Frontiers in Weather and Climate Modeling

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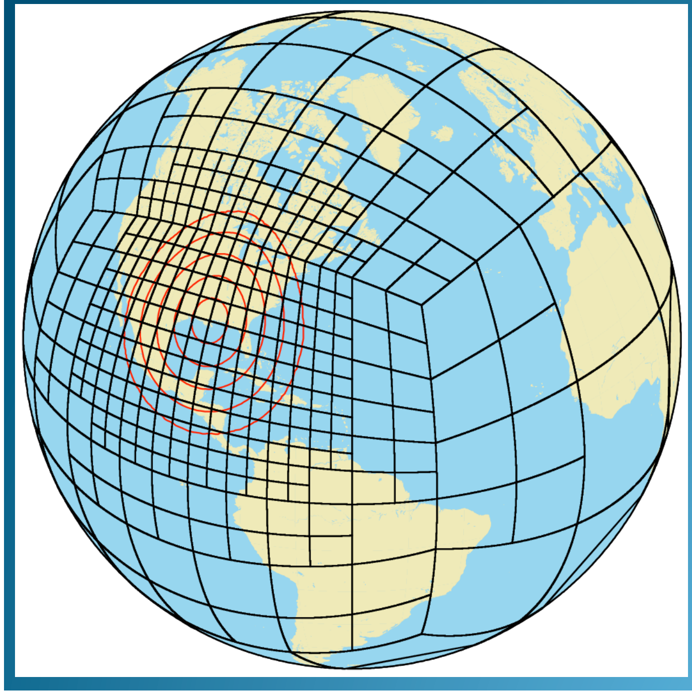
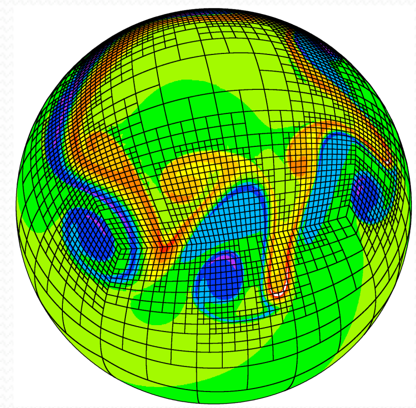


In collaboration with:
Phillip Colella and Hans Johansen (LBNL),
Mark Taylor (Sandia National Laboratories),
Michael Levy (NCAR)

DoE ASCAC Meeting, Washington D.C.
August/14/2012

Overview and Keywords

- Atmospheric General Circulation Models (GCMs): Research at the University of Michigan
  - High-order finite-volume non-hydrostatic dynamical core modeling on cubed-sphere grids
  - Adaptive Mesh Refinement (AMR) and variable-resolution grids
  - Objective evaluations of dynamical cores: Dynamical Core Model Intercompaison Project (DCMIP)



- My goal is to present our vision and highlight where we see exciting future opportunities for dynamical cores and GCM modeling.

Who are 'we'?

Phillip Colella, Hans Johansen
Lawrence Berkeley National Laboratory

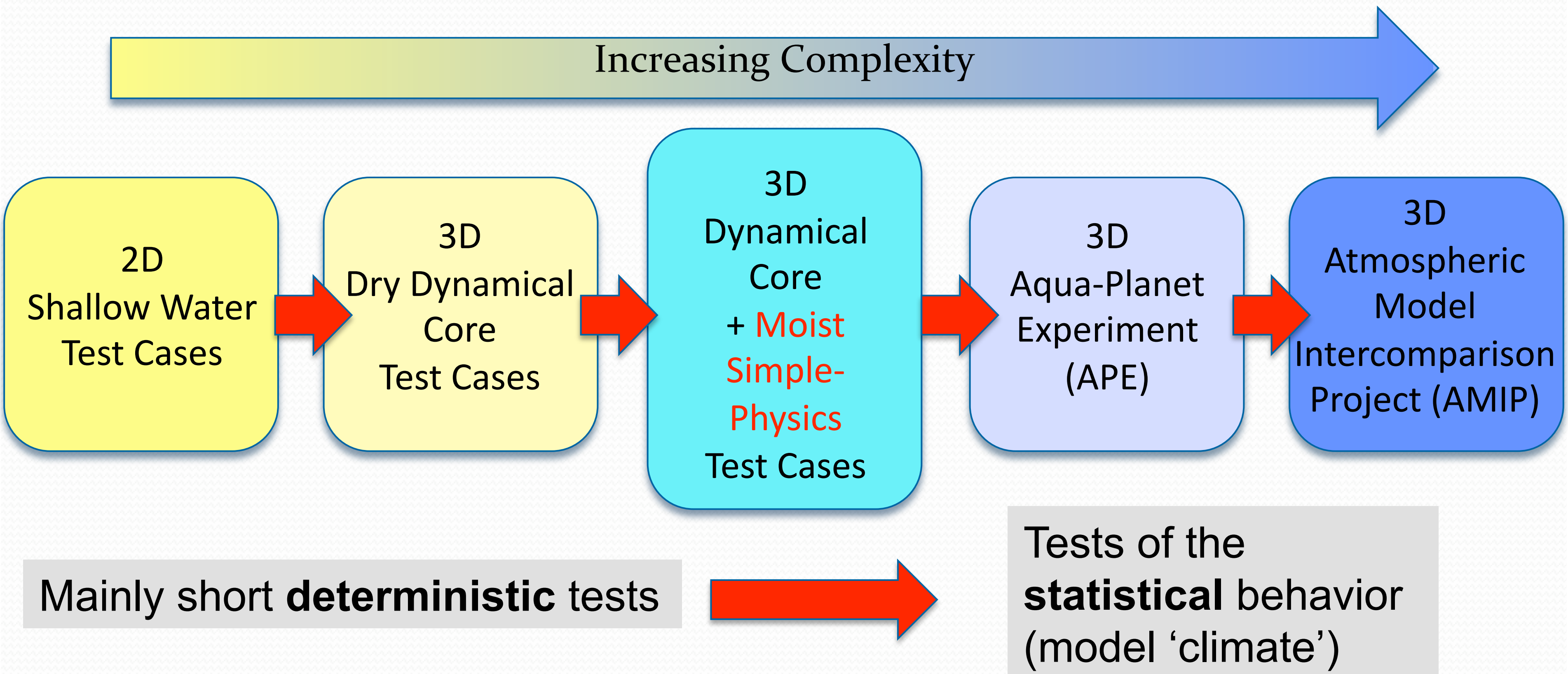
University of Michigan (UM) team:
in particular for this work Paul, Colin, Kevin & Christiane

