Introducing Enabling Computational Tools to the Climate Sciences: Multi-Resolution Climate Modeling with Adaptive Cubed-Sphere Grids

Final Report, July 2015
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1 Executive Summary

The research investigates and advances strategies how to bridge the scale discrepancies between local, regional and global phenomena in climate models without the prohibitive computational costs of global cloud-resolving simulations. In particular, the research explores new frontiers in computational geoscience by introducing high-order Adaptive Mesh Refinement (AMR) techniques into climate research. AMR and statically-adapted variable-resolution approaches represent an emerging trend for atmospheric models and are likely to become the new norm in future-generation weather and climate models. The research advances the understanding of multi-scale interactions in the climate system and showcases a pathway how to model these interactions effectively with advanced computational tools, like the Chombo AMR library developed at the Lawrence Berkeley National Laboratory. The research is interdisciplinary and combines applied mathematics, scientific computing and the atmospheric sciences.

In this research project, a hierarchy of high-order atmospheric models on cubed-sphere computational grids have been developed that serve as an algorithmic prototype for the finite-volume solution-adaptive Chombo-AMR approach. The foci of the investigations have lied on the characteristics of both static mesh adaptations and dynamically-adaptive grids that can capture flow fields of interest like tropical cyclones. Six research themes have been chosen. These are (1) the introduction of adaptive mesh refinement techniques into the climate sciences, (2) advanced algorithms for nonhydrostatic atmospheric dynamical cores, (3) an assessment of the interplay between resolved-scale dynamical motions and subgrid-scale physical parameterizations, (4) evaluation techniques for atmospheric model hierarchies, (5) the comparison of AMR refinement strategies and (6) tropical cyclone studies with a focus on multi-scale interactions and variable-resolution modeling. The results of this research project demonstrate significant advances in all six research areas. The major conclusions are that statically-adaptive variable-resolution modeling is currently becoming mature in the climate sciences, and that AMR holds outstanding promise for future-generation weather and climate models on high-performance computing architectures.

2 Final Scientific Report: Summary of the Accomplishments

2.1 Background

Numerical predictions of high-impact local weather events and the vastly growing demand for regional-local climate predictions are grand challenge problems and one of the main drivers for petascale and exascale computing. The software challenge that is faced by all applied sciences is the explosion in hardware parallelism. This requires a significant redesign of science applications, libraries, and algorithms to reach the level of parallelism needed to fully utilize the newest generations of computer architectures. The Adaptive Mesh Refinement (AMR) and variable-resolution climate science research, that was funded in this project, bridges this ever-widening gap between computer hardware and software development.

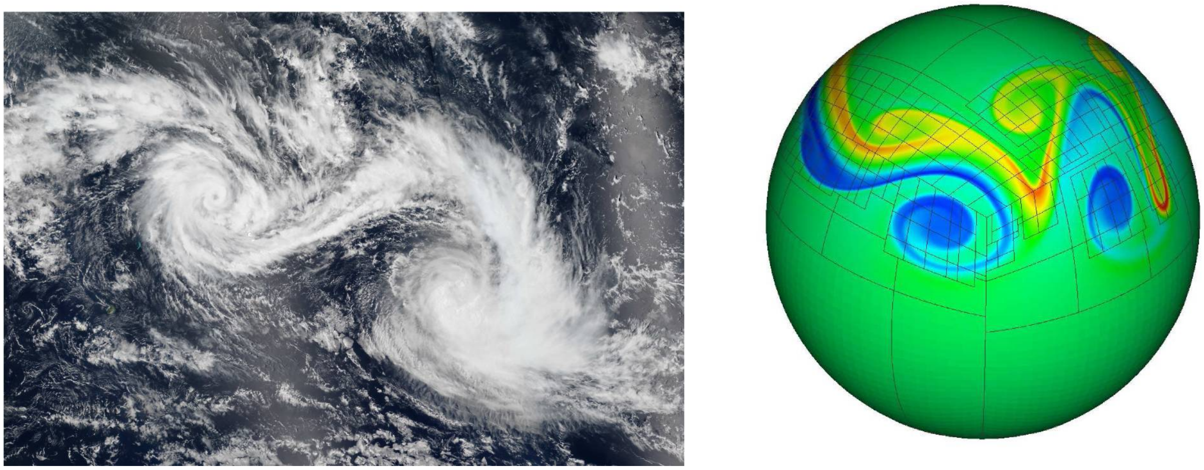


Figure 1: Left: Pair of tropical cyclones in the Southern Hemisphere with clockwise rotation (source: NASA's Earth Observatory, satellite image) and (right) an example of an AMR-Chombo simulation that focuses its computational grid on the relative vorticity extremes of an unstable barotropic wave at model day 6. Blue: clockwise rotation. Red: counterclockwise rotation.

The climate system is characterized by complex nonlinear interactions over a broad range of scales. The research objective of this proposal was to determine how these multi-scales interact and how to use enabling computational tools to mathematically represent scale interactions in seamless climate models. Small-scale circulations are for example induced by complex distributions of surface characteristics, such as topography, sea surface temperatures (SSTs), coastlines, and vegetation which vary on typical scales between 1-100 km and finer. These provide feedbacks to the large-scale circulation by, for example, having a large impact on the regional precipitation. An example of the many scales in the climate system is shown in Fig. 1 which exemplifies the major goal of this research project. The right figure highlights how the AMR research with the AMR library Chombo (Adams et al. 2014), developed by our LBNL project partners, can focus its cubed-sphere computational grid on features of interest. The features in the example here are the vorticity patterns of an unstable barotropic wave in the 2D shallow water system on the sphere (Galewsky et al. 2004). This idealized flow field closely mimics the pair of tropical cyclones depicted in the left satellite image, and thereby demonstrates how small-scale phenomena can be identified and followed by the newly-developed Chombo-AMR model (McCorquodale et al. 2015b; Ferguson et al. 2015). This capability is a major outcome of this research effort.

The research has focused on scale interactions in the so-called dynamical core of Atmospheric General Circulation Models (GCM). The dynamical core refers to the fluid dynamics component of a GCM and encompasses the numerical methods used to solve the equations of motion on the resolved scales. The research explored how AMR and other variable-resolution mesh techniques allow high resolution meshes in regions of interest like the eye of a cyclone or over mountainous terrain. All variable-resolution approaches evaluated in this research project have been built upon a cubed-sphere computational grid that is an emerging grid structure in the weather and climate community.

The trend towards variable-resolution climate predictions faces many barriers that are attributable to both our limited understanding of small-scale processes and our computational capability to capture their complex multi-scale interactions. The open questions, for example, address how to use mathematical and computational techniques as an enabling tool for multi-scale models, how to define subgrid-scale physical parameterizations (like precipitation and clouds) that function reliably at variable scales, how to conservatively couple atmosphere, ocean, ice and land models with variable resolutions, and how to ensure the quality and skill of variable-resolution simulations. Such a research field has enormous potential for innovation and scientific discovery. The research project has made significant contributions to these open questions. In particular, the original research proposal had outlined six research fields, and the accomplishments for each of these six research areas are documented in detail in Sections 3.1-3.6.

The research was built upon a synergistic collaboration between mathematicians, computer scientists and application specialists from DoE's Lawrence Berkeley National Laboratory and the University of Michigan (UM). The application of LBNL's AMR library Chombo in the climate sciences showcases the technology transfer and introduced enabling computational tools to the climate community. In addition, the PI closely collaborated with Dr. Mark Taylor from Sandia National Laboratories on the static variable-resolution aspects of an alternative GCM. The research has the potential to transform classical regional climate modeling by providing numerical and physical consistency at the boundaries of nested high-resolution domains. Ultra-high spatial resolutions in selected regions (at or below 10 km grid spacing) enable an unprecedented representation of dynamic events, like tropical cyclones, and provide vastly improved representations of local forcing mechanisms like steep orography or the land-sea boundary.

Before all accomplishments are highlighted in detail, this final report first lists the overall achievements in a concise bulleted form in the following subsections.

2.2 Funded Research Team at the University of Michigan and their Careers

The following Ph.D. students and postdoctoral researcher were partly funded by 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.

Dr. Paul A. Ullrich

- Ph.D. in Atmospheric and Space Science and Scientific Computing, University of Michigan, graduation in May 2011.

- 6/2011-8/2012: Postdoctoral Researcher in PI's group, University of Michigan
- since 9/2012: Assistant Professor, Department of Land, Air and Water Resources, University of California, Davis, CA
- since 9/2012: LBNL Affiliated Researcher, Dr. Ullrich has continued his close collaboration with the Chombo AMR modeling team at LBNL and holds a courtesy appointment

Dr. Kevin Reed

- Ph.D. in Atmospheric and Space Science, Graduate Certificate in Public Policy, University of Michigan, graduation in April 2012.
- 5/2012-8/2012: Postdoctoral Researcher in PI's group, 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

Dr. Peter Bosler

- Ph.D. in Mathematics, University of Michigan, Department of Mathematics, Program in Applied and Interdisciplinary Mathematics (AIM), graduation in May 2013.
- 9/2013-5/2014: Postdoctoral Assistant Professor, Department of Mathematics, University of Michigan
- 6/2014-7/2014: Postdoctoral Researcher in PI's group, University of Michigan
- since 8/2014: John von Neumann Postdoctoral Research Fellow in Computational Science at Sandia National Laboratories, Albuquerque, NM

Dr. Colin M. Zarzycki

- Ph.D. in Atmospheric and Space Science, Graduate Certificate in Computational Discovery and Engineering, University of Michigan, graduation in May 2014.
- 6/2014-8/2014: Postdoctoral Researcher in PI's group, University of Michigan
- since 9/2014: Postdoctoral Fellowship Holder, Advanced Study Program (ASP) and Climate and Global Dynamics Division (CGD), NCAR

Diana R. Thatcher

- Ph.D. Candidate, Graduate Certificate in Computational Discovery and Engineering, University of Michigan, expected to graduate in 2017. Diana works on variable-resolution aspects of GCMs, in particular on the scale awareness of physical parameterizations and the physics-dynamics coupling.

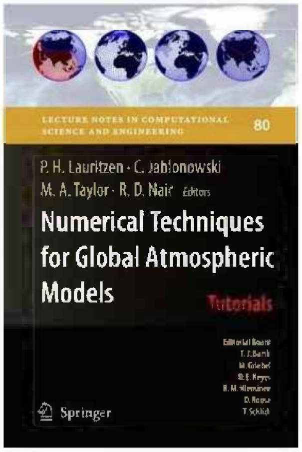
Jared O. Ferguson

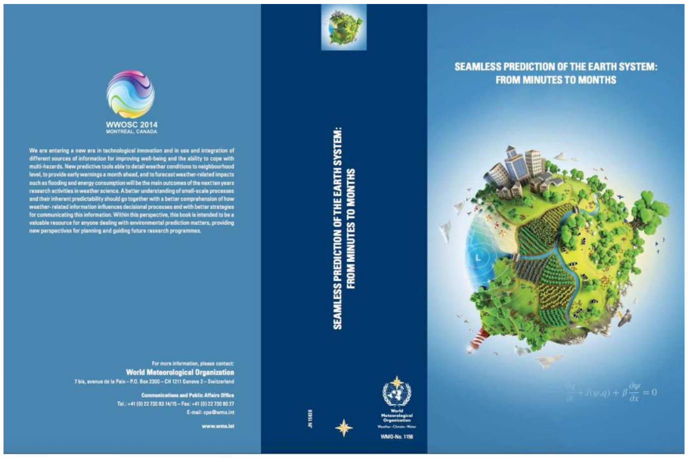
- Ph.D. Candidate, Graduate Certificate in Computational Discovery and Engineering, University of Michigan, Applied Physics Program, expected to graduate in 2017. Jared closely collaborates with the LBNL scientists Dr. Johansen and Dr. McCorquodale on the development of the Chombo-AMR model.

2.3 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 in subsections 3.1-3.6 where they are grouped into the six originally-proposed research themes.

- **# Journal Articles:** 28 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:** 106
- **# Ph.D. Theses, University of Michigan:** 4 completed, 2 in progress

Dr. Paul A. Ullrich
Atmospheric Modeling with High-Order Finite-Volume Methods, 2011, 299 pages

Dr. Kevin Reed
An Exploration of Tropical Cyclone Simulations in NCAR's Community Atmosphere Model, 2012, 196 pages

Dr. Peter Bosler
Particle Methods for Geophysical Flow on the Sphere, 2013, 209 pages

Dr. Colin M. Zarzycki
Variable-resolution frameworks for the simulation of tropical cyclones in global atmospheric general circulation models, 2014, 210 pages

Diana R. Thatcher
Scale-Interactions in Variable-Resolution General Circulation Models, in preparation (2017)

Jared Ferguson
Adaptive Mesh Refinement (AMR) Modeling of Geophysical Flows with the Chombo-AMR Model, in preparation (2017)

- **Press Coverage:**
  - News article highlighting the Parallel Computing 101 tutorial at SuperComputing'13 http://www.networkworld.com/news/2013/100813-sc13-show-274621.html
  - Online article about selected participants (including two UM participants) of the Dynamical Core Model Intercomparison Project (DCMIP) and Summer School at NCAR in August 2012: http://www2.cisl.ucar.edu/newsroom/former-siparcs-interns-evaluating-next-generation-climate-models
  - Press coverage (September 2011) concerning my Presidential Early Career Award for Scientists and Engineers (PECASE): http://www.whitehouse.gov/the-press-office/2011/09/26/president-obama-honors-outstanding-early-career-scientists http://energy.gov/articles/thirteen-department-energy-researchers-honored-presidential-early-career-award-scientists http://science.energy.gov/about/honors-and-awards/pecase/winners-since-1996/ http://www.ur.umich.edu/update/archives/110927/pecase http://www.annarbor.com/news/three-university-of-michigan-researchers-receive-presidential-early-career-awards/ http://www.michigandaily.com/news/u-profs-receive-presidential-research-grant?page=0,0
  - Online endorsement of the climate modeling panel discussion at SC'10, 9/11/2010: http://insidehpc.com/2010/11/09/supercomputing-for-a-changing-planet-simulation-and-climate-change/
  - Department of Energy, ASCR Magazine, Online article about the DoE Early Career Award, 3/31/2010: http://ascr-discovery.science.doe.gov/newfaces/ecrp1.shtml
  - Crain's Detroit Business, Online article about the DoE Early Career Award, 1/19/2010, http://www.crainsdetroit.com/article/20100120/GE001/100129993/1159

2.4 Organized Events related to this Research Project

- Co-organizer of the workshop 'Physics-Dynamics coupling in geophysical models – Bridging the gap', in Ensenada, Baja California, Mexico, December 2-4, 2014
- Full-day tutorial instructor of the tutorial 'Parallel Computing 101' at the conferences SuperComputing: SC'10 in New Orleans, SC'13 in Denver, SC'14 in New Orleans
- 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, August 16-21, 2014

- Co-convener of the session 'Recent developments in numerical Earth System Modelling' at the European Geosciences Union (EGU) General Assembly 2014 in Vienna, Austria, April 27 - May 2, 2014
- 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
- Organizer and leader of the panel discussion 'Pushing the Frontiers of Climate and Weather Models: High-Performance Computing, Numerical Techniques and Physical Consistency', at the conference SuperComputing SC'10, New Orleans, November 18, 2010, panel members: P. H. Lauritzen (NCAR). D. L. Randall (CSU), S.-J. Lin (GFDL), W. Putman (NASA), T. Davies (UK Met Office)
- Co-Organizer of the IPAM Workshop on 'Numerical Model Hierarchies for Climate Modeling' (April 2010) as part of the IPAM long program on 'Model and Data Hierarchies for Simulating and Understanding Climate', Institute for Pure and Applied Mathematics (IPAM), NSF Math Institute at UCLA, Los Angeles, March 8 - June 10, 2010

2.5 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 (since 2015)
- Member of the Steering Committee of the Michigan Institute for Computational Discovery and Engineering (since 2013)
- Executive Board Committee Member, Earth System Modeling Framework (ESMF, since 2010)

