Yao, W. and C. Jablonowski (2013)
Yao, W. and C. Jablonowski (2015a)
Yao, W. and C. Jablonowski (2015b)

3.5) Physics-Dynamics Coupling

GCMs discretize separately the processes described by the adiabatic equations driving the evolution of the grid scale variables (the *dynamics*) and the bulk parametrizations of the mean effects of the subgrid and/or diabatic processes (the *physics*). These two components then need to be coupled to each other. This coupling of physics parametrizations to the resolved fluid dynamics is an important aspect of weather and climate models. However, often model development is strictly segregated into either physics or dynamics and the coupling often guided by technical convenience rather than analysis. Hence, this area has many more unanswered questions than in-depth understanding. Furthermore, recent developments in the design of dynamical cores (significant increase of resolution, move to non-hydrostatic equation sets, adaptive meshes etc), extended process physics (prognostic microphysics, 3D turbulence, etc) and predicted future changes of the computational infrastructure (exascale with its stronger need for task parallelism, data locality and asynchronous time stepping for example) is adding even more complexity and new questions.

To address these issues the PI co-organized the first Physics-Dynamics Coupling (PDC) workshop (http://pdc.cicese.mx), and is on the planning committee for the successor workshop in September 2016. The workshops address the complexity of the physics-dynamics coupling. The PI uses idealized moist Held-Suarez experiments to investigate the impact of the coupling frequency on the circulation and contributed to the following publications:

Relevant papers: Gross, M., S. Malardel, C. Jablonowski and N. Wood (2015),
Wan, H., P. J. Rasch, M. A, Taylor and C. Jablonowski (2015)

3.6) Quantifying the relationship between dynamical cores and physical parameterizations by object-based methods

Deterministic weather predictions are often validated with feature-by-feature comparison whereas probabilistic climate projections are evaluated with statistical methods. We developed model evaluation strategies that identify like “objects” – coherent systems with an associated set of measurable parameters. This makes it possible to evaluate processes in models without needing to reproduce the time and location of, for example, a particular observed cloud system. Process- and object-based evaluation preserves information in the observations by avoiding the need for extensive spatial and temporal averaging. As a concrete example, we focused on analyzing how the choice of dynamical core impacts the representation of precipitation in the Pacific Northwest of the United States, Western Canada, and Alaska; this brings attention to the interaction of the resolved and the parameterized components of the model. Two dynamical cores are considered within the Community Atmosphere Model. These are the EUL Spectral transform model, which relies on global basis functions, and the Finite Volume (FV), which uses only local numerical discretizations. We introduced the concept of "meteorological realism" that is, do local representations of large-scale phenomena, for example, fronts and orographic precipitation, look like the

observations? A follow-on question is, whether the representation of these phenomena improve with resolution.

Our approach to quantify meteorological realism started with the identification and isolation of key features of orographic precipitation that are represented differently by Spectral and FV models, using objective pattern recognition methods. We made use of semantic lists for isolated objects to define their characteristics, which led to a quantification of the relationships of these objects to other variables such as topography or moisture. In addition, we conducted tcomparisons between different models and observations (i.e. GPCC gauge based data) for validation purposes. We pose that these methods intrinsically link local, weather-scale phenomena to important climatological features and provide a quantitative bridge between weather and climate.

Relevant papers: Yorgun, M. S. and R. B. Rood (2015)
Yorgun, M. S. and R. B. Rood (2014)

4.) Products developed under this grant (point 6 of the reporting requirements)

Published and submitted papers, related to this DoE project (in chronological order)

2015

Yao, W. and C. Jablonowski (2015b), **An Analysis of Sudden Stratospheric Warmings and their QBO Teleconnections with GCM Dynamical Cores,** J. Atmos. Sci., in review

Hall, D. M., P. A. Ullrich, K. A. Reed, C. Jablonowski, R. D. Nair and H. M. Tufo (2015), **Dynamical Core Model Intercomparison Project (DCMIP) Tracer Transport Test Results for CAM-SE**, Quart. J. Roy. Meteorol. Soc., revised

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Gross, M., S. Malardel, C. Jablonowski and N. Wood (2015), **Bridging the (Knowledge) Gap between Physics and Dynamics**, Bull. Amer. Meteorol. Soc., doi:10.1175/BAMS-D-15-00103.1, in press