Mark Taylor (SNL)

+ Many other people that inspire this work, e.g.:
Bram van Leer (UM)

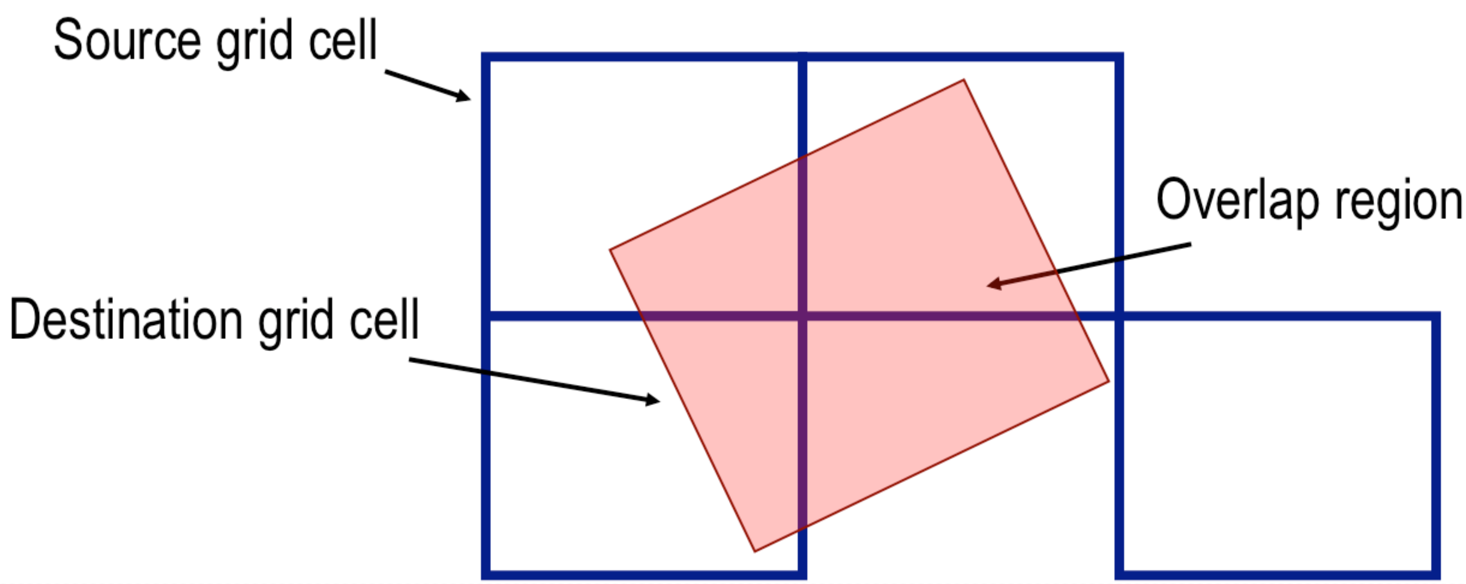
Hierarchy: GCM modeling and evaluations

- Typical hierarchy: Dynamical core and GCM modeling, and the model assessments



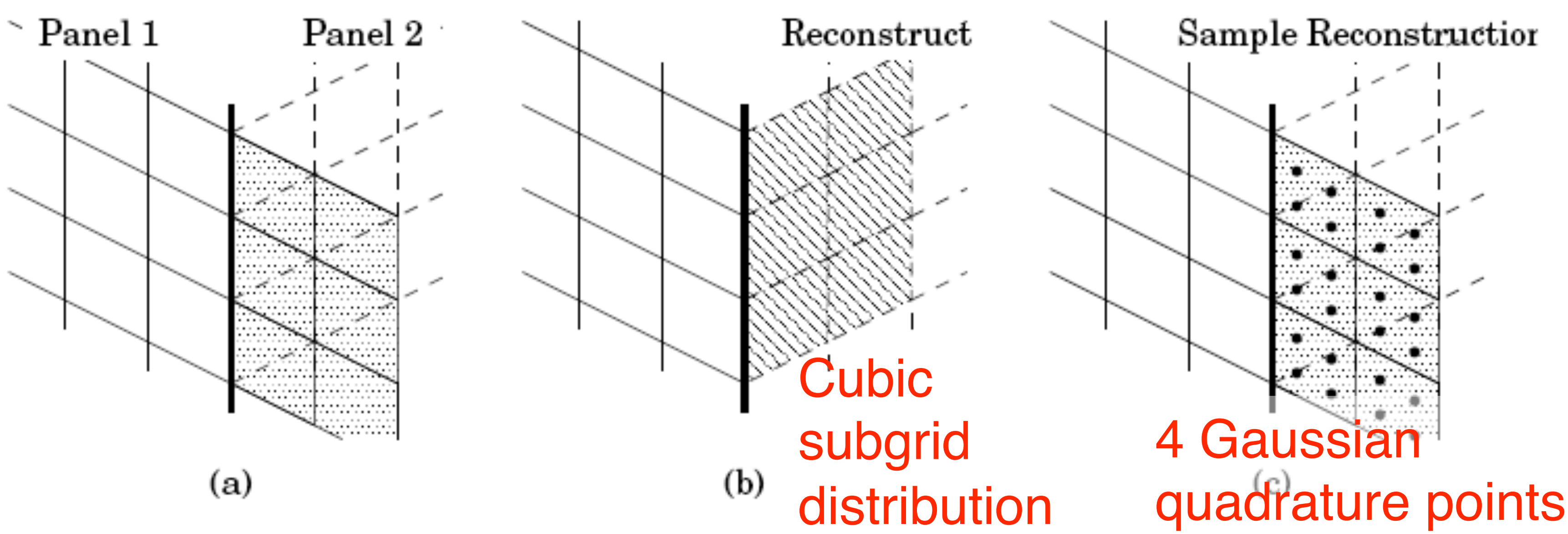
GCM Modeling Hierarchy: Remapping

- What got us started back in 2008 was the presumably 'simple' problem how to accurately remap data from a cubed-sphere grid to a latitude-longitude grid and vice versa (Ullrich, Lauritzen and Jablonowski, MWR (2009))
- Project let us think about high-order (3rd or 4th order) finite-volume subgrid reconstructions, conservative remapping, it introduced us to cubed-sphere computational grids



GCM Modeling Hierarchy: Shallow Water

- In 2009 we started building a finite-volume shallow water model on the cubed-sphere (Ullrich, Jablonowski, van Leer, JCP (2010))
- Bram van Leer (UM) gave us ideas how to obtain 3rd or 4th-order convergence with finite-volume schemes
- We learned how to treat cubed-sphere panel boundaries and high-order reconstructions in their ghost cells



GCM Modeling Hierarchy: 3D Channel Model

- In the summer of 2010 we used the 3rd and 4th-order finite-volume technique to develop a nonhydrostatic model in a Cartesian 2D x-z slice and 3D channel configuration (Ullrich and Jablonowski, MWR 2012a)