2.6 Awards won by the PI (since 2010)

- Presidential Early Career Award for Scientists and Engineers (PECASE), Oct. 2011
- Department of Energy Early Career Award, Apr. 2010 (this research project)

2.7 Research Awards won by the PI's Ph.D. Students (related to this project)

- Jared Ferguson: 2nd place (poster competition: Michigan Geophysical Union (MGU) Student Research Symposium, Apr. 1, 2015
- Diana Thatcher: Graduate Visitor Fellowship, National Center for Atmospheric Research, Feb. - Aug. 2015

- Diana Thatcher: People's Choice Award (poster competition), Michigan Institute for Computational Discovery and Engineering (MICDE), Nov. 6, 2014
- Colin Zarzycki and Christiane Jablonowski: AGU Newsletter "AGUniverse" Publication Highlight, Nov. 6, 2014
- Colin Zarzycki: NCAR Postdoctoral Fellowship, Advanced Study Program (ASP), Sep. 2014 -Aug. 2016
- Peter Bosler: John von Neumann Postdoctoral Research Fellow in Computational Science, Sandia National Laboratories, Aug. 2014 -Jul. 2016
- Diana Thatcher: 1st place at the UM 2013 College of Engineering Graduate Symposium (EGS), Nov. 15, 2013
- Diana Thatcher: AGU Travel Award, Fall 2013 meeting, Sep. 5, 2013
- Colin Zazrycki: Rackham Predoctoral Fellowship, University of Michigan, May 2013 - Apr. 2014
- Kevin Reed: Honorable Mention Distinguished Dissertation Award (among the best 21 Ph.D. theses out of 750 that year), University of Michigan, Feb. 2013
- Colin Zazrycki: American Meteorological Society (AMS) Annual Meeting, Best Oral Presentation Award, Jan. 30, 2013
- Kevin Reed: NCAR Postdoctoral Fellowship, Advanced Study Program (ASP), Sep. 2013 - Aug. 2015
- Colin Zarzycki: 1st place at the UM 2012 College of Engineering Graduate Symposium (EGS), Nov. 2, 2012
- Diana Thatcher: Rackham Merit Fellowship, University of Michigan, Sep. 2012 - Apr. 2014
- Kevin Reed: AGU Congressional Science Fellowship, Washington D.C., Sep. 2012 - Aug. 2013
- Colin Zarzycki: Isaac Newton Institute for Mathematical Sciences, Cambridge, U.K., Research visit, Aug. 22 - Oct. 27, 2012
- Kevin Reed: American Geophysical Union (AGU) Outstanding Student Paper Award, Mar. 31, 2011
- Paul Ullrich: American Geophysical Union (AGU) Outstanding Student Paper Award, Mar. 31, 2011
- Kevin Reed: CoE Graduate Distinguished Achievement Award, University of Michigan, Mar. 20, 2011
- Kevin Reed: 1st place (poster competition) at the UM 2010 CoE Engineering Graduate Symposium, Nov. 12, 2010
- Paul Ullrich: AOSS Finalist: Outstanding Ph.D. Student Research Award at the UM 2010 CoE Engineering Graduate Symposium, Nov. 12, 2010
- Colin Zarzycki: College of Engineering Dean?s Fellowship, University of Michigan, Sep. 2010 - Apr. 2011
- Kevin Reed: DoE Global Change Education Program (GCEP) Graduate Student Fellowship, Sep. 2010 - Aug. 2012
- Paul Ullrich: Rackham Predoctoral Fellowship, University of Michigan, May 2010 - Apr. 2011

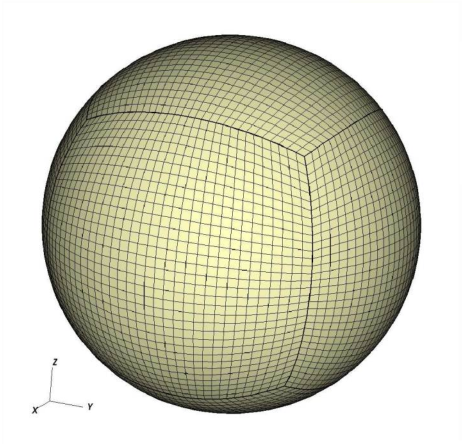
3 Summary of the Project Activities (includes points 4-7 of the reporting requirements)

The original research proposal had outlined six research fields. The accomplishments for each of these six research areas are documented in detail in the next six subsections. This includes the comparison of the proposed and actual research, the Chombo-AMR model description and all developed products which are grouped into these areas.

3.1 Introducing Adaptive Mesh Refinement Techniques into the Climate Sciences

3.1.1 Description of the Chombo-AMR Approach and the AMR Research

As originally proposed, this research project introduced DoE's open-source AMR library Chombo (Adams et al. 2014) into the climate sciences. Chombo is a mature and enabling tool hat provides the software infrastructure for block-structured adaptive mesh research. The library incorporates parallel computing support via the Message Passing Interface (MPI), load-balancing algorithms and toolboxes for numerical solvers. An important outcome of the project is that Chombo now supports mapped multi-blocks for cubed-sphere grid geometries. This includes (1) parallel data structures for data defined on nested hierarchies of unions of rectangles, (2) high-level interfaces for exchanging ghost cells between rectangular patches at the same level, (3) averaging and interpolation between different levels of refinement, and (4) tools for the computation of coarse / fine boundary conditions and for maintaining conservation at refinement boundaries for finite-volume discretizations. The cubed-sphere grid geometry and its associated grid resolutions are shown in Fig. 2. The left panel shows a base c32 grid that contains six cubed-sphere faces with 32×32 horizontal grid points each. The table on the right lists the approximate horizontal grid spacing Δx for each cXX resolution.



Resolution	Δx
c32	313 km
c64	156 km
c128	78.2 km
c256	39.1 km
c512	19.5 km
c1024	9.78 km

Figure 2: Cubed-sphere grid geometry: The left figure shows a base c32 grid that contains six cubed-sphere faces with 32×32 horizontal grid points each. The table on the right lists the approximate horizontal grid spacing Δx for each cXX resolution.

Figure 3 displays further implementation details of the Chombo-AMR approach as used in this project. Our model combines a 4-stage Runge-Kutta time discretization with a fourth-order finite-volume spatial discretization which allows adaptive mesh refinement in space and time. This is depicted in the left panel that shows the sub-cycling in time on the refined level-1 (L_1) grid. At intermediate time steps $t_n + \Delta t/2$ the already advanced underlying coarse-grid L_0 information is then interpolated in space and time to provide the boundary information for the embedded high-resolution simulation. At common time snapshots $t_n + \Delta t$ the more accurate fine-grain L_1 information is averaged back to the coarse grid which closely connects the Chombo grid hierarchy. The right panel of Fig. 3 depicts a typical numerical stencil. Here, the central red point needs neighboring information (blue) from both its refined southern neighbor and the surrounding grid cells at the same refinement level. The communication across refinement levels is handled via ghost cells that reach into the neighboring domain. The fine grid data are conservatively averaged to provide consistent ghost cell boundary data at the interfaces. Furthermore, numerical fluxes are averaged to guarantee mass conservation in the global domain.

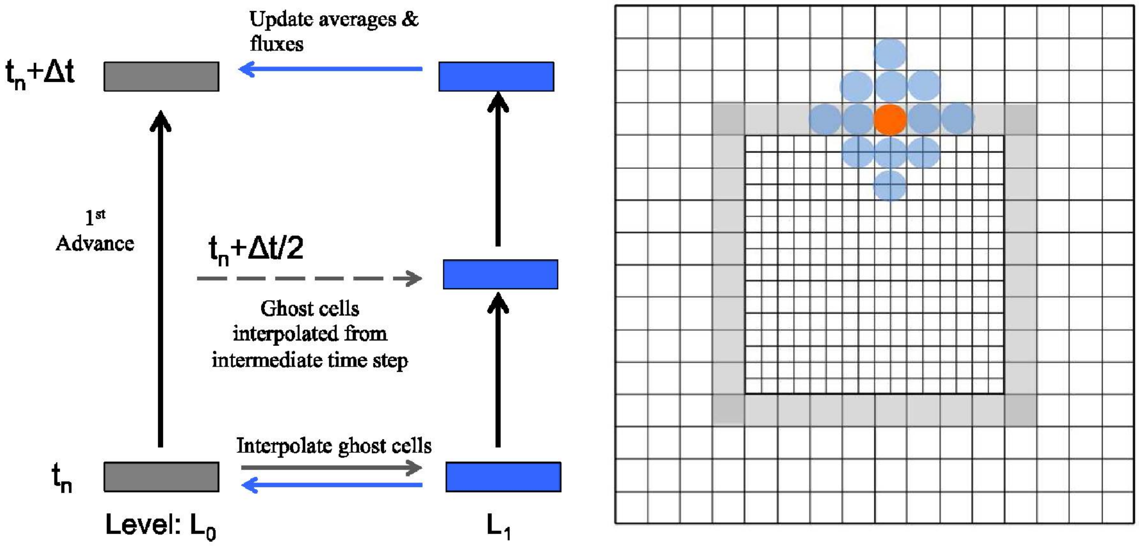


Figure 3: Schematics that show the (left) adaptive time stepping scheme in AMR simulations and (right) the locations of the stencil and ghost cells in the cubed-sphere grid geometry.

These ghost cell exchanges also involve parallel communication, depending on the given domain decomposition. All parallel computing tasks are handled by Chombo including the load-balancing of the application in a parallel computing environment. The promise is that AMR applications save significant computational resources while providing high-quality simulations of selected phenomena. Both memory and runtime savings can be materialized despite the added AMR overhead, which is generally small in Chombo.

3.1.2 The Chombo-AMR Shallow-Water Model

As the PI and her team highlighted in Ullrich et al. (2010) and as it was also pursued in the recent Chombo-AMR publication by our LBNL collaborators (McCorquodale et al. 2015b) the first step in the development of a new global atmospheric modeling system is the implementation of a 2D shallow-water model, which captures many of the important properties of the equations of motion for the atmosphere. In particular, the shallow-water equations exhibit Rossby waves, inertia-gravity waves and trapped tropical waves and thereby provide an idealized test bed for atmospheric flows without the added complexity of a vertical dimension. All algorithmic details of the Chombo-AMR design are provided in McCorquodale et al. (2015b). Here, only a very brief summary is given. Two fundamental observations can be made as listed in McCorquodale et al. (2015b). First, because the computational domain is on the surface of a sphere, which is a 2D manifold in a 3D space, the evolution equations must include metric terms. Second, because the vector quantities (velocities and momentum) are expressed in different bases on different cubed-sphere panels, the procedure for coordinating them across a panel boundary must include a basis transformation. The following shallow-water equation set, written in flux-form, is used

$$\frac{\partial}{\partial t}(J\mathbf{U}) + \nabla \cdot (J\vec{\mathbf{F}}) = J\mathbf{\Psi},$$

$$\mathbf{U} = \begin{pmatrix} h \\ hu^{\alpha} \\ hu^{\beta} \end{pmatrix}, \ \mathbf{F}^k = \begin{pmatrix} hu^k \\ \mathcal{T}^{\alpha k} \\ \mathcal{T}^{\beta k} \end{pmatrix}, \ \mathbf{\Psi} = \begin{pmatrix} 0 \\ \mathbf{\Psi}^{\alpha}_{\mathrm{M}} + \mathbf{\Psi}^{\alpha}_{\mathrm{B}} + \mathbf{\Psi}^{\alpha}_{\mathrm{C}} \\ \mathbf{\Psi}^{\beta}_{\mathrm{M}} + \mathbf{\Psi}^{\beta}_{\mathrm{B}} + \mathbf{\Psi}^{\beta}_{\mathrm{C}} \end{pmatrix}$$

$$\mathcal{T}^{ki} = hu^k u^i + g^{ki}\tfrac{1}{2}Gh^2$$

where $\mathbf{U}$ is the state vector, $\mathbf{F}$ denotes the flux vector, $\mathbf{\Psi}$ symbolizes the source vector which are further explained in the second row. In the shallow water system, h stands for the height of the shallow water system, u^{α} and u^{β} are the contravariant components of the velocity vector with units rad s^{-1} in their natural cubed-sphere basis, g^{ki} is a contravariant metric, G is gravity, and the subscripts M, B, C in the source vector stand for the source terms due to the curvature of the manifold, bottom topography and Coriolis force, respectively. The Jacobian on the manifold is symbolized by J. These terms are explained in detail in Ullrich et al. (2010) and McCorquodale et al. (2015b). Furthermore, the latter provide the details of the 4th-order finite-volume discretization in the Chombo-AMR model which makes use of the mapped-grid technology and the convolution-deconvolution technique by Colella et al. (2011) and Barad and Colella (2005). McCorquodale et al. (2015b) also describe the fourth-order Runge-Kutta time-stepping algorithm, explain the least-squares ghost cell interpolation technique at cubed-sphere panel boundaries and grid-refinement interfaces, and briefly sketch the artificial dissipation mechanism to smooth out oscillations due to the central difference operators.

3.1.3 The Characteristics of the Adaptive Blocks

An example of Chombo's block-adaptive, cubed-sphere shallow-water implementation is depicted in Fig. 4 that showcases how the mapped multi-blocks track merging tropical-cyclone-like vortices. Here, two refinement levels with a 1:4 refinement ratio were used in a single simulation that span the resolutions c64/c256/c1024 with the grid spacings 156, 39 and 10 km. The high-resolution domains are guided by a relative vorticity criterion that places the adaptive blocks where needed for accuracy. In the mapped space, the domains of different blocks are disjoint and each patch must be contained in only one block. All refinement levels stay active during the course of a simulation. This means that an overlaid fine-resolution block updates the solution of the underlying coarse block at each time step via a conservative averaging mechanism. The particular Chombo-AMR example in Fig. 4 exemplifies the results of our research (Ferguson et al. 2015). The adaptive blocks, here shown at day 1, successfully track the propagating and merging vortices that travel in the north-westerly direction. This can further be seen in Fig. 14 that shows additional snapshots of the 4-day simulation. The refinement criterion is checked every two coarse-grid time steps which is a user-defined choice. Other user-defined choices determine the minimum size of the adaptive blocks and their buffer zones, as well as the definition and threshold of the refinement criterion. The refinement thresholds can also be made adaptive which scales the thresholds depending on the refinement level. Figure 4 depicts a 4:1 refinement jump. We have also evaluated 2:1 and 8:1 refinement configurations which were used for careful evaluations of the convergence properties.

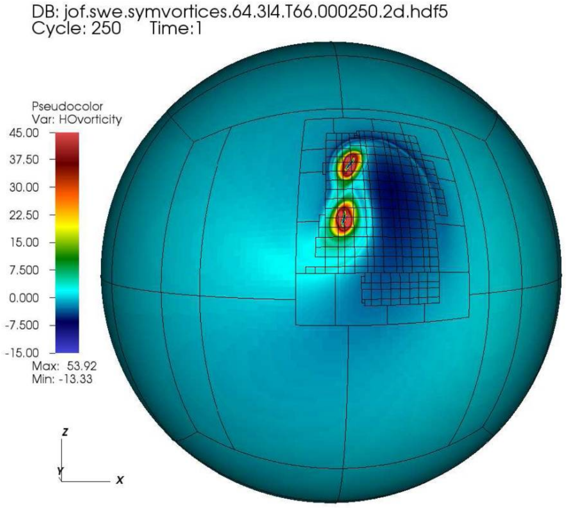


Figure 4: Block-structured adapted cubed-sphere mesh that tracks the relative vorticity extremes of two merging tropical-cyclone-like vortices. Day 1 is depicted.