Ullrich, P. A., K. A. Reed and C. Jablonowski (2015), **Analytical initial conditions and an analysis of baroclinic instability waves in f- and β-plane 3D channel models**, Quart. J. Roy. Meteorol. Soc., Vol. 141, 2972-2988

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Zarzycki, C. M., C. Jablonowski, D. R. Thatcher and M. A. Taylor (2015), **Effects of localized grid refinement on the general circulation and climatology in the Community Atmosphere Model**, J. Climate, Vol. 28, 2777-2803

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Ullrich, P. A., T. Melvin, C. Jablonowski and A. Staniforth (2014), **A proposed baroclinic wave test case for deep- and shallow-atmosphere dynamical cores,** Quart. J. Roy. Meteorol. Soc., Vol. 140, 1590–1602

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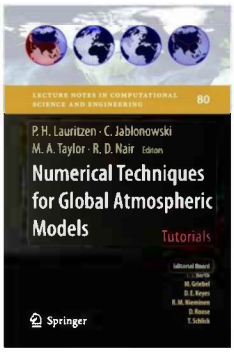

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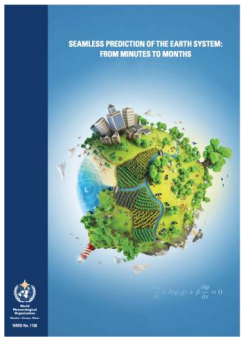

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Refereed Conference Proceedings

Zarzycki, C. and C. Jablonowski (2012): **Using Variable Resolution Meshes to Model Tropical Cyclones in NCAR'S CAM General Circulation Model,** 30th AMS Conference on Hurricanes and Tropical Meteorology, Ponte Vedra Beach, FL, USA, April 15-20, 2012, available online at http://ams.confex.com/ams/30Hurricane/webprogram/meeting.html#Tuesday

Technical Reports

Ullrich, P.A., C. Jablonowski, J. Kent, P. H. Lauritzen, R. D. Nair, M. A. Taylor (2012), **Dynamical Core Model Intercomparison Project (DCMIP) Test Case Document**, Version 1.7, download from https://www.earthsystemcog.org/projects/dcmip-2012/test_cases

Conference Presentations (in chronological order)

2015

Wan, H., P. J, Rasch, M. A. Taylor and C. Jablonowski, **A Simple But Effective Method for Quantifying and Attributing Time-Stepping Errors in Climate Models**, SIAM Conference on Mathematical & Computational Issues in the Geosciences, Stanford, CA, USA, June 29 – July 2, 2015

Thatcher, D., C. Jablonowski and C. Zarzycki, **Extra-tropical transition of tropical cyclones in variable-resolution in CAM5**, Oral presentation at the 20th Annual CESM Workshop, Breckenridge, CO, USA, June 15-18, 2015

Jablonowski, C., D. Thatcher, J. Ferguson, C. Zarzycki, A. Gettelman, J. Bacmeister, J. Richter, R. Neale, C. Hannay, P. Lauritzen, P. Callaghan, V. Larson, K. Reed, P. Ullrich, M. Wehner, M. Taylor, **The Path Forward: High-Resolution Next-Generation CESM Simulations and Scale-Aware Physics**, Oral presentation at the 20th Annual CESM Workshop, Breckenridge, CO, USA, June 15-18, 2015

Jablonowski, C., J. Ferguson, H. Johansen, P. McCorquodale, P. A. Ullrich, P. Colella, C. Zarzycki and M. Taylor, **High-Order Adaptive Mesh Refinement (AMR) and Variable-Resolution Techniques for Weather and Climate Models**, invited seminar at Notre Dame University, South Bend, IN, USA, April 16, 2015

Jablonowski, C., J. Ferguson, H. Johansen, P. McCorquodale, P. A. Ullrich, P. Colella, C. Zarzycki and M. Taylor, **High-Order Adaptive Mesh Refinement (AMR) and Variable-Resolution Techniques for Atmospheric General Circulation Models**, invited seminar Oak Ridge National Laboratory, April 8, 2015

Jablonowski, C., J. Ferguson, H. Johansen, P. McCorquodale, P. A. Ullrich, P. Colella, C. Zarzycki and M. Taylor, **High-Order Adaptive Mesh Refinement (AMR) and Variable-Resolution Techniques for Atmospheric General Circulation Models**, invited presentation at the Workshop on Galerkin Methods with Applications in Weather and Climate Forecasting, Edinburgh, United Kingdom, March 23-27, 2015