- Why Cartesian geometry? Because we needed to learn about
  - nonhydrostatic modeling
  - the treatment of high-speed sound waves (vertically implicit)
  - incorporation of orography in a height-based vertical coordinate system
  - nonhydrostatic test cases: warm bubble, mountain waves

GCM Modeling Hierachy: 3D dynamical core

- In early 2011 we used all the lessons learned and built a high-order finite-volume nonhydrostatic dynamical core on the cubed-sphere grid (MCORE),
  Ullrich and Jablonowski, JCP (2012b)
  - 4th-order in the horizontal, explicit time stepping
  - 2nd-order in the vertical, implicit
  - Can be configured for shallow- and deep-atmosphere configurations
  - Prepares us for our next step: adaptive mesh refinement application on cubed-sphere grids, in collaboration with the Phil Colella and Hans Johansen (LBNL)
- The main ideas and highlights are presented next

Review of the Main Ideas: **Design**

- Quasi-uniform grid: Equiangular cubed-sphere, co-located variables (unstaggered)
- Finite-Volume methods: Physical consistency
  - built-in conservation laws
  - can be easily made to satisfy monotonicity and positivity constraints (i.e. to avoid negative tracer densities)
- High-order techniques (e.g. 4^{th}-order) can hide grid-imprinting of the cubed-sphere grid geometry
- High-order supports the use of adaptive meshes that lose an order of accuracy at refinement boundaries