3.1.4 Evaluations of the Chombo-AMR Approach

The Chombo-AMR shallow water evaluations, that we conducted for this project, followed a very strict protocol that is based on a hierarchy of test cases with increasing complexity. As outlined in the original proposal, the test hierarchy incorporates pure advection tests with prescribed wind speeds, utilizes steady-state and unsteady-state solid-body rotation tests with analytical solutions and leads to fully nonlinear shallow water tests without and with topography. One such test is the unsteady solid body rotation (USBR) test by Läuter et al. (2005) which is used as a "do-no-harm" test. This test is characterized by a very smooth large-scale flow that does not need any refinement regions to be fully resolved. The wavenumber-1-like flow field of this test case, depicted in Fig. 5, rotates around the sphere once per day, and any grid-imprinting from inhomogeneous model resolutions can be closely monitored due to the availability of the analytical solution. This is a difficult test for AMR since the background errors in unrefined simulations are very small. Furthermore, the test can be used for numerical convergence studies due to the smoothness of the flow field.

An example of our USBR investigations is displayed in Fig. 5. The left panel shows the height field with the overlaid cubed-sphere block structure and a statically-embedded high-resolution nested domain. The right panel depicts the time series of the normalized l_2 height error norms for uniform-resolution and Chombo-AMR simulations with one and two refinement levels as indicated by the 'c' notation in the legend (see also the table in Fig. 2). We utilize a 1:4 refinement ratio. The l_2 norms show that the Chombo-AMR model passes the "do-no-harm" test since the presence of the refined patch does not negatively impact the error measures in comparison to uniform-resolution simulations. Even very slight decreases in the overall errors are present in the AMR runs. Furthermore, the test reveals that the Chombo-AMR shallow water model converges with fourth-order accuracy under global grid refinement as theoretically expected from the numerical method.

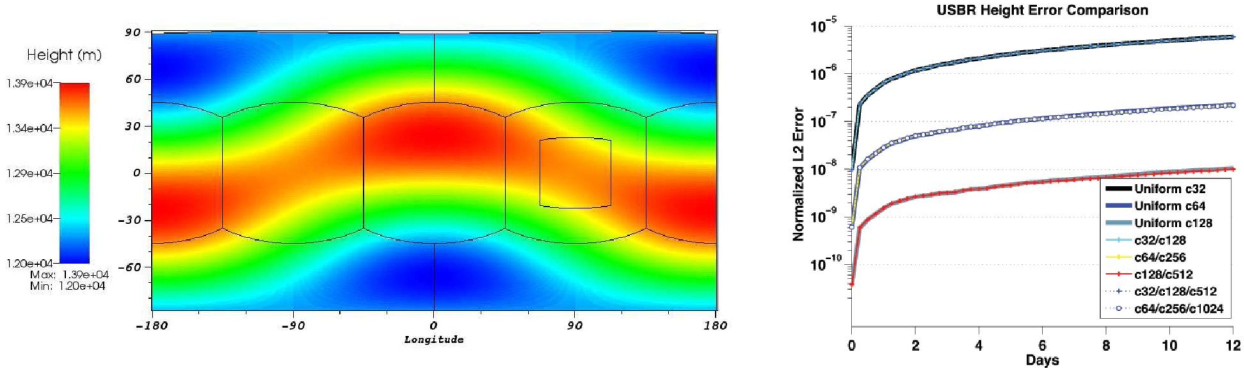


Figure 5: Convergence tests with the Unsteady Solid Body Rotation (USBR) test by Läuter et al. (2005). Left: Height field with the overlaid cubed-sphere block structure and a statically-embedded high-resolution nested domain. Right: Time series of the normalized l_2 height error norms for uniform-resolution and AMR simulations with one and two refinement levels as indicated by the 'c' notation.

3.1.5 I/O and Visualization

As originally proposed we utilize the Hierarchical Data Format (HDF5) for unstructured grids that is supported by the Chombo AMR library. Chombo is also linked to VisIT, the DoE visualization tool, which has been developed by the Visualization and Analytics Center for Enabling Technologies (VACET) at the Lawrence Livermore National Laboratory. All Chombo-AMR figures in this report were generated via VisIT.

3.1.6 Open Chombo-AMR Research Tasks

The original proposal also specified a variety of tasks that addressed science questions with the 3D nonhydrostatic version of the Chombo-AMR model. These were extended tests of the Chombo-AMR dynamical core with idealized 3D test cases and the coupling of the Chombo AMR model to simplified and complex physical parameterization packages and a simplified mixed-layer ocean. The proposal furthermore suggested investigating tropical cyclones with the Chombo-AMR approach. While our LBNL project partners developed the first prototype 3D nonhydrostatic version of the Chombo-AMR model in August 2014, which we also highlight in the next subsection in Fig. 7, the code was computationally inefficient. This prevented further investigations such as the coupling to a moist physics package. Instead, the decision was made to refactor portions of the Chombo-AMR implementation to optimize for computational speed and efficiency. Therefore, the 3D progress in the AMR-Chombo model development has been slower than anticipated in the proposal. Even the 2D Chombo-AMR shallow-water model developments were slower than initially thought due to software problems that our rigorous testing strategy kept revealing.

This delayed the Combo-AMR shallow water publications until this year (Ferguson et al. 2015; McCorquodale et al. 2015b).

However, many of the research questions from the original proposal can also be addressed in other models. Therefore, we also investigated alternative variable-resolution modeling approaches, such as generic grid refinement issues in 1D finite-volume advection codes (Ullrich and Jablonowski 2011), the AMR capabilities of 2D particle methods on the sphere (Bosler et al. 2014), and statically-nested variable-resolution methods (Zarzycki et al. 2014a) in an alternative 3D dynamical core, which is the DoE/NCAR Community Atmosphere Model (CAM) with the high-order Spectral Element (SE) scheme (Taylor and Fournier 2010; Dennis et al. 2012). These alternative models have enabled the PI and her team to complete all 3D research tasks of the original proposal. Therefore, major advances were made in all six originally-proposed research themes. The findings from the alternative variable-resolution models are further detailed in the following subsections. They will be directly applicable to the Chombo-AMR model, once the code base is more stable again. In addition, the 3D Chombo-AMR code base needs further advances such as the inclusion of monotonicity constraints like the fourth-order Colella and Sekora (2008) limiters, or the inclusion of topography via either topography-following coordinates or the so-called cut-cell method. These latter design decisions are closely tied to the choice of the vertical coordinate in the 3D model. Furthermore, parallel performance and scaling tests need to be conducted to ensure that the Chombo-AMR software design promotes high performance on the most recent hardware architectures and that the AMR overhead is low, as expected.

The PI continues her very successful collaboration with the LBNL Chombo team and will seek out new new funding opportunities for this innovative research theme. Furthermore, the PI is an organizer of the upcoming nonhydrostatic Dynamical Core Model Intercomparison Project (DCMIP-2016) in June 2016. We anticipate that the PI and the LBNL Chombo team will participate in DCMIP-2016 with the refactored 3D nonhydrostatic Chombo-AMR model.

3.1.7 Products

Journal Articles

- **McCorquodale et al. (2015b)**
  McCorquodale, P., P. A. Ullrich, H. Johansen and P. Colella (2015), An adaptive multi-block high-order finite-volume method for solving the shallow-water equations on the sphere. Comm. Appl. Math. Comput. Sci., in press
- **Ferguson et al. (2015)**
  J. Ferguson, C. Jablonowski, H. Johansen, P. McCorquodale and P. Colella (2015), Assessing the Chombo-AMR Adaptive Mesh Refinement approach for geophysical flows. Mon. Wea. Rev., in preparation
- **Bosler et al. (2014)**
  Bosler, P., L. Wang, R. Krasny and C. Jablonowski (2014), A Particle/Panel Method for the Barotropic Vorticity Equation on a Rotating Sphere, Fluid Dynamics Research, Vol. 46, 031406, doi:10.1088/0169-5983/46/3/031406
- **Ullrich and Jablonowski (2011)**
  Ullrich, P. A. and C. Jablonowski (2011), An Analysis of 1D Finite-Volume Methods for Geophysical Problems on Refined Grids, J. Comput. Phys., Vol. 230, 706-725

Conference and Seminar Presentations

1. Ferguson, J., C. Jablonowski, H. Johansen, P. McCorquodale and P. Colella, Assessing Adaptive Grid Refinement Techniques with the Chombo-AMR Model in Shallow Water Model, Poster Presentation at the 20th Annual CESM Workshop, Breckenridge, CO, USA, June 15-18, 2015
2. 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
3. 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
4. Ferguson, J., C. Jablonowski, H, Johansen, P. McCorquodale and P. Colella, Assessing Adaptive Grid Refinement Techniques with the Chombo-AMR Model in Shallow Water Model, Poster Presentation at the 2015 Michigan Geophysical Union (MGU) Meeting, Ann Arbor, MI, USA, April 1, 2015
5. 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
6. Ferguson, J., C. Jablonowski, H. Johansen, R. E. English, P. McCorquodale, P. Colella, J. Benedict, W. D. Collins, J. Johnson and P. A. Ullrich, Assessing Grid Refinement Strategies in the Chombo Adaptive Mesh Refinement Model, oral presentation at the American Geophysical Union (AGU) Fall Meeting 2014, Abstract A13M-06, San Francisco, CA, USA, December 15-19, 2014
7. Bosler, P., R. Krasny and C. Jablonowski, Adaptive Particle / Panel Methods for Global Geophysical Flow, poster presentation at the American Geophysical Union (AGU) Fall Meeting 2014, Abstract A21A-3009, San Francisco, CA, USA, December 15-19, 2014
8. Johansen, H., E. Goodfriend, P. McCorquodale, P. Colella, W. Collins, J. Johnson, D. Rosa, J. Benedict, P. Ullrich, J. Ferguson, C. Jablonowski, Progress towards a space-time adaptive non-hydrostatic dynamical core, oral presentation at the Physics-Dynamics Coupling Workshop (PDC14), Ensenada, Mexico, December 2-4, 2014
9. 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
10. Jablonowski, C., J. Ferguson, J. Benedict, W. Collins, E. English, H. Johansen, J. Johnson, P. McCorquodale, P. Colella, P. Ullrich, The Chombo Adaptive Mesh Refinement (AMR) Technique for Future GCM Dynamical Cores, poster presentation at the 19th Annual CESM Workshop, Breckenridge, CO, USA, June 16-19, 2014

11. Benedict, J., W. D. Collins, J. N. Johnson, H. Johansen, E. English, P. McCorquodale, C. Jablonowski, J. Ferguson, Development of a multiscale global climate model with adaptive mesh refinement, poster presentation at the 19th Annual CESM Workshop, Breckenridge, CO, USA, June 16-19, 2014
12. Ferguson, J., C. Jablonowski, H. Johansen, E. English, P. Ulrich, P. McCorquodale and P. Colella, Assessments of the Chombo adaptive mesh refinement model in shallow water mode, oral presentation at the 2014 Partial Differential Equations on the Sphere (PDEs on the Sphere) Workshop, Boulder, CO, USA, April 7-11, 2014
13. 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
14. 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
15. Jablonowski, C., A Seamless World: Challenges and Opportunities, invited talk at the High-Performance Computational Science with Structured Meshes and Particles (HPCS-SMP) Workshop on Simulation and Modeling in Climate, Berkeley, CA, USA, Oct. 14-16, 2013
16. Jablonowski, C., P. A. Ullrich and K. A. Reed, High-Order Methods and Nonhydrostatic Designs on Quasi-Uniform and Variable-Resolution Grids: Tackling the Numerical Challenges for Future-Generation GCMs, Invited presentation at the Global-to-Regional Climate Simulation Workshop, Santa Fe, NM, USA, August 3-5, 2011
17. Jablonowski, C. and P. A. Ullrich, An Analysis of Finite-Volume schemes: High-order Methods and Grid Reflections on Adaptive Grids, Invited oral presentation at the NSF Institute for Pure and Applied Mathematics (IPAM), Workshop II: Numerical Hierarchies for Climate Modeling, Los Angeles, CA, USA, April 16, 2010

Related Web Sites and Online Resources

- Chombo web site
  `https://commons.lbl.gov/display/chombo/Chombo+-+Software+for+Adaptive+Solutions+of+Partial+Differential+Equations`
- Mapped Mutilblock Grids in Chombo
  `https://commons.lbl.gov/display/chombo/Mapped+Multiblock+Grids`
- VisIt: DoE's open source visualization software which was used for this project
  `https://wci.llnl.gov/simulation/computer-codes/visit/`
- University of Michigan: Atmospheric Dynamics Modeling Group
  `http://aoss-research.engin.umich.edu/groups/admg/projects.php`

Fostered Networks and Collaborations

- The research project established a close collaboration with the Lawrence Berkeley National Laboratory, in particular with Dr. Colella's Chombo research group. Dr. Colella is an expert in AMR and finite volume methods, and furthermore the group leader of the Applied Numerical Algorithms Group (ANAG) that is part of the Computational Research Division at LBNL. We have communicated regularly with Dr. Johansen and Dr. McCorquodale (LBNL) who are integral members of the Chombo research team. In addition to LBNL, we also have collaborated closely with NCAR scientists on high-resolution climate modeling issues, such as the scale-awareness of the physical parameterizations for variable-resolution climate models.

Other Products Including Audio, Video and Educational Tools

- Full-day ’Parallel Computing 101’ tutorials at the conferences SuperComputing: SC’10 in New Orleans, SC’13 in Denver, SC’14 in New Orleans
- Organizer and leader of the panel discussion ’Pushing the Frontiers of Climate and Weather Models: High-Performance Computing, Numerical Techniques and Physical Consistency’, at the conference SuperComputing SC’10, New Orleans, November 18, 2010, panel members: P. H. Lauritzen (NCAR). D. L. Randall (CSU), S.-J. Lin (GFDL), W. Putman (NASA), T. Davies (UK Met Office)

3.2 Design of Nonhydrostatic Dynamical Cores & Algorithmic Advances

Dynamical cores are the central component of every climate and weather research model. They determine not only the choice of the computational grid but also design issues like the choice of conservation laws and prognostic variables.

3.2.1 Model Design Choices and the Model Hierarchy

As specified in the original proposal we designed and built a hierarchy of fourth-order finite-volume models on a cubed-sphere grid during the early phases of this research project between 2010-2012 while LBNL progressed on the design of mapped multi-block grids in the Chombo AMR library. In particular, our model hierarchy consists of a 2D shallow water model (Ullrich et al. 2010) on the gnomonic cubed-sphere grid, a nonhydrostatic 2D x-z-slice and 3D dynamical core in Cartesian geometry (Ullrich and Jablonowski 2012b), and its 3D spherical extension, called MCore, in cubed-sphere grid geometry (Ullrich and Jablonowski 2012a). The nonhydrostatic 3D dynamical core MCore includes switchable shallow-atmosphere and deep-atmosphere equation sets in conservation form which is a unique feature.