Jablonowski, C. and W. Yao, **Understanding the Impact of GCM Dynamical Cores and Dissipation Mechanisms on Idealized QBO-like Oscillations**, oral presentation at the QBO Modelling and Reanalyses Workshop, Victoria BC, Canada, March 16-18, 2015

2014

Zarzycki, C. M. and C. Jablonowski**, Improving Tropical Cyclone Track and Intensity in a Global Model with Local Mesh Refinement,** oral presentation at the American Geophysical Union (AGU) Fall Meeting 2014, Abstract A13R-06, San Francisco, CA, USA, December 15-19, 2014

Kent, J., C. Jablonowski and R. B. Rood**, Diagnosing Energy and Potential Enstrophy Transfers in Dynamical Cores of GCMs,** poster presentation at the American Geophysical Union (AGU) Fall Meeting 2014, Abstract A21B-3018, San Francisco, CA, USA, December 15-19, 2014

Thatcher, D. R., C. M. Zarzycki, J. Ferguson and C. Jablonowski**, Extratropical Transition Using 23 Years of Tropical Cyclones in a Variable-Resolution Global GCM,** poster presentation at the American Geophysical Union (AGU) Fall Meeting 2014, Abstract A33L-3379, San Francisco, CA, USA, December 15-19, 2014

Zarzycki, C. M., C. Jablonowski and M. A. Taylor, **Recent application of variable-resolution CAM-SE to investigate extreme weather phenomena**, invited seminar presentation in the NCAR

Climate and Global Dynamics Seminar Series, Boulder, CO, December 2014

Jablonowski, C. and D. R. Thatcher, **Physics-Dynamics Test Strategies: Bridging the Gap with Simplified Moist Test Cases,** oral presentation at the Physics-Dynamics Coupling Workshop (PDC14), Ensenada, Mexico, December 2-4, 2014

Zarzycki, C. M., C. Jablonowski and M. A. Taylor, **Physics Scaling in Multi-Resolution CAM Simulations,** oral presentation at the Physics-Dynamics Coupling Workshop (PDC14), Ensenada, Mexico, December 2-4, 2014

Thatcher, D. R. and C. Jablonowski, **Intercomparison of numerical methods in climate simulations with idealized moisture parameterization,** poster presentation at the Michigan Institute for Computational Discovery and Engineering (MICDE) Fall 2014 Research Computing Symposium, Ann Arbor, MI, USA, November 6, 2014

Jablonowski, C., C. M. Zarzycki, J. O. Ferguson, M. A. Taylor, H. Johansen, W. D. Collins, R. E. English, P. McCorquodale, P. Colella and P. A. Ullrich, **Variable-resolution modeling with the Spectral Element Community Atmosphere Model (CAM-SE) and the Adaptive Mesh Refinement dynamical core AMR-Chombo**, invited talk at the joint 6th International Workshop on Global Cloud Resolving Modeling (GCRM) and 3rd International Workshop on Nonhydrostatic Numerical Models (NHM), Kobe, Japan, September, 24-26, 2014

Jablonowski, C. and C. M. Zarzycki, **Advancing the Frontiers of Tropical Cyclone Modeling with the Variable-Resolution General Circulation Model CAM-SE**, invited keynote talk at the World Weather Open Science Conference (WWOSC) 2014, Montreal, Canada, August 16-21, 2014

Zarzycki, C. M., C. Jablonowski, D. Thatcher and M. Taylor, **Evaluating the impact of localized grid refinement on global climatology in CAM**, oral presentation at the 19th Annual CESM Workshop, Breckenridge, CO, USA, June 16-19, 2014

Yao, W., C. Jablonowski, J. Richter and J. Bacmeister, **The characteristics of the QBO and SSW with different GCM dynamical cores in idealized simulations**, poster presentation at the 19th Annual CESM Workshop, Breckenridge, CO, USA, June 16-19, 2014

Thatcher, D. R. and C. Jablonowski, **Dynamical core intercomparison using a moist variant of the Held-Suarez test case on CAM5**, poster presentation at the 19th Annual CESM Workshop, Breckenridge, CO, USA, June 16-19, 2014