Choosing the Non-Hydrostatic Equations

- We use the conservation form:

$$\frac{\partial \rho}{\partial t} + \frac{1}{J}\frac{\partial}{\partial x^k}(J\rho u^k) = 0,$$

$$\frac{\partial \rho u^\alpha}{\partial t} + \frac{1}{J}\frac{\partial}{\partial x^k}(J(\rho u^\alpha u^k + G^{\alpha k} p')) = \psi_H^\alpha + \psi_M^\alpha + \psi_C^\alpha,$$

$$\frac{\partial \rho u^\beta}{\partial t} + \frac{1}{J}\frac{\partial}{\partial x^k}(J(\rho u^\beta u^k + G^{\beta k} p')) = \psi_H^\beta + \psi_M^\beta + \psi_C^\beta,$$

$$\frac{\partial \rho u^r}{\partial t} + \frac{1}{J}\frac{\partial}{\partial x^k}(J(\rho u^r u^k + G^{rk} p')) = \psi_G^r,$$

$$\frac{\partial \rho \theta}{\partial t} + \frac{1}{J}\frac{\partial}{\partial x^k}(J\rho\theta u^k) = 0.$$

Flux terms

Source terms
(metric, Coriolis, gravity)

- Many complexities such as the formulation of the covariant metric G^{ij} are hidden here, J is the determinant of G^{ij}

Choosing the Non-Hydrostatic Equations

- The equation of state is:

$$p = p_0 \left(\frac{R_d(\rho\theta)}{p_0} \right)^{c_p/c_v}$$

- We split the prognostic variables into a local hydrostatic base state and a nonhydrostatic contribution:

$$\begin{aligned}
\rho(\mathbf{x}, t) &= \rho^h(\mathbf{x}) + \rho'(\mathbf{x}, t), \\
p(\mathbf{x}, t) &= p^h(\mathbf{x}) + p'(\mathbf{x}, t), \\
(\rho\theta)(\mathbf{x}, t) &= (\rho\theta)^h(\mathbf{x}) + (\rho\theta)'(\mathbf{x}, t),
\end{aligned}$$

Designing the Numerical Scheme

- We integrate the system of equations and apply the Gauss divergence theorem, leads to compact notation with the volume-averaged state vector $\overline{\overline{q}}$ and fluxes ***F***:

$$\frac{\partial}{\partial t}\bar{\bar{\mathbf{q}}} + \frac{1}{|\mathcal{Z}|}\int\int_{\partial \mathcal{Z}} \mathcal{F} \cdot \mathbf{n} dS = \bar{\bar{\psi}}_H + \bar{\bar{\psi}}_M + \bar{\bar{\psi}}_C + \bar{\bar{\psi}}_G$$

- Split it into its horizontal (H) and vertical (V) parts:

$$\frac{\partial}{\partial t}\overline{\overline{\mathrm{q}}}_{i,j,k} = \mathrm{H}(\mathrm{q}) + \mathrm{V}(\mathrm{q}) \qquad \text{with}$$

$$\mathbf{H}(\mathbf{q}) = \frac{1}{|\mathcal{Z}|_{i,j,k}}[\mathbf{F}_{i-1/2,j,k} - \mathbf{F}_{i+1/2,j,k} + \mathbf{F}_{i,j-1/2,k} - \mathbf{F}_{i,j+1/2,k}] + \bar{\bar{\psi}}_H + \bar{\bar{\psi}}_M + \bar{\bar{\psi}}_C$$

$$\mathbf{V}(\mathbf{q}) = \frac{1}{|\mathcal{Z}|_{i,j,k}}[\mathbf{F}_{i,j,k-1/2} - \mathbf{F}_{i,j,k+1/2}] + \bar{\bar{\psi}}_G$$

Choosing the Time-Stepping Approach

- We use a Strang-carryover approach to couple an explicit time integration in the horizontal (H) and and implicit (Newton-Krylov) integration in the vertical (V):

implicit

$$\frac{\mathbf{q}^{(1)} - \mathbf{q}^n}{(\Delta t/2)} - \mathbf{V}(\mathbf{q}^{(1)}) = 0$$

explicit

$$\begin{aligned}
\mathbf{q}^{(2)} &= \mathbf{q}^{(1)} + \frac{\Delta t}{2}\mathbf{H}(\mathbf{q}^{(1)}), \\
\mathbf{q}^{(3)} &= \mathbf{q}^{(1)} + \frac{\Delta t}{2}\mathbf{H}(\mathbf{q}^{(2)}), \\
\mathbf{q}^{(4)} &= \mathbf{q}^{(1)} + \Delta t\mathbf{H}(\mathbf{q}^{(3)}), \\
\mathbf{q}^{*} &= -\frac{1}{3}\mathbf{q}^{(1)} + \frac{1}{3}\mathbf{q}^{(2)} + \frac{2}{3}\mathbf{q}^{(3)} + \frac{1}{3}\mathbf{q}^{(4)} + \frac{\Delta t}{6}\mathbf{H}(\mathbf{q}^{(4)})
\end{aligned}$$