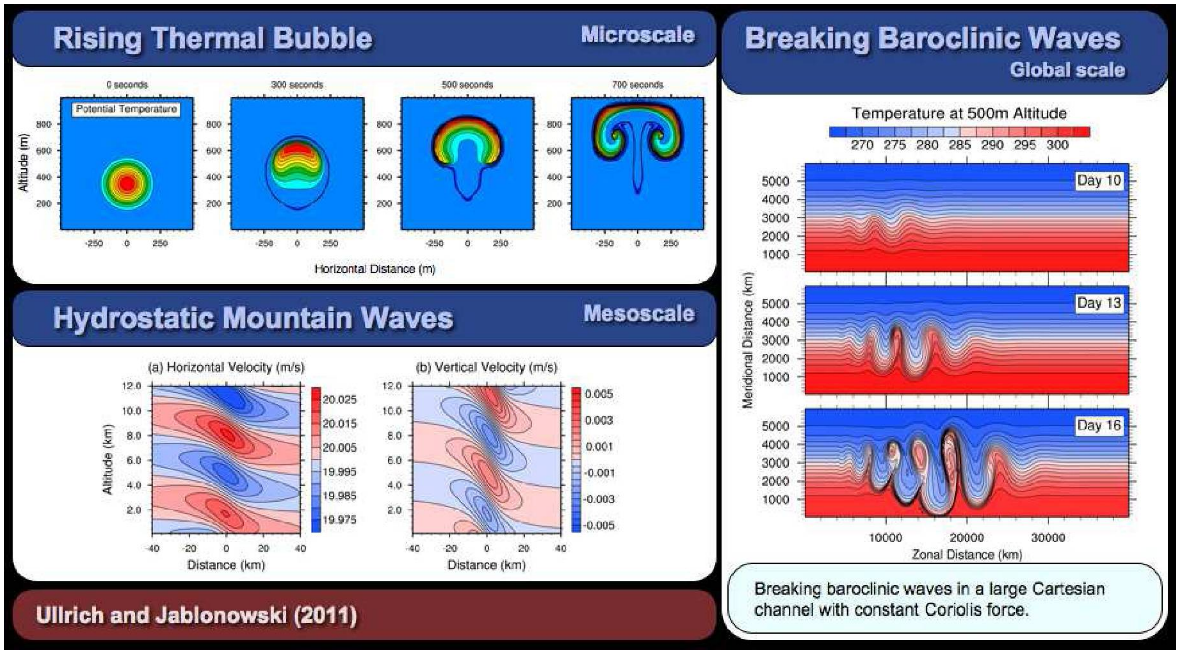
This model hierarchy represents a systematic increase in complexity. The shallow water configuration evaluates the horizontal and temporal discretizations as well as all challenges related to the cubed-sphere grid. The nonhydrostatic 2D x-z slice model and 3D configuration in Cartesian geometry is built upon the shallow water approach and adds the vertical dimension. In particular, it trained us which vertical coordinate to use and how to couple an explicit time-stepping scheme in the horizontal with an implicit integration in the vertical. The latter keeps the fast-travelling sound waves stable for long time steps. As the last step, we combined all lessons learned from the shallow water and Cartesian formulation, and built the 3D nonhydrostatic dynamical core MCore which served as the prototype for all subsequent AMR-Chombo model developments. All stages of the model development were accompanied by a rigorous testing strategy that even led to the extension of the dynamical core test suite as further discussed in subsection 3.4.

The design elements of our model developments are documented in the three journal articles cited above. In brief, they are

- equations in conservation form

- fully-compressible nonhydrostatic equations in 3D including both shallow-atmosphere and deep-atmosphere formulations
- gnomonic cubed-sphere grid with an equiangular projection (Ronchi et al. 1996)
- co-located Arakawa A-grid (no horizontal staggering)
- fourth-order accurate sub-grid reconstructions in the horizontal leading to fourth-order convergence
- computation of fluxes uses the convolution / deconvolution ideas by Barad and Colella (2005)
- use of approximate Riemann solvers for flux calculations, in particular the AUSM$^+$-up solver (Liou 2006)
- fourth-order Runge-Kutta time-stepping algorithm
- orography-following height-based coordinate in the vertical direction (Gal-Chen and Somerville 1975)
- second-order accurate sub-grid reconstructions and flux calculations in the vertical direction
- mass conservative
- explicit integration in the horizontal combined with implicit integration in the vertical using the newly-developed Strang-carryover approach (Ullrich and Jablonowski 2012b)
- parallelized model design based on MPI

These algorithmic design choices match the originally-proposed list of model design elements almost perfectly. Figure 6 shows some selected results from our Cartesian model evaluations (Ullrich and Jablonowski 2012b). These results highlight that the fourth-order finite-volume model



Breaking baroclinic waves in a large Cartesian channel with constant Coriolis force.

Figure 6: Collection of the test case results in a Cartesian channel that are documented in Ullrich and Jablonowski (2012b). Results are from the newly-developed channel version of the nonhydrostatic MCore model that is built upon a 4th-order finite-volume method.

is an adequate choice for all scales. The displayed flow fields include thermal convection at the microscale (depicted by the rising bubble), mountain-generated gravity waves at the mesoscale, and baroclinic instability waves at the global scale. This demonstrates that our model design accurately captures the motions at all scales (proof-of-concept) which makes it suitable for adaptive mesh refinement applications.

3.2.2 Related Modeling and Research Efforts

We also evaluated some related modeling options, such as a control-volume approach for the nonhydrostatic equations with a floating Lagrangian coordinate in the vertical direction (Chen et al. 2013), adaptive Lagrangian particle methods for global atmospheric flows (Bosler et al. 2014) and an 'incremental-remap'-based semi-Lagrangian algorithm (Ullrich et al. 2013, 2014a). Furthermore, the PI wrote two book chapters that discuss the diffusion and filtering mechanisms for dynamical cores (Jablonowski and Williamson 2011) as well as the future design of next-generation dynamical cores (Côté et al. 2015).

3.2.3 Relationship between the UM Model Hierarchy and Chombo

All algorithmic developments were done in preparation for the Chombo implementation and informed the design of today's Chombo-AMR model. In particular, the former UM Ph.D. student Dr. Paul Ullrich is now a faculty member at the University of California (UC) Davis and holds a courtesy appointment at LBNL (since 9/2012), which ensures that our extensive experience with MCore infuses the Chombo-AMR model design. The UM Ph.D. student Jared Ferguson has continued our close collaboration with LBNL since 9/2012. The mapped cubed-sphere multiblock extensions of the Chombo AMR library became first available in the 2011-2012 time frame (Colella et al. 2011; McCorquodale et al. 2015a). These library extensions were developed by our LBNL project partners and enabled the UM-LBNL team to test the first 2D advection tests with Chombo on the uniform-resolution cubed-sphere grid in late 2012. The fourth-order finite-volume implementation of the Chombo shallow water model followed in 2013, and was first tested in an adaptive mode from late 2013 onwards (Ferguson et al. 2014a,b; Jablonowski et al. 2014). Meanwhile, two shallow water journal publications are in press or in preparation (Ferguson et al. 2015; McCorquodale et al. 2015b).

These 2D Chombo model developments were accompanied by 3D adaptive advection tests that were paired with moisture and a large-scale condensation scheme (Benedict et al. 2014a,b). The latter effort was led by our LBNL project partners. In addition, our LBNL partner led the development of the first 3D prototype nonhydrostatic Chombo-AMR model (August 2014, E. English). An example simulation of this configuration is shown in Fig. 7 which displays a snapshot of a non-rotational gravity wave test (DCMIP test case 3-1, see also Ullrich et al. (2012) and subsection 3.4). One refinement level with a 2:1 refinement ratio is used that tracks the strong gradient regions of the propagating potential temperature perturbations (in color, red warm, blue cold). The simulation uses 10 vertical levels that are projected along the equator in the local upward direction. However, as mentioned in subsection 3.1.6 the 3D Chombo-AMR code was computationally inefficient which prevented further investigations such as the coupling to a moist physics package. Currently, the software is being refactored to optimize for computational speed and efficiency. We expect to have a vastly improved 3D nonhydrostatic version by the end of the 2015 calendar year, which will allow more advanced studies in the 2016 time frame. The 3D nonhydrostatic model is also scheduled to participate in the upcoming DCMIP-2016 dynamical core model intercomparison event which will take place from June/6-17/2016 at NCAR. DCMIP-2016 is a successor project of the highly successful DCMIP-2012 event that the PI led (see also subsection 3.4). The PI is again an organizer of DCMIP-2016, which will feature new dynamical core test cases with simplified moist physics and chemistry interactions.

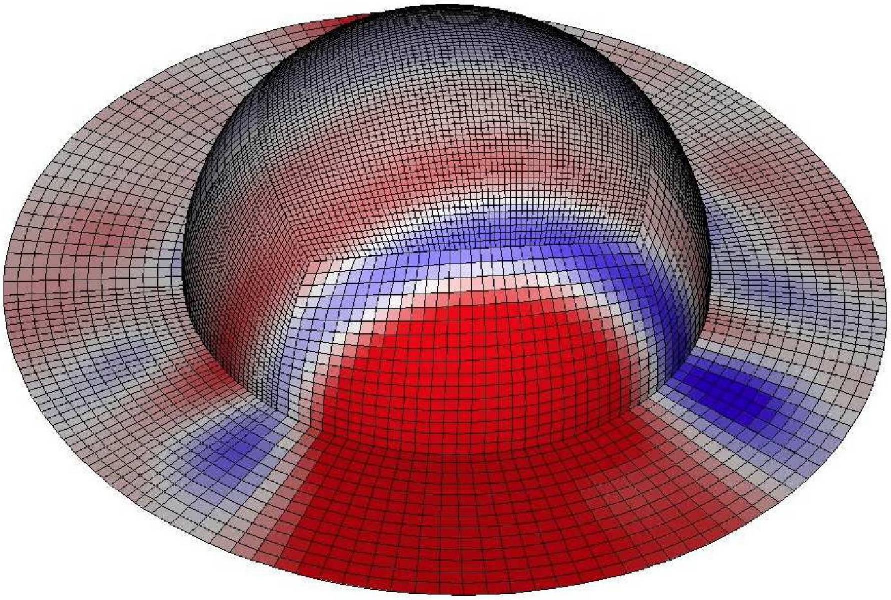


Figure 7: DCMIP gravity wave test case 3-1 conducted with the 3D Chombo-AMR model. One refinement level is used that tracks the strong gradient regions of the propagating potential temperature perturbations (in color, red warm, blue cold). The simulation uses 10 vertical levels that are projected along the equator in the local upward direction (figure generated by E. English).

3.2.4 Products

Journal Articles and Book Chapters

- **Côté et al. (2015)**
  Côté, J., C. Jablonowski, P. Bauer and N. Wedi (2015), Numerical Methods of the Atmosphere and Ocean, in: Brunet, G., S Jones and P. M. Ruti (Eds.), Seamless Prediction of the Earth System: from Minutes to Months, World Meteorological Organization (WMO) No. 1156, Geneva, available at
  `http://library.wmo.int/pmb_ged/wmo_1156_en.pdf`
- **Ullrich et al. (2014a)** Ullrich, P. A., C. Jablonowski and P. H. Lauritzen (2014), A high-order ‘incremental-remap’-based semi-Lagrangian shallow water model, International Journal for Numerical Methods in Fluids, Vol. 75, 103-133
- **Ullrich et al. (2013)**
  Ullrich, P. A., P. H. Lauritzen and C. Jablonowski (2013), Some considerations for high-

order 'incremental remap'-based transport schemes: edges, reconstructions and area integration, International Journal for Numerical Methods in Fluids, Vol. 71, 1131-1151

- **Chen et al. (2013)**
  Chen, X., N. Andronova, B. Van Leer, J. E. Penner, J. P. Boyd, C. Jablonowski and S.-J. Lin (2013), A Control-Volume Model of the Compressible Euler Equations with a Vertical Lagrangian Coordinate, Mon. Wea. Rev., Vol. 141, 2526-2544
- **Ullrich and Jablonowski (2012a)**
  Ullrich, P. A. and C. Jablonowski (2012b), MCore: A Non-hydrostatic Atmospheric Dynamical Core Utilizing High-Order Finite-Volume Methods, J. Comput. Phys., Vol. 231, 5078-5108
- **Ullrich and Jablonowski (2012b)**
  Ullrich, P. A. and C. Jablonowski (2012a), Operator-Split Runge-Kutta-Rosenbrock Methods for Nonhydrostatic Atmospheric Models, Mon. Wea. Rev., Vol. 140, 1257-1284
- **Jablonowski and Williamson (2011)**
  Jablonowski, C. and D. L. Williamson (2011), The Pros and Cons of Diffusion, Filters and Fixers in Atmospheric General Circulation Models, In: Lauritzen, P. H., C. Jablonowski, M. A. Taylor, R. D. Nair (Eds.), Numerical Techniques for Global Atmospheric Models, Lecture Notes in Computational Science and Engineering, Springer, Vol. 80, 381-493, download at `http://aoss-research.engin.umich.edu/groups/admg/springer_book_chapter_jablonowski_2011.pdf`
- **Lauritzen et al. (2011)**
  Lauritzen, P. H., C. Jablonowski, M. A. Taylor and R. D. Nair (Eds.) (2011), Numerical Techniques for Global Atmospheric Models, Lecture Notes in Computational Science and Engineering, Springer, Vol. 80, 556 pp., also available as an e-book, more details at `http://www.springer.com/us/book/9783642116391`
- **Ullrich et al. (2010)**
  Ullrich, P. A., C. Jablonowski and B. van Leer (2010), High-order finite-volume methods for the shallow-water equations on the sphere, J. Comput. Phys., Vol. 229, 6104-6134

Conference and Seminar Presentations

1. Bosler, P., R. Krasny and C. Jablonowski, Lagrangian particle methods for global atmospheric flow, oral presentation at the 2014 Partial Differential Equations on the Sphere (PDEs on the Sphere) Workshop, Boulder, CO, USA, April 7-11, 2014
2. Bosler, P. A., C. Jablonowski and R. Krasny, Particle Methods for Geophysical Flow on the Sphere, oral presentation at the Workshop on the Solution of Partial Differential Equations on the Sphere, Cambridge, U.K., September 24-28, 2012
3. Bosler, P. A., R. Krasny and C. Jablonowski, Particle Methods for Geophysical Flow on the Sphere, poster presentation at the 2012 SIAM Annual Meeting, Minneapolis, MN, USA, July 9-13, 2012
4. Ullrich, P. A. and C. Jablonowski, MCore: A High-Order Finite-Volume Dynamical Core for Atmospheric General Circulation Models, oral presentation at the AGU Fall Meeting 2011, Abstract A41G-07, San Francisco, CA, USA, December 5-9, 2011
5. Jablonowski, C. and P. A. Ullrich, A High-Order Finite-Volume Scheme for the Dynamical Core of Weather and Climate Models, Invited poster presentation at the Scientific Discovery

through Advanced Computing Program (SciDAC) Conference, Denver, CO, USA, July 10-14, 2011

6. Ullrich, P. A. and C. Jablonowski, MCore: A High-Order Finite-Volume Dynamical Core, Poster presentation at the 16th Annual CCSM Workshop, Breckenridge, CO, USA, June 20-23, 2011
7. Jablonowski, C., P. A. Ullrich and K. A. Reed, Tackling the numerical challenges of future-generation climate models: High-order methods, nonhydrostatic designs, variable-resolution and cubed-sphere grids, and how to test models, Invited presentation at the Institute for Mathematics and Its Applications (IMA), Workshop 'Societally Relevant Computing', Minneapolis, MN, USA, April 11-15, 2011
8. Jablonowski, C., P. A. Ullrich, A High-Order Finite-Volume Scheme for the Dynamical Core of Weather and Climate Models, Poster presentation at the Institute for Mathematics and Its Applications (IMA), Workshop 'Societally Relevant Computing', Minneapolis, MN, USA, April 11-15, 2011
9. Bosler, P. A., R. Krasny and C. Jablonowski, A Lagrangian Particle Method for Scalar Transport on the Sphere, oral presentation at the Workshop on Transport Schemes on the Sphere, National Center for Atmospheric Research (NCAR), Boulder, CO, USA, March 30-31, 2011
10. Ullrich, P. A. and C. Jablonowski, A Family of High-Order Finite-Volume Schemes for Simulating Atmospheric Flows, SIAM Conference on Mathematical and Computational Issues in the Geosciences, Long Beach, CA, USA, March 21-24, 2011
11. Jablonowski, C. and P. A. Ullrich, A High-Order Finite-Volume Technique for Nonhydrostatic Dynamical Cores on (Adaptive) Cubed-Sphere Grids, Invited presentation at the NCAR/UKMO/NCAS Workshop on Next Generation Weather and Climate Models, Boulder, CO, USA, 7-9 March 2011
12. Ullrich, P. A. and C. Jablonowski, A look at high-order Finite-Volume schemes for simulating atmospheric flows, oral presentation at the AGU Fall Meeting 2010, Abstract A41G-07, San Francisco, CA, USA, December 13-17, 2010
13. Ullrich, P. A. and C. Jablonowski, High-order finite-volume schemes for simulating atmospheric flows, poster presentation at the UM 2010 CoE Graduate Engineering Symposium, Ann Arbor, MI, USA, November 12, 2010
14. Ullrich, P. A. and C. Jablonowski, A look at high-order Finite-Volume schemes for simulating atmospheric flows, Oral presentation at the Workshop on Partial Differential Equations on the Sphere, Potsdam, Germany, August 24-27, 2010
15. Jablonowski, C., The Design of Future-Generation Dynamical Cores and GCMs, Invited presentation at the IPAM Culminating Workshop, Lake Arrowhead, CA, USA, June 7-11, 2010
16. Jablonowski, C. and P. A. Ullrich, An Analysis of Finite-Volume schemes: High-order Methods and Grid Reflections on Adaptive Grids, Invited oral presentation at the NSF Institute for Pure and Applied Mathematics (IPAM), Workshop II: Numerical Hierarchies for Climate Modeling, Los Angeles, CA, USA, April 16, 2010
17. Ullrich, P. A. and C. Jablonowski, High-Order Finite-Volume Methods for Geophysical Flow Problems, Poster presentation at the NSF Institute for Pure and Applied Mathematics (IPAM), Workshop II: Numerical Hierarchies for Climate Modeling, Los Angeles, CA, USA, April 12, 2010

Related Web Sites and Online Resources

- Web page of the 2014 Partial Differential Equations (PDEs) on the Sphere Conference in Boulder, CO: https://www2.cgd.ucar.edu/events/workshops/pdes2014
- Web page of the 2012 Partial Differential Equations (PDEs) on the Sphere Conference in Cambridge, U.K.: http://www.newton.ac.uk/event/ammw02
- Web page of the 2010 Partial Differential Equations (PDEs) on the Sphere Conference in Potsdam, Germany: http://www.awi-potsdam.de/pde2010/pdes2010
- Projects of the University of Michigan Atmospheric Dynamics Modeling Group: http://aoss-research.engin.umich.edu/groups/admg/projects.php

Fostered Networks and Collaborations

- The PDEs on the Sphere conferences foster lively interactions among atmospheric dynamical core developers, provide excellent networking opportunities and are a platform for emerging research themes like high-order numerical methods and AMR. The PI and her students are regular attendees and presenters at the PDEs conferences.