Zarzycki, C. M., C. Jablonowski, M. A. Taylor and M. N. Levy, **Using idealized tests to diagnose the impact of physical parameterizations on atmospheric simulations**, poster presentation at the 19th Annual CESM Workshop, Breckenridge, CO, USA, June 16-19, 2014

Jablonowski, C., C. M. Zarzycki and M. A. Taylor, **Tropical Cyclone Modeling with the DoE/NCAR Variable-Resolution General Circulation Model CAM-SE**, oral presentation at the Department of Energy (DoE) Principal Investigator Meeting, Potomac, MD, USA, May 12-14, 2014

Jablonowski, C., R. B. Rood, J. Kent, D. R. Thatcher, W. Yao, C. M. Zarzycki, J. P. Whitehead, P. H. Lauritzen, K. A. Reed, R. D. Nair, P. A. Ullrich and M. A. Taylor, **Diagnosing and Improving the Characteristics of Atmospheric Model Dynamical Cores via Idealized Test Cases**, oral presentation at the Department of Energy (DoE) Principal Investigator Meeting, Potomac, MD, USA, May 12-14, 2014

Zarzycki, C. M., C. Jablonowski, M. A. Taylor and M. N. Levy, **Using idealized tests to diagnose the impact of physical parameterizations on atmospheric simulations**, poster presentation at the Department of Energy (DoE) Principal Investigator Meeting, Potomac, MD, USA, May 12-14, 2014

Jablonowski, C. and C. M. Zarzycki, **New Frontiers: Tropical Cyclone Modeling with NCAR's Variable-Resolution General Circulation Model CAM-SE**, invited oral presentation at the

European Geosciences Union (EGU) General Assembly 2014, Vienna, Austria, April 27 - May 2, 2014

Jablonowski, C. and W. Yao, **Idealized Simulations of the Quasi-Biennial Oscillation and Sudden Stratospheric Warmings with an Ensemble of Dry GCM Dynamical Cores**, oral presentation at the European Geosciences Union (EGU) General Assembly 2014, Vienna, Austria, April 27 - May 2, 2014

Jablonowski, C. and D. Thatcher, **A Moist Variant of the Held-Suarez Test for the Assessment of Atmospheric Model Dynamical Cores**, poster presentation at the European Geosciences Union (EGU) General Assembly 2014, Vienna, Austria, April 27 - May 2, 2014

Kent, J., C. Jablonowski, J. Thuburn and N. Wood, **An Energy Backscatter Model For The Shallow Water Equations On The Sphere**, poster presentation at the European Geosciences Union (EGU) General Assembly 2014, Vienna, Austria, April 27 - May 2, 2014

Zarzycki, C. M. and C. Jablonowski, **The impact of localized grid refinement on sub-grid parameterization in idealized climate experiments**, poster presentation at the 2014 Partial Differential Equations on the Sphere (PDEs on the Sphere) Workshop, Boulder, CO, USA, April 7-11, 2014

Reed, K. A., B. Medeiros, P. Lauritzen, J. Bacmeister and C. Jablonowski, **Idealized tropical cyclone experiments of varying complexity: a tool for model development**, poster presentation at the 2014 Partial Differential Equations on the Sphere (PDEs on the Sphere) Workshop, Boulder, CO, USA, April 7-11, 2014

Jablonowski, C., J. Kent, P. A. Ullrich, K. A. Reed, P. H. Lauritzen, R. D. Nair and M. A. Taylor, **Updates on the Dynamical Core Model Intercomparison Project (DCMIP)**, oral presentation at the 2014 Partial Differential Equations on the Sphere (PDEs on the Sphere) Workshop, Boulder, CO, USA, April 7-11, 2014

Yao, W. and C. Jablonowski, **A Stratospheric Perspective of a GCM Dynamical Core Intercomparison**, poster presentation at the 2014 Partial Differential Equations on the Sphere (PDEs on the Sphere) Workshop, Boulder, CO, USA, April 7-11, 2014

Thatcher, D. and C. Jablonowski, **A Moist Variant of the Held Suarez Test for-Atmospheric Model Dynamical Core Intercomparisons**, poster presentation at the 2014 Partial Differential Equations on the Sphere (PDEs on the Sphere) Workshop, Boulder, CO, USA, April 7-11, 2014