4^{th}-order Runge-Kutta scheme

implicit

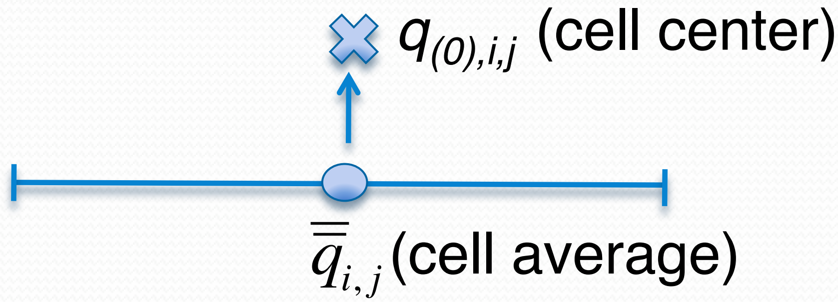
$$\frac{\mathbf{q}^{n+1} - \mathbf{q}^{*}}{(\Delta t/2)} - \mathbf{V}(\mathbf{q}^{n+1}) = 0$$

Overall: 2^{nd}-order accurate

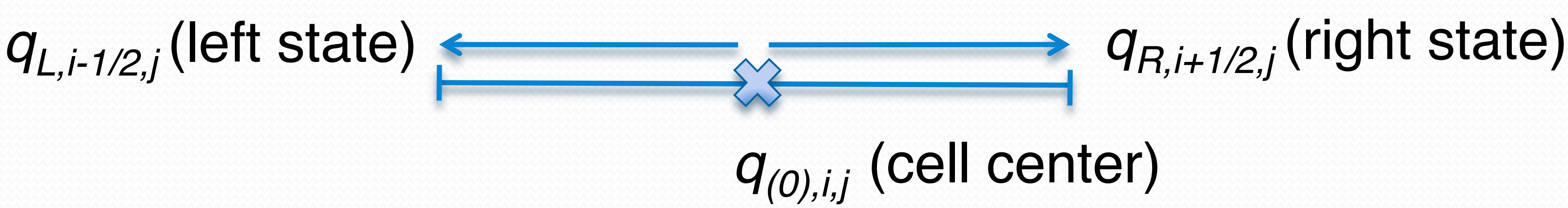
High-Order Fluxes *F* Across Cell Edges (1)

There are four steps:

- 1) Compute the cell-centered components of the state $q_{(0)i,j}$ based on the cell-average $\overline{\overline{q}}_{i,j}$ following Barad and Colella (2005)

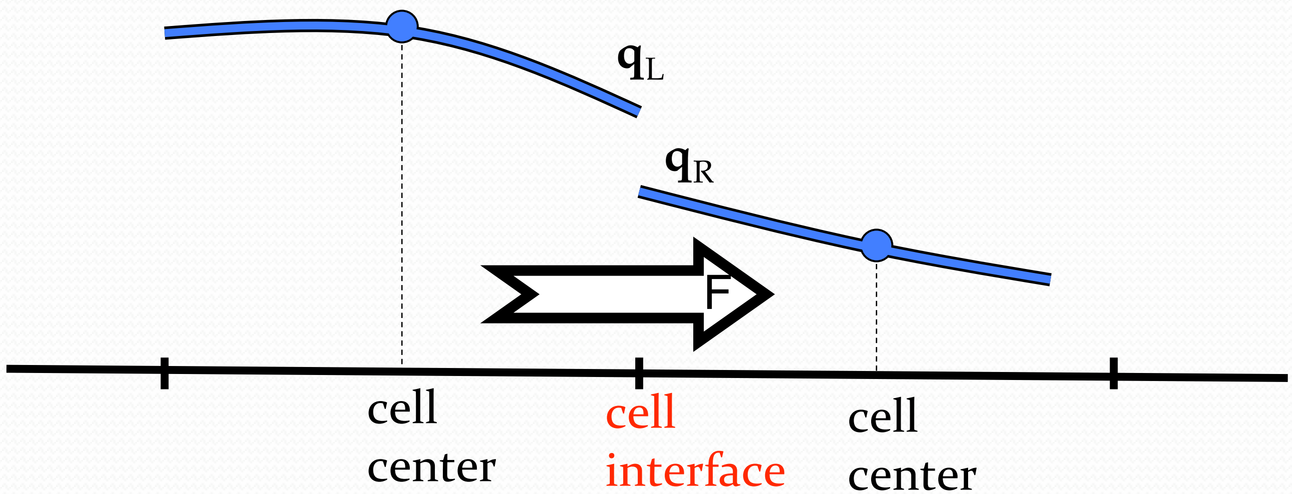


- 2) Use the cell-centered value to reconstruct a 4[th]-order edge value at the cell interface (cubic subgrid distribution)