Other Products Including Audio, Video and Educational Tools

- Web site for the 'Art of Climate Modeling' course at UM, taught in the Fall 2013: https://sites.google.com/a/umich.edu/aoss589-f13/
- Presentations from the 2014 PDEs on the Sphere conference (presentation files): https://www2.cgd.ucar.edu/events/workshops/pdes2014/presentations
- Recorded presentations from the 2012 PDEs on the Sphere conference (audio & video & presentation files): http://www.newton.ac.uk/event/ammw02/seminars
- All recorded lectures from DCMIP-2012 (audio & video & presentation files): https://www.earthsystemcog.org/projects/dcmip-2012/lectures

3.3 The Physics-Dynamics Interplay

In atmospheric modeling, sub-grid scale processes that remain unresolved by chosen uniform grid resolutions are parameterized to take their average effect on the resolvable features into account. Generally, these parameterizations are grid-dependent although the scale of the grid box is not explicitly accounted for in physical packages. However, since the parameterizations are calculated for individual grid boxes, the scale of the forcing decreases with increasing horizontal mesh resolution. This raises questions concerning the convergence of model results. For example, an increase in resolution does not necessarily lead to improved model predictions due to complex, nonlinear interactions between the dynamics and physics packages (Williamson 1999). An increase in resolution might even increase the sensitivity to errors in the modeled physical processes that can decrease the overall forecast quality. Therefore, the physics-dynamics interactions must be re-examined when demanding that they function reliably over a wide range of grid scales.

3.3.1 Physics-Dynamics Coupling Workshop

As envisioned in the original proposal, this research project supported a variety of investigations that shed light on the physics-dynamics interplay. Most recently, the PI was a co-organizer of the "Physics-Dynamics Coupling Workshop" in December 2014, that brought together the international GCM modeling community (Gross et al. 2015). This workshop discussed a broad range of physics-dynamics coupling issues, such as the development of idealized moist test cases (Thatcher and Jablonowski 2015) to reveal the intricacies of the coupling, convergence studies with respect to reduced physics time steps in the model CAM5-SE (Wan et al. 2015), process-split versus time-split coupling strategies (Williamson 2002), varying computational grids for the dynamics and physics processes, the consistency of the GCM equations and built-in model assumptions, the theory behind the coupling, and the sensitivity of the CAM4 and CAM5 physical parameterization packages (Neale et al. 2010b,a) to variable-resolution grids in CAM-SE aquaplanet configurations (Zarzycki et al. 2014b).

3.3.2 Idealized Tests of the Physics-Dynamics Coupling

An example of our physics-dynamics assessments is shown in Fig. 8 that highlights our contributions to a new set of moist idealized test cases. As explained in Thatcher and Jablonowski (2015)

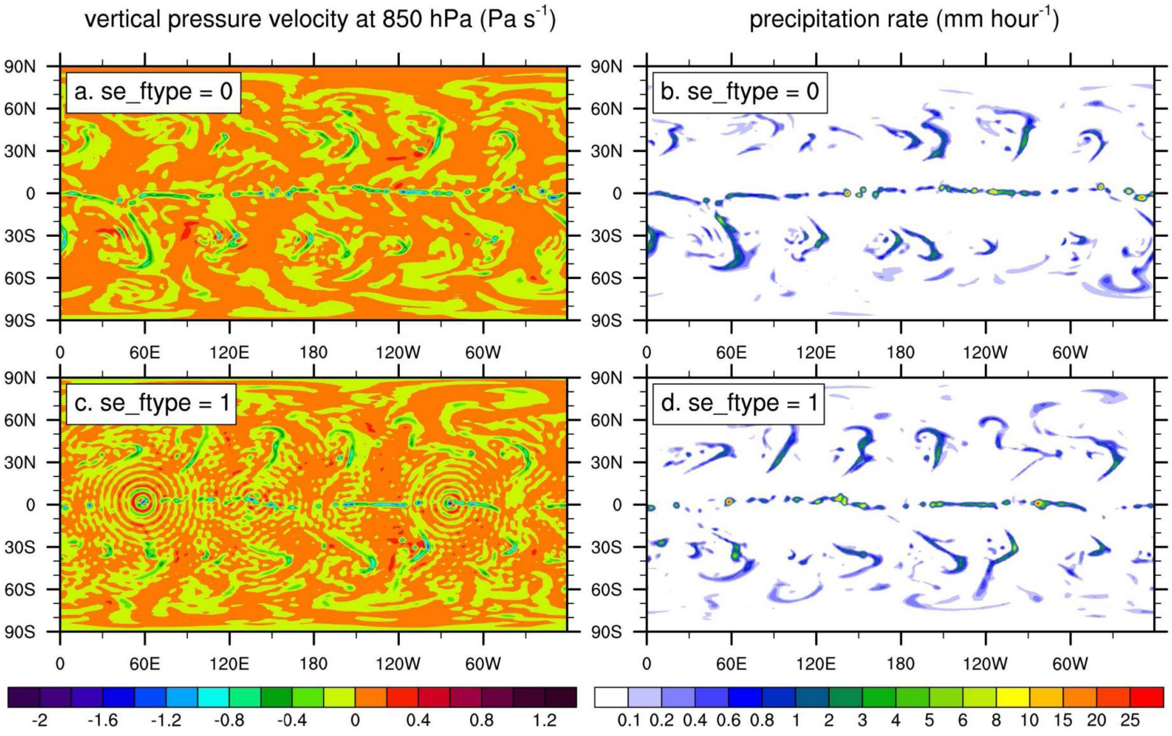


Figure 8: Demonstration of physics-dynamics coupling issues in the model CAM5-SE with two different coupling options se_ftype=0 (gradual physics adjustments) and se_ftype=1 (sudden physics adjustments). Left: instantaneous snapshots of the 850hPa vertical pressure velocity field and (right) the corresponding large-scale precipitation rates. The simulations follow the Thatcher and Jablonowski (2015) test protocol.

the new test is built upon the simple-physics package by Reed and Jablonowski (2012) and the dry dynamical core test by Held and Suarez (1994). It incorporates surface fluxes of latent and sensible heat as well as momentum, boundary-layer mixing, large-scale precipitation and a thermal temperature relaxation which mimics radiation. Such a configuration allows the analysis of the physics-dynamics interplay without the complexity of a complex physical parameterization package.

Figure 8 shows some randomly selected snapshots of the 850hPa vertical pressure velocity field (left) and the corresponding large-scale precipitation rates (right) in the model CAM5-SE. Two physics-dynamics coupling options are investigated with the Thatcher and Jablonowski (2015) test protocol which are a sudden adjustment of the prognostic variables (se_ftype=1) after each long physics time step (1800 s), and a gradual application of the physical forcing tendencies (se_ftype=0) at each sub-cycled dynamics time step (300 s). As shown in Fig. 8c the sudden application of the physical forcings (se_ftype=1) leads to large-scale, circular gravity waves in the tropical regions that are co-located with grid-scale precipitation extremes (so-called grid-point storms) along the equator (Fig. 8d). These undesirable gravity waves are remedied when changing the physics-dynamics coupling strategy. In case of se_ftype=0 the physical forcing tendencies are transferred to the dynamical core and applied gradually during the dynamics sub-cycling steps. Despite the presence of grid-point storms in Fig. 8b, the 850 hPa vertical pressure velocity is now free of spurious gravity wave oscillations (Fig. 8a) and shows a physically plausible and consistent flow field.

3.3.3 Scale-Aware Physical Parameterizations and Physics Sensitivities

In addition, we also paid special attention to the behavior of CAM's deep convection parameterization under grid refinement and different physics time steps (Reed et al. 2012), and investigated the sensitivity of tropical cyclones to the design of the deep convection parameterization in CAM3 and CAM4 (Reed and Jablonowski 2011a). Furthermore, we assessed the impact of a new planetary boundary layer parameterization and new shallow convection & macrophysics scheme, called Cloud Layers Unified By Binormals or CLUBB (Golaz et al. 2002; Bogenschutz et al. 2012), on tropical cyclones in ultra-high resolution configurations of CAM5-SE with variable-resolution grid spacings down to 14 km (Zarzycki and Jablonowski 2015). CLUBB promises to be scale-adaptive. We thereby shed light on the convergence properties and uncertainty of the model simulations. The general challenge, that is faced by all variable-resolution models, is the lack of scale-aware physical parameterizations that adjust their response correctly with decreasing grid sizes. This was recently discussed by Jablonowski et al. (2015) and the UM group pursues further research into the scale-awareness of cloud schemes. Once the 3D nonhydrostatic Chombo-AMR model is coupled to moist processes, all of these newly developed physics-dynamics analysis techniques will be directly applicable to the Chombo model.

3.3.4 Products

Journal Articles

- **Thatcher and Jablonowski (2015)**
  Thatcher, D. R. and C. Jablonowski (2015), A moist aquaplanet variant of the Held-Suarez

test for atmospheric model dynamical cores, Geoscientic Model Development Discussions, submitted

- **Gross et al. (2015)**
  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
- **Wan et al. (2015)**
  Wan, H., P. J. Rasch, M. A, Taylor and C. Jablonowski (2015), Short-term time step convergence in a climate model, J. Adv. Model. Earth Syst., Vol 7, 215-225, doi:10.1002/2014MS000368
- **Zarzycki et al. (2014b)**
  Zarzycki, C. M., M. N. Levy, C. Jablonowski, M. A. Taylor, J. R. Overfelt and P. A. Ullrich (2014), Aquaplanet Experiments Using CAM's Variable Resolution Dynamical Core, J. Climate, Vol. 27, 5481-5503
- **Reed et al. (2012)**
  Reed, K. A., C. Jablonowski and M. A. Taylor (2012), Tropical Cyclones in the Spectral Element Configuration of the Community Atmosphere Model, Atm. Sci. Lett., 13, 303-310, doi:10.1002/asl.399
- **Reed and Jablonowski (2011a)**
  Reed, K. A. and C. Jablonowski (2011b), Impact of physical parameterizations on idealized tropical cyclones in the Community Atmosphere Model, Geophys. Res. Lett., Vol. 38, L04805

Conference and Seminar Presentations

1. 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
2. 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
3. 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
4. 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
5. 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
6. 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 pre-

sentation at the Department of Energy (DoE) Principal Investigator Meeting, Potomac, MD, USA, May 12-14, 2014

7. 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
8. 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
9. 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
10. 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
11. Reed, K. A. and C. Jablonowski, Assessing the uncertainty of tropical cyclone simulations in GCMs, Poster presentation at the 3rd International Summit on Hurricanes & Climate Change, Rhodes, Greece, June 27-July 2, 2011
12. Reed, K. A. and C. Jablonowski, Role of the convection parameterization in AGCM simulations of idealized tropical cyclones, Poster presentation at the COST Water Vapor in the Climate System Winter School, Venice, Italy, February 6-12, 2011
13. Reed, K. A. and C. Jablonowski, Assessing the Significance of Varying AGCM Physics Packages on Idealized Tropical Cyclone Simulations, poster presentation at the AGU Fall Meeting 2010, Abstract A23A-0214, San Francisco, CA, USA, December 13-17, 2010
14. Reed, K. A. and C. Jablonowski, Idealized tropical cyclones in atmospheric general circulation models: sensitivity to convective parameterizations, Oral presentation at 29th AMS Conference on Hurricanes and Tropical Meteorology, Tucson, USA, AZ, May 14, 2010

Related Web Sites and Online Resources

- Web site of the Physics-Dynamics Coupling (PDC-14) Workshop, Dec. 2014:
  `http://usuario.cicese.mx/~mgross/2014workshop/`

Fostered Networks and Collaborations

- The research project fostered new collaborations with international colleagues from the U.K. Met Office, the European Centre for Medium-Range Weather Forecasts (ECMWF), U.K. and the Ensenada Center for Scientific Research and Higher Education (Mexico) which led to the organization of the first 'Physics-Dynamics Coupling (PDC-14) Workshop' in Dec. 2014, and the publication of a journal article in the Bulletin of the American Meteorological Society. The successor workshop PDC-16 will take place at DoE's Pacific Northwest Research Laboratory (PNNL) in September 2016.

Other Products Including Audio, Video and Educational Tools

- Physics-Dynamics Coupling Workshop – videos of the talks and presentation files: http://usuario.cicese.mx/~mgross/2014workshop/program_day_by_day.html
- Recorded presentation on ’Evaluating the impact of the CAM 5 dynamical core in idealized tropical cyclone simulations’ by Kevin Reed, 92nd AMS Annual Meeting and 24th Conference on Climate Variability and Change, https://ams.confex.com/ams/92Annual/webprogram/Paper196680.html
- Recorded presentation on ’Structural Uncertainty of Tropical Cyclone Simulations in General Circulation Models’ by Christiane Jablonowski, 30th AMS Conference on Hurricanes and Tropical Meteorology, https://ams.confex.com/ams/30Hurricane/webprogram/Paper206217.html
- Recorded presentation on ’Idealized tropical cyclones in atmospheric general circulation models: sensitivity to convective parameterizations’ by Kevin Reed, 29th AMS Conference on Hurricanes and Tropical Meteorology, https://ams.confex.com/ams/29Hurricanes/techprogram/paper_168038.htm

3.4 Evaluating the Model Hierarchies

Thorough model evaluations are the key to an improved understanding of the multi-scale interactions in variable-resolution models. They are also paramount to checking the correctness and convergence properties of variable-resolution models. As outlined in the original proposal our evaluation methods are split into two parts: the 2D shallow-water assessments and the 3D dynamical core tests. This split reflects our hierarchical approach to the modeling effort and ensures the quality of each milestone. As proposed, we tested our variable-resolution cubed-sphere modeling approaches with the following suite of test cases. Each test family covered unique scientific and numerical modeling aspects and varies in complexity.