Jablonowski, C., C. M. Zarzycki, J. Ferguson, M. A. Taylor, H. Johansen and P. Colella, **Pushing the Frontiers of High-Resolution Climate Modeling**, invited presentation at the Applied Physics Seminar, University of Michigan, Ann Arbor, MI, USA, April 2, 2014

Zarzycki, C. M. and C. Jablonowski, **Deterministic Forecasts of Tropical Cyclones Using a Variable-Resolution Global Model**, oral presentation at the 31st Conference on Hurricanes and Tropical Meteorology, San Diego, CA, USA, March 31 – April 4, 2014

Zarzycki, C. M., C. Jablonowski and D. Thatcher, **The impacts of high-resolution refinement in variable-resolution CAM-SE on regional climate in CESM**, Atmospheric Working Group Meeting (AMWG), National Center for Atmospheric Research, Boulder, CO, USA, February 10-12, 2014

Soner, M. S. and R. B. Rood, **A Decision Tree Algorithm for Investigation of Model Biases Related to Dynamical Cores and Physical Parameterizations**, oral presentation at the American Meteorological Society (AMS) 94th Annual Meeting, Atlanta GA, February/2-6/2014

Yao, W. and C. Jablonowski, **Idealized Simulations of Sudden Stratospheric Warmings with an Ensemble of Dry GCM Dynamical Cores**, poster presentation at the SPARC General Assembly 2014, Queenstown, New Zealand, January 12-17, 2014

Jablonowski, C. and W. Yao, **Spontaneous QBO-like Oscillations in Atmospheric Model Dynamical Cores**, poster presentation at the SPARC General Assembly 2014, Queenstown, New Zealand, January 12-17, 2014

2013

Zarzycki, C. M. and C. Jablonowski, **Evaluating the Impact of Localized GCM Grid Refinement on Regional Tropical Cyclone Climatology and Synoptic Variability using Variable-Resolution CAM-SE**, oral presentation at the American Geophysical Union (AGU) Fall Meeting 2013, Abstract A42D-01, San Francisco, CA, USA, December 9-13, 2013

Soner, M. S. and R. B. Rood, **Investigation of Model Bias of Dynamical Cores and Physical Parameterizations by Object-Based Methods**, poster presentation at the American Geophysical Union (AGU) Fall Meeting 2013, Abstract GC11D-1022, San Francisco, CA, USA, December 9-13, 2013

Thatcher, D., C. Jablonowski and C. Zarzycki, **A Moist Idealized Test Case for Atmospheric General Circulation Models**, poster presentation at the American Geophysical Union (AGU) Fall Meeting 2013, Abstract A33B-0202, San Francisco, CA, USA, December 9-13, 2013

Reed, K. A., C. Jablonowski, P. A. Ullrich, J. Kent, P. H. Lauritzen, M. A. Taylor and R. Nair, **Multi-model GCM ensemble simulations of idealized tropical cyclones**, poster presentation at the American Geophysical Union (AGU) Fall Meeting 2013, Abstract A33B-0219, San Francisco, CA, USA, December 9-13, 2013

Yao, W. and C. Jablonowski, **Idealized Simulations of Sudden Stratospheric Warmings with an Ensemble of Dry GCM Dynamical Cores**, poster presentation at the American Geophysical Union (AGU) Fall Meeting 2013, Abstract SA23A-2048, San Francisco, CA, USA, December 9-13, 2013

Jablonowski, C., C. Zarzycki, M. A. Taylor, H. Johansen and Phillip Colella, **Pushing the frontiers of high-resolution climate modeling**, invited Keynote talk at the University of Michigan CyberInfrastructure (CI) Days, Ann Arbor, MI, USA, Nov 13-14, 2013

Yao, W. and C. Jablonowski, **The influence of moisture and gravity wave drag in idealized simulations of Quasi-Biennial Oscillation**, poster presentation, UM College of Engineering Graduate Symposium (EGS), Ann Arbor, MI, USA, Nov. 15, 2013

Thatcher, D. and C. Jablonowski, **Comparison of a moist idealized test case and aquaplanet simulations in an atmospheric general circulation model**, poster presentation, UM College of Engineering Graduate Symposium (EGS), Ann Arbor, MI, USA, Nov. 15, 2013