High-Order Fluxes *F* Across Cell Edges

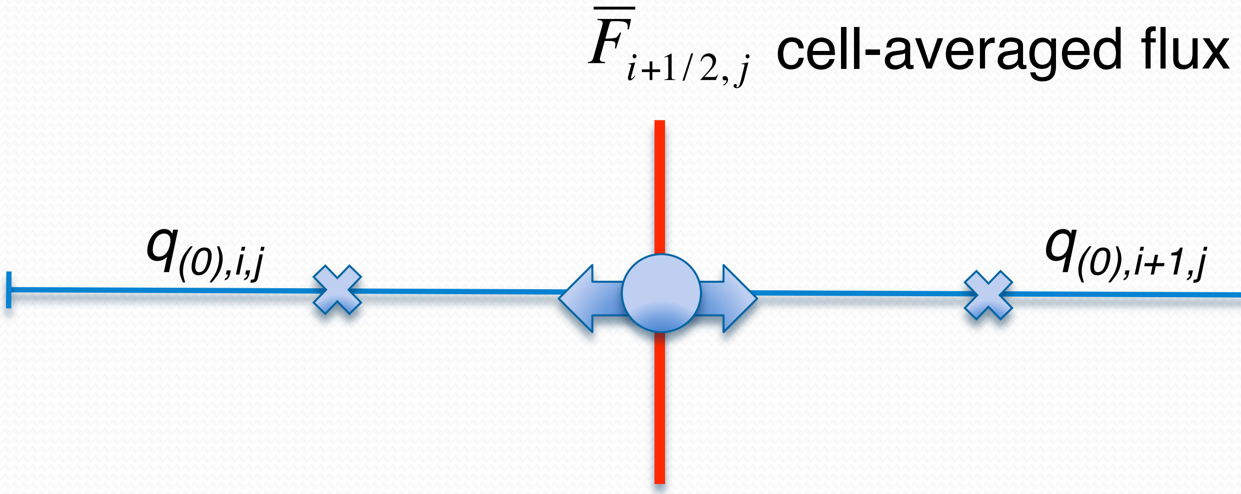
- 3) The cubic sub-grid reconstruction are discontinuous at cell interfaces (we have a left value $\mathbf{q}_L$ and right value $\mathbf{q}_R$), necessitates Riemann solvers to compute the flux F



We explored the AUSM$^+$-up solver by Liou (2006), highly accurate (low diffusion) for low Mach number flows
We also tried others: Rusanov, Roe, HLL (more diffusive)

High-Order Fluxes *F* Across Cell Edges (3)

- 4) The numerical flux $F_{(0),i+1/2,j}$ is a pointwise flux, we need to recover the cell-averaged flux $\overline{F}_{i+1/2,j}$ to achieve 4th-order accuracy