3.4.1 Shallow Water and 2D Advection Tests

As mentioned earlier, the 2D shallow water system addresses the majority of the modeling challenges that are associated with the temporal and horizontal discretization techniques in spherical geometry. These include the choice of the horizontal grid, the treatment of high-speed gravity waves, numerical dispersion and the stability of the numerical scheme. Within the climate modeling community, any novel numerical methodology will not be widely accepted unless it successfully passes the standard shallow water test suite by Williamson et al. (1992). It comprises the advection of a cosine bell, a global steady-state nonlinear geostrophic flow, the zonal flow over an isolated mountain and a Rossby-Haurwitz wave. All tests describe large-scale flow fields with various degrees of challenges for the numerical scheme and adaptive mesh refinement configurations. In addition, we have assessed the Chombo-AMR and UM shallow water models with the barotropic instability test by Galewsky et al. (2004) as shown in Ullrich et al. (2010) and McCorquodale et al.

(2015b), the unsteady solid body rotation test by Läuter et al. (2005) depicted in Fig. 5, the deformational flow advection test (Lauritzen and Thuburn 2012; Lauritzen et al. 2014), and the rotating vortices advection test by Nair and Jablonowski (2008) with prescribed wind speeds.

The Chombo-AMR results of the Nair and Jablonowski (2008) test are displayed in Fig. 9 (see also Ferguson et al. (2015)). The figure shows four snapshots (day 0, 4, 8, 12) of a 12-day time series which are characterized by a rotating and propagating tracer field (in color). These tracer vortices have analytical solutions so that the accuracy of the results can be exactly measured. The wind field transports the rotating tracer along the equator once around the sphere in 12 days. During these 12 days the evolving strong gradients of the tracer field are tracked by a gradient AMR threshold which places new adaptive blocks where needed for accuracy. In particular, two refinement levels with a 1:4 refinement ratio are used (c32/c128/c512) that correspond to the actual grid spacings between 313 km in the coarsest blocks to about 20 km in the finest blocks. The black lines represent the block outlines of the three resolution levels which all contain additional grid points within the blocks (not shown for clarity). This Chombo-AMR example demonstrates that the adaptive blocks reliably track the evolving feature with high resolution which significantly improves the solution accuracy (Ferguson et al. 2015). Furthermore, computational resources are saved since the fine resolution is not needed in domains with smooth tracer gradients. We note that the stripes near the North and South Poles are visualization artifacts and do not indicate a modeling problem.

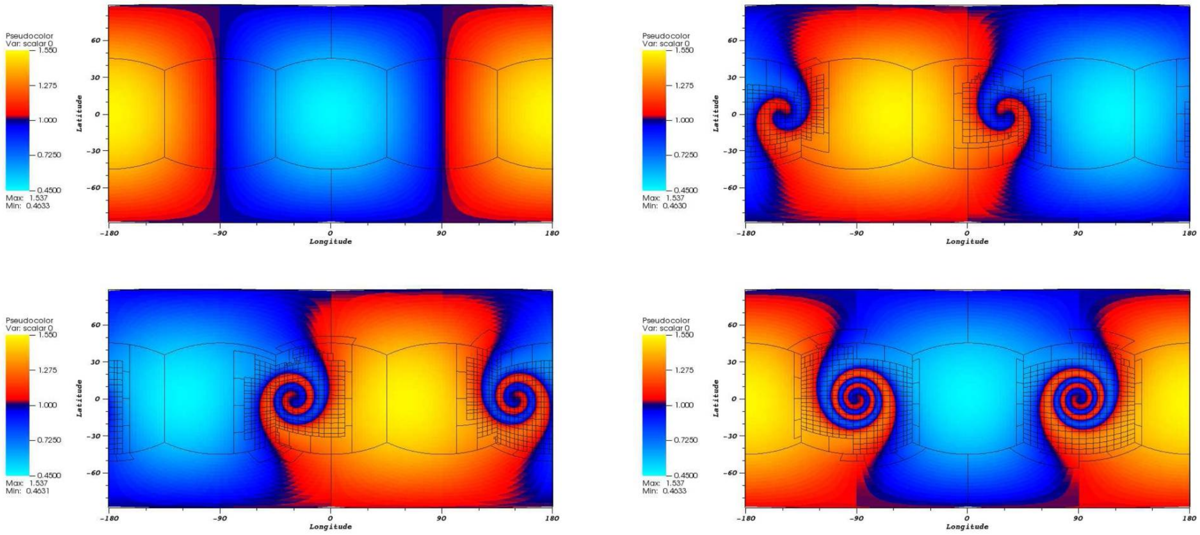


Figure 9: Example of a 2D shallow water advection test case (Nair and Jablonowski 2008) that is characterized by evolving and propagating vortices. The figure shows the Chombo-AMR model results at (top) day 0 and 4 and (bottom) day 8 and 12. The tracer (in color) propagates along the equator around the sphere in 12 days and develops sharp gradients that are tracked by the adaptive meshes. The adapted blocks with two refinement levels are overlaid in black. The stripes near the poles are visualization artifacts.

3.4.2 2D Nonhydrostatic Assessments

As proposed, we used the classical non-hydrostatic 2D vertical slice test cases like the warm bubble experiment (Robert 1983), density currents (Straka et al. 1993), and the hydrostatic & nonhydrostatic mountain waves (Dudhia 1993; Schär et al. 2002) for the evaluation of our fourth-order nonhydrostatic finite-volume model in Cartesian geometry (Ullrich and Jablonowski 2012b). In addition, we developed and documented a new 3D steady-state and baroclinic wave test case for Cartesian channel models that is based upon analytical initial data (Ullrich and Jablonowski 2012b; Ullrich et al. 2015).

3.4.3 3D Dynamical Core Tests With and Without Moisture

As proposed, we assessed all 3D hydrostatic and non-hydrostatic dynamical cores with a comprehensive test suite without and with the Earth's rotation. This hierarchy of test cases with increasing complexity includes

- three newly-developed 3D advection tests with prescribed wind speeds (Kent et al. 2014) that are a 3D deformational flow, a Hadley-cell-like flow and a zonal flow in the presence of mountains with transported cloud-like tracer fields
- new mountain gravity wave tests on a reduced-size planet without the Earth's rotation (DCMIP test cases 2-X, see Ullrich et al. (2012) and Klemp et al. (2015))
- a new gravity wave test on a reduced-size planet without the Earth's rotation (DCMIP test cases 3-1, see Ullrich et al. (2012); Ullrich and Jablonowski (2012a))
- baroclinic waves for both shallow-atmosphere (Jablonowski and Williamson 2006; Lauritzen et al. 2010; Ullrich et al. 2014b) and deep-atmosphere equation sets (Ullrich et al. 2014b)
- an idealized tropical cyclone vortex initailization technique without a background flow (Reed and Jablonowski 2011a) and with a background flow (He et al. 2015)
- wavenumber four Rossby-Haurwitz waves
(Jablonowski et al. 2008; Ullrich and Jablonowski 2012a)
- and mountain-induced Rossby waves (Jablonowski et al. 2008; Ullrich and Jablonowski 2012a).

A selection of these test cases is highlighted in Ullrich and Jablonowski (2012a) who used them for the thorough evaluations of the nonhydrostatic fourth-order finite-volume model MCore on the cubed-sphere grid.

In addition, the PI and her team developed two simplified physical parameterization packages for short-term and long-term moist dynamical core assessments in an aqua-planet mode. The long-term idealized climate and physics-dynamics coupling studies were conducted with the approach by Thatcher and Jablonowski (2015) that was mentioned earlier in subsection 3.3.2 and Fig. 8. The short-term deterministic studies with the Reed and Jablonowski (2012) "simple-physics" package focused on the evolution of moist baroclinic waves (DCMIP test cases 4-2 and 4-3, see Ullrich et al. (2012)) and the evolutions of idealized tropical cyclones (Reed and Jablonowski 2012). We also paired the Reed and Jablonowski (2011a) idealized tropical cyclone initialization technique with the complex CAM5 physics package and tested the evolution of tropical cyclones in the variable-resolution model CAM5-SE (Zarzycki et al. 2014a). This analysis shed light on the physical properties of tropical cyclones that enter or leave a high-resolution area, and furthermore provided information about potential wave reflection issues at refinement boundaries. In addition, the adequacy and scale-awareness of the physical parameterizations for tropical cyclone studies is revealed at the varying resolutions. For example, it is shown in Zarzycki and Jablonowski (2014, 2015) that tropical cyclones have the tendency to over-intensify in CAM5-SE at grid spacings between 14-28 km which points to deficiencies in the physical parametrizations.

3.4.4 Dynamical Core Model Intercomparison Project (DCMIP)

As outlined in the original proposal (year 3 activity in the management plan), this research project played a fundamental role in the international Dynamical Core Model Intercomparison Project in 2012 (DCMIP-2012) that the PI led. In particular, DCMIP accelerated the development of new dynamical core test cases that have the potential to become the new community standard. A snapshot of the DCMIP model intercomparison is provided in Fig. 10 that shows the results of the 3D deformational-flow advection test that furthermore transports the tracer once around the sphere over the course of 12 days (DCMIP test 1-1, described in Kent et al. (2014)). The 3D wind speeds are prescribed which stretch the tracer $q1$ with an initially spherical shape over a time period of 6 days. Then the flow reverses and the tracer fields should return to their original shape and position which serve as the analytical solution at day 12. In Fig. 10, the horizontal cross sections at a height of 4.9 km show the q_1 tracer fields of 12 different DCMIP dynamical cores at day 6 when they are stretched to their maximum. These tracer distributions thereby give insight into the numerical characteristics of the advection algorithms. The dark blue areas denote numerical undershoots that were not controlled by a monotonicity or positive-definite constraint. In addition, the color intensity in the red color regime provides information about the

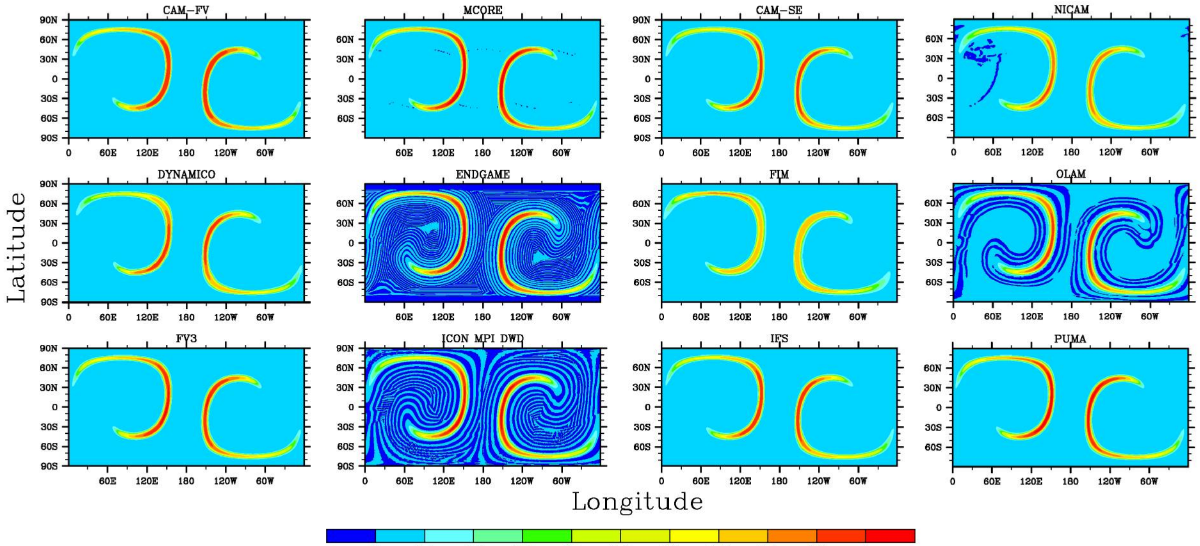


Figure 10: Snapshot of the DCMIP 1-1 tracer advection test with a deformational flow field (Kent et al. 2014). The horizontal cross sections of the tracer field is shown for 12 different dynamical cores at a height of 4.9 km at model day 6. The dark blue areas show numerical undershoots.

diffusive properties of the advection schemes and potential overshoots. Other objective accuracy measures, such as the consistency between two correlated tracers, were also assessed as part of the DCMIP comparisons as e.g. shown in Kent et al. (2014), Hall et al. (2015) and on the DCMIP web site `https://www.earthsystemcog.org/projects/dcmip-2012/Test_Cases/results_by_model`.

3.4.5 Open Model Assessment Tasks

Due to the delayed 3D nonhydrostatic Chombo-AMR model developments mentioned in subsection 3.1.6 we were not yet able to couple the Chombo-AMR model to a moist physics package or a mixed-layer ocean model as originally proposed. These development steps are currently ongoing, and our LBNL partners are in the process of preparing the Chombo software for the "System for Atmospheric Modeling" (SAM) physics package (see Khairoutdinov and Randall (2003) and `http://rossby.msrc.sunysb.edu/~marat/SAM.html`). So far, only the 3D Chombo advection code with a moisture tracer has been coupled to a large-scale condensation scheme and was tested for a Hadley-cell-like prescribed flow field by Benedict et al. (2014a,b). Once the 3D Chombo-AMR model matures, these open model assessment and coupling tasks will be completed which will enable us to conduct further, more advanced tests of the Chombo-AMR approach and the science applications. Nevertheless, we completed all open tasks with the alternative variable-resolution cubed-sphere model CAM5-SE that we tested extensively in a coupled mode with an interactive land model, a prescribed data ocean, and a mixed-layer model model (Zarzycki et al. 2014a,b; Zarzycki and Jablonowski 2014; Zarzycki et al. 2015; Zarzycki and Jablonowski 2015).

3.4.6 Products

Journal Articles and Technical Reports

- **Hall et al. (2015)**
  Hall, D. M., P. A. Ullrich, K. A. Reed, C. Jablonowski, R. D. and H. M. Tufo (2015), Dynamical Core Model Intercomparison Project (DCMIP) Tracer Transport Test Results for CAM-SE, Quart. J. Roy. Meteorol. Soc., in review
- **Ullrich et al. (2015)**
  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., in press
- **He et al. (2015)**
  He, F., D. J. Posselt, C. M. Zarzycki and C. Jablonowski (2015), A Balanced Tropical Cyclone Test Case for AGCMs with Background Vertical Wind Shear, Mon. Wea. Rev., Vol. 143, 1762-1781
- **Ullrich et al. (2014b)**
  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
- **Kent et al. (2014)**
  Kent, J., P. A. Ullrich and C. Jablonowski (2014), Dynamical Core Model Intercomparison Project: Tracer Transport Test Cases, Quart. J. Roy. Meteorol. Soc., Vol. 140, 1279-1293

- **Lauritzen et al. (2014)**
  Lauritzen, P. H., P.A. Ullrich, C. Jablonowski, P.A. Bosler, D. Calhoun, A.J. Conley, T. Enomoto, L. Dong, S. Dubey, O. Guba, A. B. Hansen, E. Kaas, J. Kent, J. F. Lamarque, M. J. Prather, D. Reinert, V. V. Shashkin, W. C. Skamarock, B. Srensen, M. A. Taylor, and M. A. Tolstykh (2014), A standard test case suite for two-dimensional linear transport on the sphere: results from a collection of state-of-the-art schemes, Geoscientific Model Development, Vol. 7, 105-145
- **Ullrich et al. (2012)**
  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, Technical Report, University of Michigan, download from `https://www.earthsystemcog.org/projects/dcmip-2012/test_cases`
- **Reed and Jablonowski (2012)**
  Reed, K. A. and C. Jablonowski (2012), Idealized tropical cyclone simulations of intermediate complexity: a test case for AGCMs, J. Adv. Model. Earth Syst., Vol. 4, M04001, doi:10.1029/2011MS000099
- **Reed and Jablonowski (2011a)**
  Reed, K. A. and C. Jablonowski (2011a), An Analytic Vortex Initialization Technique for Idealized Tropical Cyclone Studies in AGCMs, Mon. Wea. Rev., Vol. 139, 689-710
- **Lauritzen et al. (2010)**
  Lauritzen, P. H, C. Jablonowski, M. A. Taylor and R. D. Nair (2010), Rotated versions of the Jablonowski steady-state and baroclinic wave test cases: A dynamical core intercomparison, J. Adv. Model. Earth Syst., Vol. 2, Art. #15, 34 pp.