Yao, W. and C. Jablonowski, **The characteristics of the QBO and SSW with different GCM dynamical cores in idealized simulations**, oral presentation at the 19th AMS Conference on Atmospheric and Oceanic Fluid Dynamics and the 17th AMS Conference on the Middle Atmosphere, Newport, RI, USA, June 16-21, 2013

Kent, J., J. P. Whitehead, C. Jablonowski and R. B. Rood, **Methods to Determine the Effective Resolution of Dynamical Cores**, oral presentation at the 2013 SIAM Conference on Mathematical & Computational Issues in the Geosciences, Padova, Italy, June 17-20, 2013

Jablonowski, C., K. A. Reed and C. M. Zarzycki, **Uncertainty in tropical cyclone simulations in multi-model GCM ensembles**, invited oral presentation at the 4th International Summit on Hurricanes and Climate Change, Kos, Greece, June 13-18, 2013

Zarzycki, C. M. and C. Jablonowski, **High-resolution tropical cyclone climate simulations in NCAR's variable-resolution general circulation model CAM-SE,** poster presentation at the 4th International Summit on Hurricanes and Climate Change, Kos, Greece, June 13-18, 2013

Jablonowski, C., C. M. Zarzycki and M. A. Taylor, **New Frontiers: Tropical Cyclone Modeling with NCAR's Variable-Resolution General Circulation Model CAM-SE**, ZMAW(Zentrum für Marine und Atmosphärische Wissenschaften)/KlimaCampus Seminar, Hamburg, Germany, June 11, 2013

Zarzycki, C. M. and C. Jablonowski, **High-resolution, multi-decadal tropical cyclone simulations using a variable-resolution general circulation model**, oral presentation at the U.S. CLIVAR Hurricane Workshop, Geophysical Fluid Dynamics Laboratory, Princeton, NJ, USA, June 5-7, 2013

Jablonowski, C., **Uncertainty in Weather and Climate Models: A Dynamical Core Perspective**, invited oral presentation at the Workshop on Stochastic Modelling and Computing for Weather and Climate Prediction, Oriel College, Oxford, U.K., March 18-21, 2013

Zarzycki, C. M. and C. Jablonowski, **Utilizing Grid Refinement in the Cubed-sphere Spectral Element Option of CAM to Model Tropical Cyclones, oral** presentation at the minisymposium 'Cubed-Sphere Grids for Planet Earth and Beyond' at the 2013 SIAM Conference on Computational Science and Engineering, Boston, MA, USA, February 25- March 1, 2013

Jablonowski, C., P. A. Ullrich, J. Kent, K. A. Reed, M. A. Taylor, P. H. Lauritzen and R. D. Nair, **Status of the Dynamical Core Model Intercomparison Project (DCMIP),** invited oral presentation at the 2nd IS-ENES Workshop on HPC for Climate Models, Toulouse, France, January 30 – February 1, 2013

Zarzycki, C. M., C. Jablonowski and M. A. Taylor, **Assessing the Ability of Variable-Resolution Global Models to Forecast Tropical Cyclones**, oral presentation at the Special Symposium on Advancing Weather and Climate Forecasts: Innovative Techniques and Applications, 93rd Annual American Meteorological Society Meeting, Austin, TX, USA, January 6-10, 2013

Soner, M. S. and R. B. Rood, **Quantifying the Relationship between Dynamical Cores and Physical Parameterizations by Object-Based Methods**, oral presentation at the 93rd Annual American Meteorological Society Meeting, Austin, TX, USA, January 6-10, 2013

2012

Zarzycki, C. M., C. Jablonowski and M. A. Taylor, **Using the Variable-Resolution General Circulation Model CAM-SE to Simulate Regional Tropical Cyclone Climatology**, oral presentation at the AGU Fall Meeting 2012, abstract A31L-05, San Francisco, CA, USA, December 3-7, 2012

Yao, W. and C. Jablonowski, **The influence of Convection and Gravity Wave Drag Parameterizations in Idealized Simulations of the Quasi-Biennial Oscillation With Different GCM Dynamical Cores**, oral presentation at the AGU Fall Meeting 2012, abstract A13Q-08, San Francisco, CA, USA, December 3-7, 2012

Kent, J., C. Jablonowski, J. Whitehead and R. B. Rood, **Methods to Determine the Effective Resolution of Dynamical Cores of GCMs**, oral presentation at the AGU Fall Meeting 2012, abstract A52B-01, San Francisco, CA, USA, December 3-7, 2012