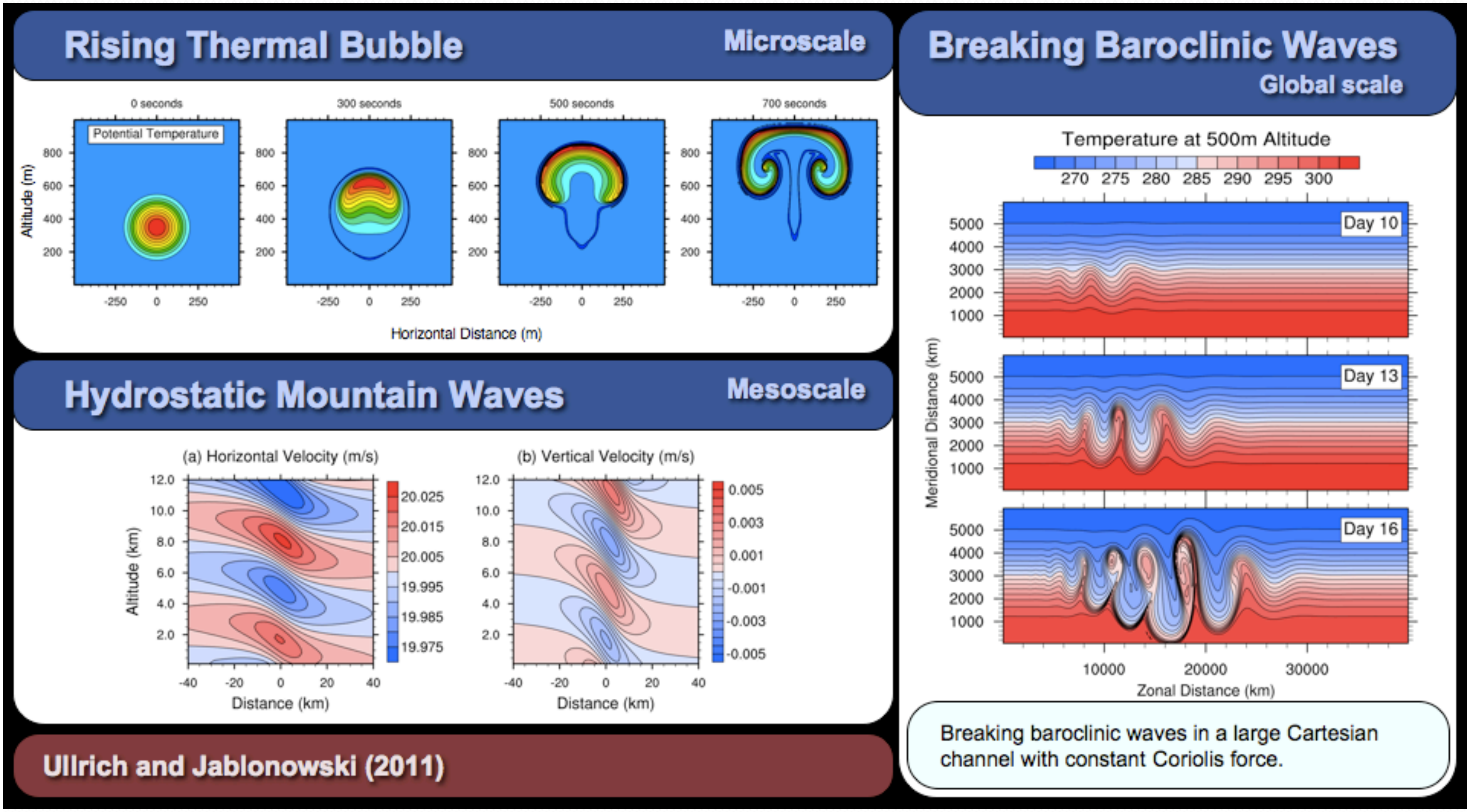


$$\overline{\mathbf{F}}_{i+1/2,j} = \mathbf{F}_{(0)i+1/2,j} + \frac{\Delta\alpha^2}{24}\left(\frac{\partial^2 \mathbf{F}}{\partial \beta^2}\right)_{i+1/2,j} + \frac{\Delta\alpha^2}{12|\partial \mathcal{Z}|_{i+1/2,j}}\left(\frac{\partial F}{\partial \beta}\right)_{i+1/2,j}\left(\frac{\partial \tilde{J}_\alpha}{\partial \beta}\right)_{i+1/2,j}$$

Convolution / deconvolution technique by Barad and Colella (2005), also used for source terms