Conference and Seminar Presentations

1. 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
2. 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
3. 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
4. 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
5. 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

6. 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
7. 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
8. Thatcher, D., C. Jablonowski and C. Zarzycki (2013), 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
9. 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
10. 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
11. 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
12. 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
13. 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
14. 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
15. 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
16. 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
17. 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

18. 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
19. 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
20. Reed, K. A., C. Jablonowski and M.A. Taylor, Evaluating the Potential of CAM HOMME to Simulate Idealized Tropical Cyclones, Poster presentation at the 16th Annual CCSM Workshop, Breckenridge, CO, USA, June 20-23, 2011
21. Reed, K. A. and C. Jablonowski, Evaluating the impact of the CAM 5 dynamical core in idealized tropical cyclone simulations, Oral presentation at the AMS 91st Annual Meeting and 23rd Conference on Climate Variability and Change, Seattle, WA, USA, January 23-27, 2011
22. Jablonowski, C. and K. A. Reed, Idealized Tropical Cyclone Simulations of Intermediate Complexity: A Test Case for Atmospheric GCMs, oral presentation at the AGU Fall Meeting 2010, Abstract A41G-06, San Francisco, CA, USA, December 13-17, 2010
23. Reed, K. A. and C. Jablonowski, Evaluating the Impact of the CAM 5 Dynamical Core in Idealized Tropical Cyclone Simulations, poster presentation at the UM 2010 CoE Graduate Engineering Symposium, Ann Arbor, MI, USA, November 12, 2010
24. Jablonowski, C. and K. A. Reed, Complementing the Hierarchy of GCM Test Cases: Idealized Tropical Cyclone Simulations of Intermediate Complexity, Oral presentation at the Workshop on Partial Differential Equations on the Sphere, Potsdam, Germany, August 24-27, 2010
25. Jablonowski, C. and K. A. Reed, Evaluating the Impact of the GCM Dynamical Core in Idealized Tropical Cyclone Simulations, Oral presentation at the Workshop on High-Resolution Global Modeling, Fort Collins, CO, USA, June 15-17, 2010
26. Jablonowski, C. and K. A. Reed, Idealized Tropical Cyclones in Atmospheric General Circulation Models: The Impact of the Dynamical Core, Poster Presentation at the 29th AMS Conference on Hurricanes and Tropical Meteorology, Tucson, USA, AZ, May 13, 2010

Related Web Sites and Online Resources

- Web site for the international Dynamical Core Model Intercomparison Project (DCMIP) in 2012: `https://www.earthsystemcog.org/projects/dcmip-2012/`
- Web page of the 2012 Partial Differential Equations (PDEs) on the Sphere Conference in Cambridge, U.K., that features results from DCMIP-2012: `http://www.newton.ac.uk/event/ammw02`
- Web page of the 2014 Partial Differential Equations (PDEs) on the Sphere Conference in Boulder, CO: `https://www2.cgd.ucar.edu/events/workshops/pdes2014`
- Projects of the University of Michigan Atmospheric Dynamics Modeling Group: `http://aoss-research.engin.umich.edu/groups/admg/projects.php`

Fostered Networks and Collaborations

- The Dynamical Core Model Intercomparison Project in 2012 (DCMIP-2012) and associated 2-week summer school established international collaborations among the members of the atmospheric dynamical core modeling community.

Other Products Including Audio, Video and Educational Tools

- Web site for the ’Art of Climate Modeling’ course at UM, taught in the Fall 2013: `https://sites.google.com/a/umich.edu/aoss589-f13/`
- All recorded lectures from DCMIP-2012 (audio & video & presentation files): `https://www.earthsystemcog.org/projects/dcmip-2012/lectures`
- Recorded presentations from the 2012 PDEs on the Sphere conference (audio & video & presentation files) that feature results from DCMIP-2012: `http://www.newton.ac.uk/event/ammw02/seminars`
- Presentations from the 2014 PDEs on the Sphere conference (presentation files). Include a discussion, led by the PI, of the upcoming event DCMIP-2016 in June 2016: `https://www2.cgd.ucar.edu/events/workshops/pdes2014/presentations`
- Recorded presentation on ’Evaluating the impact of the CAM 5 dynamical core in idealized tropical cyclone simulations’ by Kevin Reed, 91st AMS Annual Meeting and 23rd Conference on Climate Variability and Change, `https://ams.confex.com/ams/91Annual/webprogram/Paper182549.html`

3.5 Grid Refinement Strategies

Setting the right criteria for grid refinements and coarsenings is very important to minimize the computational cost associated with adaptations. The ideal criteria are those that require minimum computational efforts to evaluate and still indicate the refinement and coarsening regions reliably. In case of dynamic refinements, two basic adaptation principles need to be distinguished, namely, the physical flow-based adaptation indicators and the mathematical local truncation error estimators. We focused on flow-based adaptation criteria which are predominantly used in adaptive grid applications. They typically rely on measures of a solution gradient, vorticity or curvature that are compared to user-defined and problem-dependent thresholds. In addition, assessments of the potential vorticity, divergence or instability indicators are feasible options for atmospheric AMR applications.

3.5.1 Analysis od Adaptation Criteria and Thresholds

As originally proposed we probed a variety of refinement options, both for static and dynamic adaptations. Among them are statically refined grids over the North Atlantic for tropical cyclone studies with the model CAM5-SE (Zarzycki et al. 2014a,b; Zarzycki and Jablonowski 2014; Zarzycki et al. 2015; Zarzycki and Jablonowski 2015), and flow-based criteria with the Chombo-AMR shallow water model (Ferguson et al. 2015). These are, in particular, a horizontal gradient criterion and relative vorticity criterion which we tested in the standard shallow water test #5. This is the mountain-generated Rossby wave test described in Williamson et al. (1992). A Chombo-AMR example of test case #5 is provided in Fig. 11 that shows the horizontal gradient and relative vorticity at day 15 in the top row. The bottom row displays the corresponding total height field (fluid height plus mountain height) with the overlaid adapted blocks. One level of refinement (c32/c128) with a refinement ratio 1:4 is used which corresponds to the grid spacings 313 km and 78 km, respectively. The width and position of the conical mountain is indicated by the circle. This

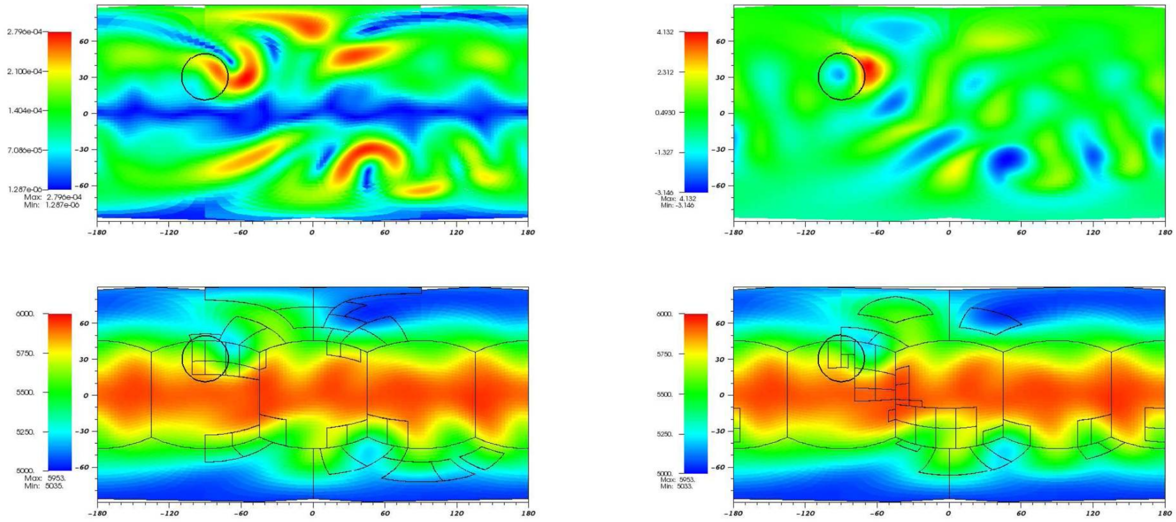


Figure 11: Comparison of different refinement criteria for the shallow water mountain test case 5. The mountain base is outlined by the circle. The top figures show the (left) horizontal gradient and (right) relative vorticity of the height field at day 15. The bottom figures depict the height field at day 15 with overlaid adapted blocks that were guided by (left) a gradient criterion and (right) a relative vorticity criterion.

comparison of the two refinement criteria shows that the general refinement regions are similar in the two simulations. They mostly focus their computational grids in the midlatitudinal Rossby wave regime in the southern hemisphere. In addition, the region in the lee of the mountain and patches in the northern midlatitudes are refined. The exact placement of the refinements differs somewhat, as expected, but both indicate the developing Rossby wave train reliably. We also experimented with different fixed threshold values and scaled threshold values in the Chombo-AMR shallow water model. The scaled threshold values adapt according to the refinement levels and are increased (become more restrictive) in the refined regions. These assessments are documented in Ferguson et al. (2015), and we will expand the analysis once the 3D Chombo-AMR model is mature.

3.5.2 Products

Journal Articles (also listed in Section 3.2.4)

- **Ferguson et al. (2015)**
  J. Ferguson, C. Jablonowski, H. Johansen, P. McCorquodale and P. Colella (2015), Assessing

the Chombo-AMR Adaptive Mesh Refinement approach for geophysical flows. Mon. Wea. Rev., in preparation

Conference and Seminar Presentations (these were also listed in Section 3.2.4)

1. Ferguson, J., C. Jablonowski, H. Johansen, P. McCorquodale and P. Colella, Assessing Adaptive Grid Refinement Techniques with the Chombo-AMR Model in Shallow Water Model, Poster Presentation at the 20th Annual CESM Workshop, Breckenridge, CO, USA, June 15-18, 2015
2. 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
3. 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
4. Ferguson, J., C. Jablonowski, H, Johansen, P. McCorquodale and P. Colella, Assessing Adaptive Grid Refinement Techniques with the Chombo-AMR Model in Shallow Water Model, Poster Presentation at the 2015 Michigan Geophysical Union (MGU) Meeting, Ann Arbor, MI, USA, April 1, 2015
5. 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
6. Ferguson, J., C. Jablonowski, H. Johansen, R. E. English, P. McCorquodale, P. Colella, J. Benedict, W. D. Collins, J. Johnson and P. A. Ullrich, Assessing Grid Refinement Strategies in the Chombo Adaptive Mesh Refinement Model, oral presentation at the American Geophysical Union (AGU) Fall Meeting 2014, Abstract A13M-06, San Francisco, CA, USA, December 15-19, 2014

3.6 Tropical Cyclone Process Studies: Multi-Scale Interactions and Variable-Resolution Modeling

Tropical cyclones exhibit multitudes of large-small-scale interactions that remain mostly unresolved at typical climate resolutions of about 100 km. This research project proposed using tropical cyclones as a demonstration tool to assess the fidelity of the AMR and variable-resolution simulations at the regional and even cloud-permitting scale. We assessed both ocean-basin simulations with static mesh adaptations in the model CAM5-SE and dynamically moving Chombo-AMR simulations that track the eye of a cyclone. The AMR mesh movements are guided by a relative vorticity refinement criterion.

3.6.1 Tropical Cyclone Assessments with the Variable-Resolution Model CAM5-SE

As originally proposed we have evaluated moist dynamical core configurations with variable-resolution grids using both realistic model setups with topography and observed sea surface temperatures (Zarzycki and Jablonowski 2014; Zarzycki et al. 2015; Zarzycki and Jablonowski 2015) and the simplified aqua-planet mode (Zarzycki et al. 2014a,b). In aqua-planet simulations, the full physics parameterization package is retained but the lower boundary condition is drastically simplified (Neale and Hoskins 2000). In particular, the complex land-surface model is replaced with a flat ocean surface and an analytically prescribed SSTs. These investigations were conducted with the static mesh refinement model CAM5-SE which provided us with information about potential grid imprinting issues, wave reflections at refinement boundaries, the scale-awareness of the physical parameterizations and the sensitivity of tropical cyclone simulations to varying grid resolutions. An example variable-resolution cubed-sphere grid is depicted in Fig. 12 which we used for long-term (23-year) tropical cyclone studies with prescribed sea surface temperatures (Zarzycki and Jablonowski 2014). The left figure shows the uniform-resolution CAM5-SE grid with an approximate grid spacing of 110 km. The right figure displays that the refined area is placed over the North Atlantic ocean basin which is covered with a 28 km grid spacing. For clarity, only the outlines of the CEM5-SE spectral elements are shown. Each spectral element contains additional collocation points which are not displayed. The fine-resolution domain is surrounded by an intermediate-scale buffer region with a grid spacing of 55 km. The fine-resolution domain covers the important tropical cyclogenesis and development regions in the North Atlantic, and allows the assessment of the spontaneous generation and evolution of hurricanes in a 23-year-long climate simulation (Zarzycki and Jablonowski 2014). We also studied the impact of this refined domain on the global climatology in Zarzycki et al. (2015) to evaluate whether refinements influence the general circulation. While there is a direct two-way-interactive benefit for the neighboring coarse

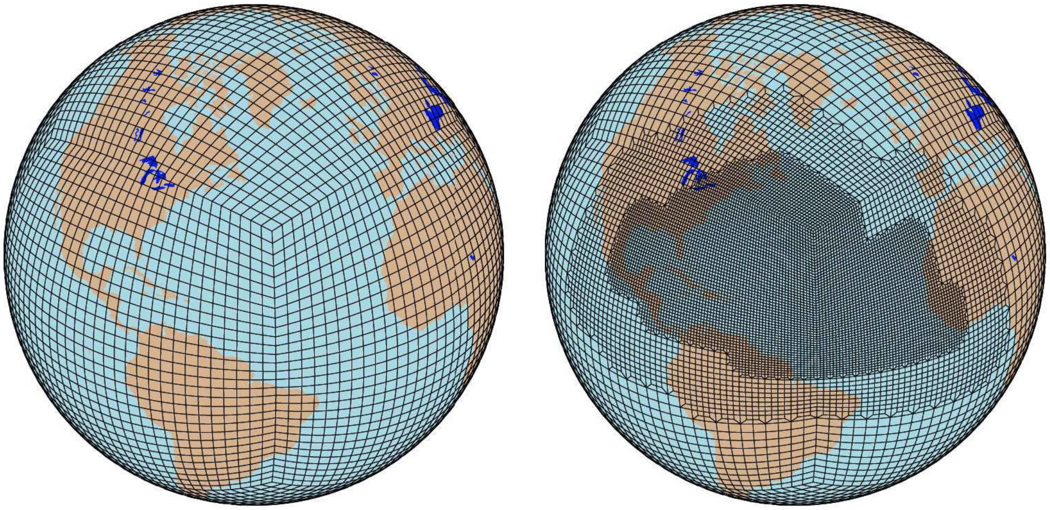


Figure 12: (Left) uniform-resolution (110 km) and (right) statically-adapted (110, 55 and 28 km) cubed-sphere grid in the model CAM-SE which is used for tropical cyclone studies in Zarzycki and Jablonowski (2014). The outlines of the spectral elements are shown.

domain, we found that the general circulation at the global scale is generally undisturbed which is the desired outcome (Laprise et al. 2008).