Ullrich, P. A., C. Jablonowski, J. Kent, K. A. Reed, M. A. Taylor, P. H. Lauritzen and R. D. Nair. **Towards a Unified Test Case Suite for Global Atmospheric Models**, poster presentation at the AGU Fall Meeting 2012, abstract A53C-0159, San Francisco, CA, USA, December 3-7, 2012

Jablonowski, C., P. A. Ullrich, J. Kent, K. A. Reed, M. A. Taylor, P. H. Lauritzen and R. D. Nair, **The 2012 Dynamical Core Model Intercomparison Project (DCMIP)**, poster presentation at the AGU Fall Meeting 2012, abstract A53C-0160, San Francisco, CA, USA, December 3-7, 2012

Zarzycki, C. M. and C. Jablonowski, **Improving weather prediction and regional climate modeling through the use of variable-resolution global atmospheric models**, poster presentation

at the UM 2012 CoE Graduate Engineering Symposium, Ann Arbor, MI, USA, November 2, 2012

Zarzycki, C. M., C. Jablonowski and M. A. Taylor, **Evaluating Variable-Resolution CAM-SE with High-Resolution Forecast Simulations**, Workshop on Weather and Climate Prediction on Next Generation Supercomputers: Numerical and Computational Aspects, U.K. Met Office, Exeter, U.K., October 22-25, 2012

Whitehead, J., C. Jablonowski, J. Kent and R. B. Rood, **Potential Vorticity: A Diagnostic Tool for General Circulation Models**, oral presentation at the Workshop on the Solution of Partial Differential Equations on the Sphere, Cambridge, U.K., September 24-28, 2012

Kent, J., C. Jablonowski and P. A. Ullrich, **DCMIP 2012: Tracer Transport Tests in Dynamical Cores**, oral presentation at the Workshop on the Solution of Partial Differential Equations on the Sphere, Cambridge, U.K., September 24-28, 2012

Zarzycki, C. M., C. Jablonowski and M. A. Taylor, **Improving Tropical Cyclone Representation in General Circulation Models through the use of Variable Resolution**, oral presentation at the Workshop on the Solution of Partial Differential Equations on the Sphere, Cambridge, U.K., September 24-28, 2012

Jablonowski, C., P. A. Ullrich, J. Kent, K. A. Reed, M. A. Taylor, P. H. Lauritzen and R. D. Nair, **Highlights of the Dynamical Core Model Intercomparison Project (DCMIP)**, oral presentation at the Workshop on the Solution of Partial Differential Equations on the Sphere, Cambridge, U.K., September 24-28, 2012

Jablonowski, C., **Model Evaluations I: How to think about and what to expect from dynamical core and GCM tests,** Tutorial presentation at the Dynamical Core Model Intercomparison Project (DCMIP) Summer School on Future-Generation Non-Hydrostatic Weather and Climate Models, National Center for Atmospheric Research, Boulder, CO. USA, July 30 - August 10, 2012

Jablonowski, C., **Model tuning II: Review of possible filtering operations and diffusive mechanisms in dynamical cores,** Tutorial presentation at the Dynamical Core Model Intercomparison Project (DCMIP) Summer School on Future-Generation Non-Hydrostatic Weather and Climate Models, National Center for Atmospheric Research, Boulder, CO. USA, July 30 - August 10, 2012

Yorgun, M. S.. and R. B. Rood, **An Object-Based Approach for Quantification of GCM Biases on Simulation of Orographic Precipitation**, poster presentation at the 17th Annual CESM Workshop, Breckenridge, CO, USA, June 18-21, 2012

Zarzycki, C. M., C. Jablonowski, M. A. Taylor and M. N. Levy, **Tropical Cyclone Modeling Using CAM-SE's Variable Resolution Option**, poster presentation at the 17th Annual CESM Workshop, Breckenridge, CO, USA, June 18-21, 2012

Reed, K. A., M. F. Wehner, C. Jablonowski and F. Li, **Tropical cyclone climatology in High Resolution CAM**, oral presentation at the 17th Annual CESM Workshop, Breckenridge, CO, USA, June 18-21, 2012