This investigation also shed light on the presence or non-presence of grid imprinting signatures at the refinement boundaries. As it can be seen in classical Limited-Area Models (LAMs), which need externally-supplied and often physically-inconsistent boundary data to force the simulation in the limited domain (Warner et al. 1997; Laprise 2008), numerical noise and spurious rainfall often develops near the boundaries of the domain. The variable-resolution CAM5-SE simulations do not suffer from these inconsistencies. Atmospheric flow features, like high and low pressure systems or frontal zones. smoothly enter and exit the refined area without wave reflections, spurious rainfall or numerical noise. This, in part, is made possible by the scale-selective diffusion mechanism in CAM5-SE that scales the diffusion coefficients in the dynamical core dependent on the grid spacing (Guba et al. 2014).

A concrete example of a flow feature that smoothly enters a refined region in CAM5-SE is shown in Fig. 13 that displays the 850 hPa wind speed over the course of 8 days (Zarzycki and Jablonowski 2012; Zarzycki et al. 2014a). In this example we placed an idealized tropical cyclone, following the initialization technique by Reed and Jablonowski (2011a), into the coarse domain (110 km grid spacing) near the fine-coarse mesh boundary. Over the course of several days the initial vortex is pulled into the north-westerly direction by the so-called β-drift (Holland 1983; Wang and Li 1992) and thereby encounters the grid transition region and high-resolution area with a fine grid spacing of 28 km. By day 8 the tropical cyclone is fully enclosed by the high-resolution area. As expected, the high-resolution helps strengthen the tropical cyclone and leads to a rapid intensification by day 6 when the cyclone has entered the high-resolution domain. By day 8, the tropical cyclone is a mature hurricane with very high peak wind speeds over 70 m/s that correspond to a category 5 hurricane on the Saffir-Simpson hurricane scale (Simpson 1974).

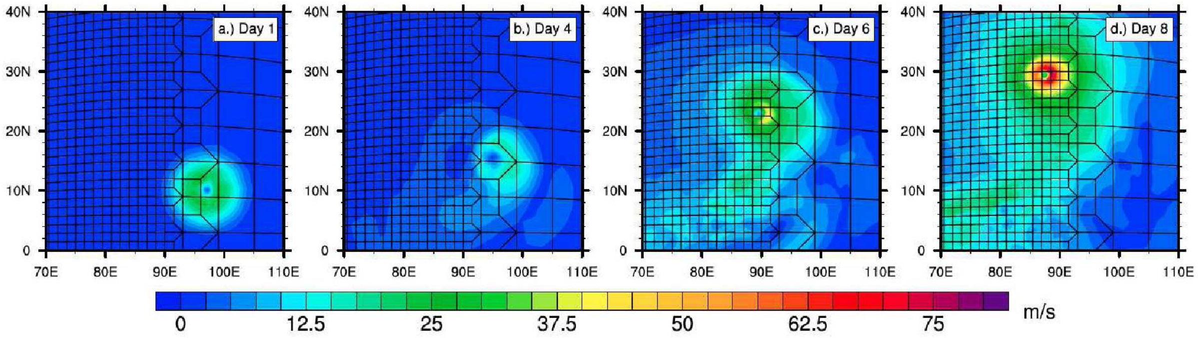


Figure 13: 8-day time series of an idealized tropical cyclone that starts in the coarse domain and moves into the statically refined region in the model CAM-SE (Zarzycki et al. 2014a). The colors show the 850 hPa wind speeds at day (a) 1, (b) 4, (c) 6 and (d) 8.

We also investigated the uncertainty of idealized tropical cyclone simulations in ensemble runs to gain an understanding of the impact of random perturbation versus systematic resolution changes (Reed and Jablonowski 2011b; Zarzycki et al. 2014a). For example, slight variations of the initial conditions or even the placement of the initial cyclone lead to a spread in the hurricane strengths. However, when compared to uniform-resolution reference solutions it becomes obvious that the impact of slight random variations is small in comparison to the changes caused by varying grid resolutions or changing physical parameterizations. The ensemble method is thereby a valuable technique to gain an understanding of the intrinsic uncertainty of the simulations. It also reveals whether new simulations fall within or outside this uncertainty range.

The important conclusions from these studies are that tropical cyclones do not exhibit any spurious numerical effects, such as grid reflections, gravity wave noise or artificially enhanced rainfall, in the grid transition regions. As shown in Zarzycki et al. (2014a) we also investigated the behavior of tropical cyclones that leave a high-resolution nest. We found that cyclones exit the high-resolution patch very smoothly without any spurious side effects that originate at the refinement boundary. As expected, the cyclones lose strength when transitioning from the 28 km mesh resolution to the 110 km grid since the physical forcings of the cyclones, such as evaporation at the surface, low-level mixing, low-level convergence and upward motions, are less well represented at the 110 km scale. These studies are highly relevant for the upcoming 3D Chombo-AMR model since the grid transition region in this CAM5-SE simulation (Fig. 13) is very narrow. To some degree this mimics the grid transitions in the block-structured Chombo-AMR code that has even more abrupt resolution changes with either 1:2, 1:4 or 1:8 refinement ratios. In general, we found the 1:4 AMR grid transition to be highly effective (quick transitions to high resolutions). Furthermore, the 1:4 ratio is noise-free in the unforced Chombo-AMR shallow water simulations. As the next step, we will test forced shallow water simulations in an adaptive mode which mimic the impact of physical parameterizations on the dynamical fields. Once the 3D Chombo-AMR model is mature, we will also investigate what the adequate and noise-free refinement ratios are for 3D Chombo-AMR simulations with and without moisture processes.

Another important topic that we investigated in our CAM5-SE variable-resolution research addressed the representation of topography. In general, topography needs to be smoothed according to the grid resolution which is a standard procedure for uniform-resolution simulation. This prevents the triggering of unsupported gravity waves and thereby numerical noise. In a variable-resolution framework, topography needs to be adaptively smoothed according to the local grid spacing to take full advantage of the improved representation of mountain ranges. This was accomplished via a scale-adaptive second-order diffusion operation as described in Zarzycki et al. (2015) which is based on the algorithm by Lauritzen et al. (2012).

3.6.2 Tropical Cyclone-like Assessments with the Chombo-AMR Model

As originally proposed we also investigated the impact of dynamic grid adaptations on tropical vortices with the Chombo-AMR approach. The assessments were done in the 2D Chombo-AMR shallow water framework which supports tropical cyclone-like vortices. These simulations serve as a prototype for the upcoming 3D Chombo-AMR investigations planned for 2016. An example of the 2D cyclone interactions is shown in Fig. 14 that displays the merger of two tropical vortices (Ferguson et al. 2015). As motivated by the satellite image in Fig. 1 such interacting vortices are present in nature, and their interplay is called the Fujiwhara effect (Fujiwhara 1921). The 2D shallow water model thereby serves as an idealized test bed for this flow scenario and the AMR application. Figure 14 displays two counterclockwise rotating vortices that merge over the four day simulation period. Their initial relative vorticities, shown in the upper left panel in Fig. 14, are defined via an analytically-derived balanced initial state. Both vortices are initially located at 10° N and have identical strengths and sizes. The adaptive mesh refinement criterion checks

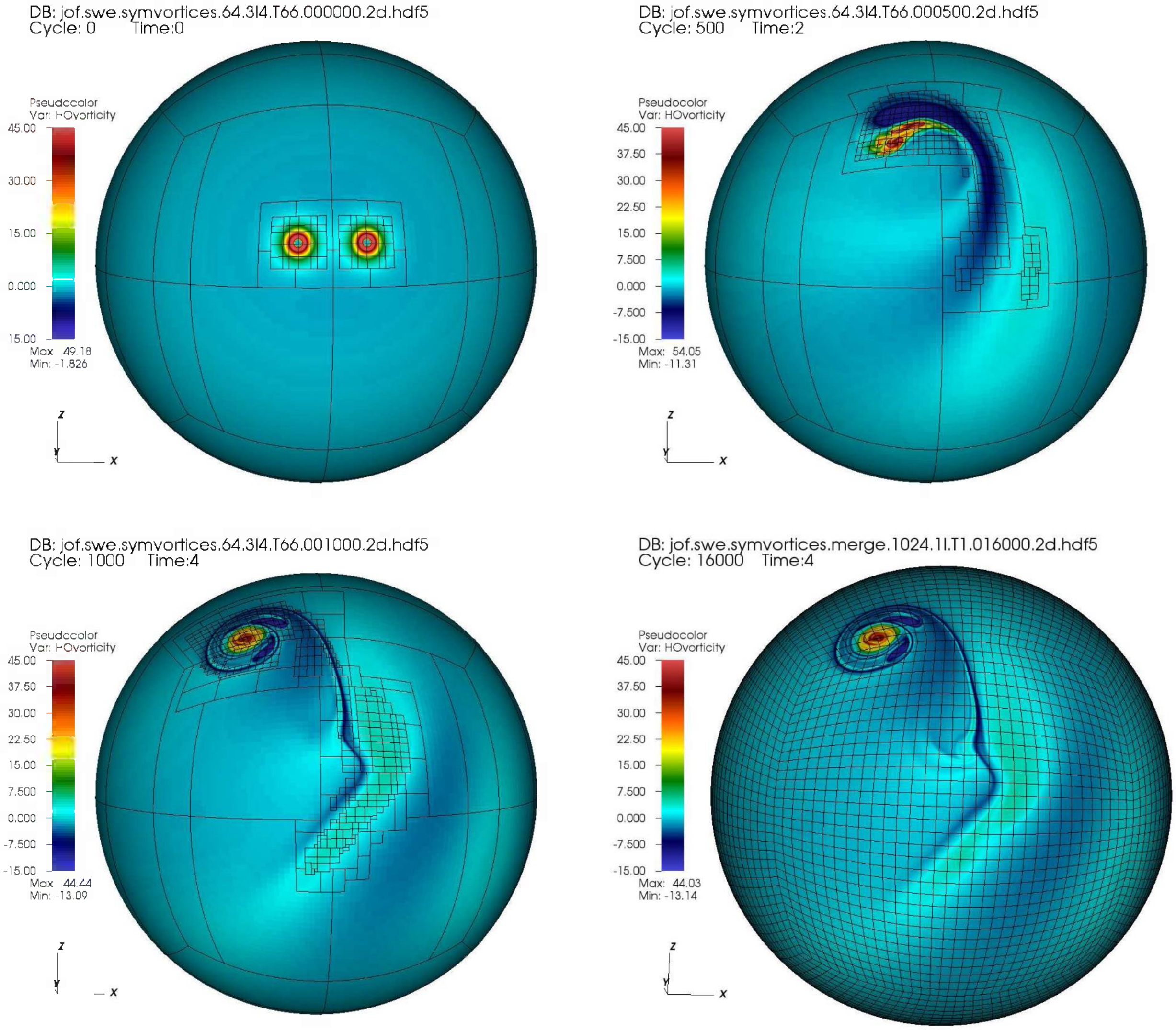


Figure 14: Merging twin cyclones that are tracked by the overlaid Chombo-AMR grid. Only the block outlines are shown that contains cells with the grid spacings of 156, 39 and 10 km. The figures depict the relative vorticity patterns of a pair of cyclones that interact and merge over the course of four days. The Top row left: day 0, top row right: day 2 and bottom row left: day 4. The bottom right figure shows a uniform-resolution c1024 ($\Delta x \approx 10$ km) comparison plot at day 4 which is almost identical to the AMR solution on the left.

for the magnitudes of the relative vorticity. In case the relative vorticity magnitude exceeds a fixed refinement threshold two refinement levels (c64/c256/c1024) with 1:4 refinement ratios are overlaid which correspond to the grid spacings 156, 39 and 10 km, respectively. The outlines of these adapted blocks are overlaid in black. They contain additional grid points that are not shown for clarity. The merger of the two cyclones is depicted by the relative vorticity fields in Fig. 4 at day 1, and in Fig. 14 (upper right) at day 2 and (lower left) at day 4. The lower right panel in Fig. 14 displays a uniform-resolution c1024 reference solution with the Chombo-AMR model which corresponds to the finest grid spacing (10 km) of the AMR run.

The important conclusion from these experiments is that the AMR simulation at day 4 is almost indistinguishable from the high-resolution uniform reference simulation. The merging vortices in the areas with high relative vorticity magnitudes show very similar signatures. This is expected since the vortices are always covered by the high-resolution domains in the AMR run that reliably tracks their moving positions. Slight differences are apparent in the areas with moderate vorticity magnitudes such as the long tail that reaches north-southward by day 4. These small-scale areas develop during the simulation and are not initially captured by the high resolution. The merging vortices also shed large-scale Rossby waves in their wake (east of the long north-southward vorticity tail) which are only partly traced in the AMR run here. The tracking of these features is sensitive to the refinement threshold since their vorticity magnitudes are low.

3.6.3 Products

Journal Articles and Conference Proceedings

- **Zarzycki and Jablonowski (2015)**
  Zarzycki, C. M. and C. Jablonowski (2015), Experimental Tropical Cyclone Forecasts using a Variable-Resolution Global Model, Mon. Wea. Rev., in press
- **Zarzycki et al. (2015)**
  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
- **Zarzycki and Jablonowski (2014)**
  Zarzycki, C. M. and C. Jablonowski (2014), A multidecadal simulation of Atlantic tropical cyclones using a variable-resolution global atmospheric general circulation model, J. Adv. Model. Earth Syst., Vol. 6, 805-828
- **Zarzycki et al. (2014a)**
  Zarzycki, C. M., C. Jablonowski and M. A. Taylor (2014), Using Variable Resolution Meshes to Model Tropical Cyclones in the Community Atmosphere Model, Mon. Wea. Rev., Vol. 142, 1221-1239
- **Zarzycki and Jablonowski (2012)**
  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`
- **Reed and Jablonowski (2011b)**

Reed, K. A. and C. Jablonowski (2011c), Assessing the Uncertainty in Tropical Cyclone Simulations in NCAR's Community Atmosphere Model, J. Adv. Model. Earth Syst., Vol. 3, Art. 2011MS000076, 16 pp.

Conference and Seminar Presentations

1. 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
2. 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
3. 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
4. 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
5. 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
6. 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
7. 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
8. 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
9. 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
10. 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
11. 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

12. 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
13. 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
14. 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 fr Marine und Atmosphrische Wissenschaften) /KlimaCampus Seminar, Hamburg, Germany, June 11, 2013
15. 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
16. 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
17. 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
18. 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
19. 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
20. 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
21. 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
22. 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

23. 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
24. 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
25. 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
26. 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
27. 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.
28. Reed, K. A. and C. Jablonowski, Evaluating the Uncertainty of Tropical Cyclone Simulations in General Circulation Models, Poster Presentation at the 2011 Michigan Geophysical Union (MGU) Meeting, Ann Arbor, MI, USA, March 25, 2011
29. 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
30. 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
31. 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
32. Reed, K. A. and C. Jablonowski, Assessing the uncertainty of tropical cyclone simulations in GCMs, Poster presentation at the 3rd International Summit on Hurricanes & Climate Change, Rhodes, Greece, June 27-July 2, 2011

Related Web Sites and Online Resources

- Colin Zarzycki's home page that features all variable-resolution & tropical cyclone presentation files and animations, `http://www.colinzarzycki.com/`

Fostered Networks and Collaborations

- The PI and her research group participated in the US CLIVAR Hurricane Working Group that was formed in January of 2011. The working group coordinated efforts to produce a set of model experiments designed to improve understanding of the variability of tropical cyclone formation in climate models: `www.usclivar.org/working-groups/hurricane`

Other Products Including Audio, Video and Educational Tools

- Recorded presentation on the 'Tropical Cyclone Structure in the High-Resolution Community Atmosphere Model' by Kevin Reed, 30th AMS Conference on Hurricanes and Tropical Meteorology, `https://ams.confex.com/ams/30Hurricane/webprogram/Paper205606.html`
- Recorded presentation on 'Using variable resolution meshes to model tropical cyclones in NCAR's CAM general circulation model' by Colin Zarzycki, 30th AMS Conference on Hurricanes and Tropical Meteorology, `https://ams.confex.com/ams/30Hurricane/webprogram/Paper205939.html`

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