Lauritzen, P. H., W. C. Skamarock, M. J. Prather, M. A. Taylor and C Jablonowski, **Assessing accuracy of transport schemes in global climate-weather models**, poster presentation at the EGU General Assembly 2012, Vienna, Austria, April 22-27, 2012

Reed, K. A., M. F. Wehner and C. Jablonowski, **Towards the Direct Simulation of Tropical Cyclones in the High-Resolution Community Atmosphere Model**, oral presentation at the EGU General Assembly 2012, Vienna, Austria, April 22-27, 2012

Jablonowski, C and K. A. Reed, **Structural Uncertainty of Tropical Cyclone Simulations in General Circulation Models**, oral presentation at the 30th AMS Conference on Hurricanes and

Tropical Meteorology, Ponte Vedra Beach, FL, USA, April 15-20, 2012

Zarzycki, C. and C. Jablonowski, **Using variable resolution meshes to model tropical cyclones in NCAR's CAM general circulation model**, oral presentation at the 30th AMS Conference on Hurricanes and Tropical Meteorology, Ponte Vedra Beach, FL, USA, April 15-20, 2012

Reed, K. A., M. F. Wehner and C. Jablonowski, **Tropical Cyclone Characteristics in the High-Resolution Community Atmosphere Model**, oral presentation at the 30th AMS Conference on Hurricanes and Tropical Meteorology, Ponte Vedra Beach, FL, USA, April 15-20, 2012

Reed, K. A., C. Jablonowski and M. F. Wehner, **Tropical Cyclone Structure in the High-Resolution Community Atmosphere Model**, oral presentation at the 1st U.S. CLIVAR Hurricane Working Group Workshop, New Orleans, LA, USA, January 27-28, 2012.

Reed, K. A. and C. Jablonowski, **Evaluating the impact of the CAM 5 dynamical core in idealized tropical cyclone simulations**, oral presentation at the 92nd American Meteorological Society (AMS) Annual Meeting and 24th Conference on Climate Variability and Change, New Orleans, LA, USA, January 22-26, 2012

Yorgun, M. S. and R. B. Rood, **Quantifying the Relationship between Global Circulation Model Behavior and Related Physics by Object-Based Methods**, oral presentation at the 92nd American Meteorological Society (AMS) Annual Meeting, New Orleans, LA, USA, January 22-26, 2012

2011

Reed, K. A. and C. Jablonowski, **Idealized Tropical Cyclone Simulations of Intermediate Complexity: A Test Case for AGCMs**, poster presentation at the AGU Fall Meeting 2011, Abstract GC11B-0921, San Francisco, CA, USA, December 5-9, 2011

Zarzycki, C. M. and C. Jablonowski, **Modeling Tropical Cyclones in NCAR's General Circulation Model with Variable-Resolution Meshes**, oral presentation at the AGU Fall Meeting 2011, Abstract A32D-05, San Francisco, CA, USA, December 5-9, 2011

Yao, W. and C. Jablonowski, **Idealized Simulations of the Quasi-Biennial Oscillation With Different GCM Dynamical Cores: The Role of Parameterized Gravity Waves**, poster presentation at the AGU Fall Meeting 2011, Abstract A51A-0216, San Francisco, CA, USA, December 5-9, 2011

Kent, J, J. Whitehead, C. Jablonowski and R. B. Rood, **Assessing the Accuracy of Tracer Transport Schemes in the Dynamical Cores of General Circulation Models**, poster presentation at the AGU Fall Meeting 2011, Abstract A51A-0225, San Francisco, CA, USA, December 5-9, 2011

Reed, K. A. and C. Jablonowski**, Towards the Simulation of Tropical Cyclones in High-Resolution GCMs:** Assessing Uncertainty, Poster presentation at the World Climate Research Programme (WCRP) Open Science Conference, Denver, CO, October 24-28, 2011

Whitehead, J., J. Kent, C. Jablonowski and R. B. Rood**, Evaluating the impact of dissipative subgrid-scale mixing processes in the dynamical cores of NCAR's Community Atmosphere Model**, Invited presentation at the Department of Energy's Climate and Earth System Modeling Program Team Meeting, Washington, D.C., USA, September 19-22, 2011

Reed, K. A. and C. Jablonowski**, Towards the Simulation of Tropical Cyclones in High-Resolution GCMs**, Invited presentation at the Workshop on Numerical Methods for Scale Interactions, Hamburg, Germany, September 21-23, 2011