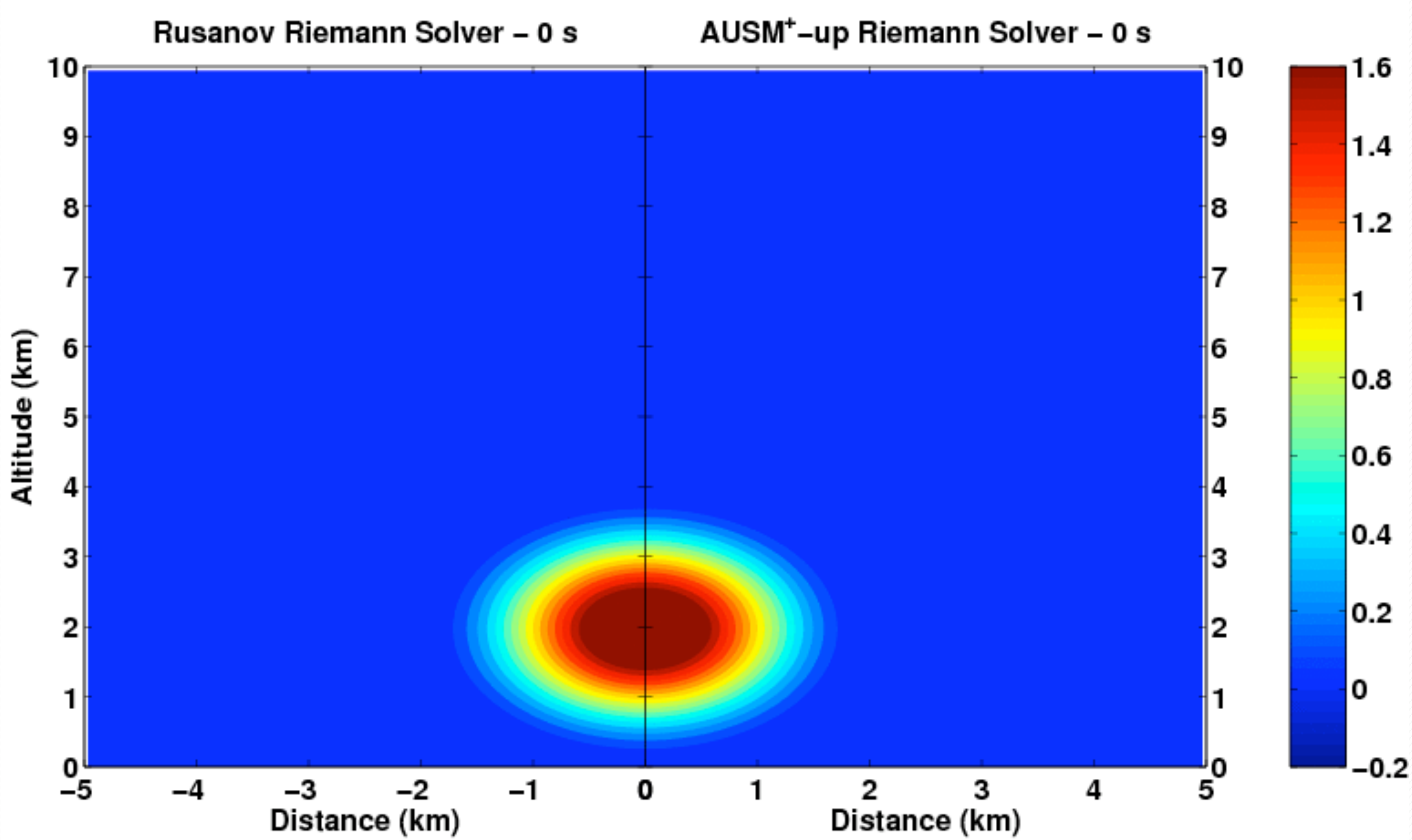
Snapshots of the Results: Cartesian

- 4^{th}-order nonhydrostatic model: microscale, mesoscale, global



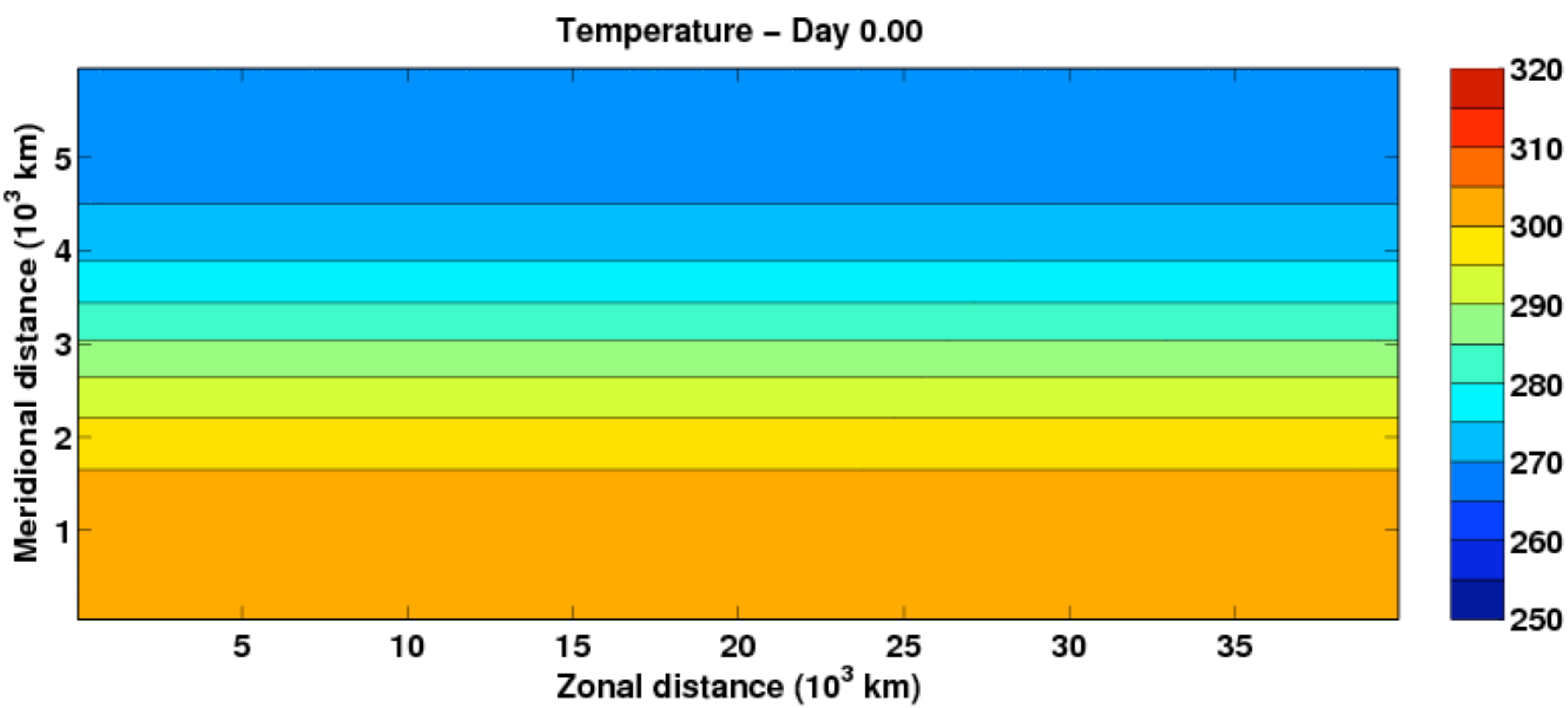
Snapshots of the Results: 2D x-z slice

- Comparison of Riemann solvers in nonhydrostatic model (warm bubble experiment, after Giraldo and Restelli, JCP (2008))



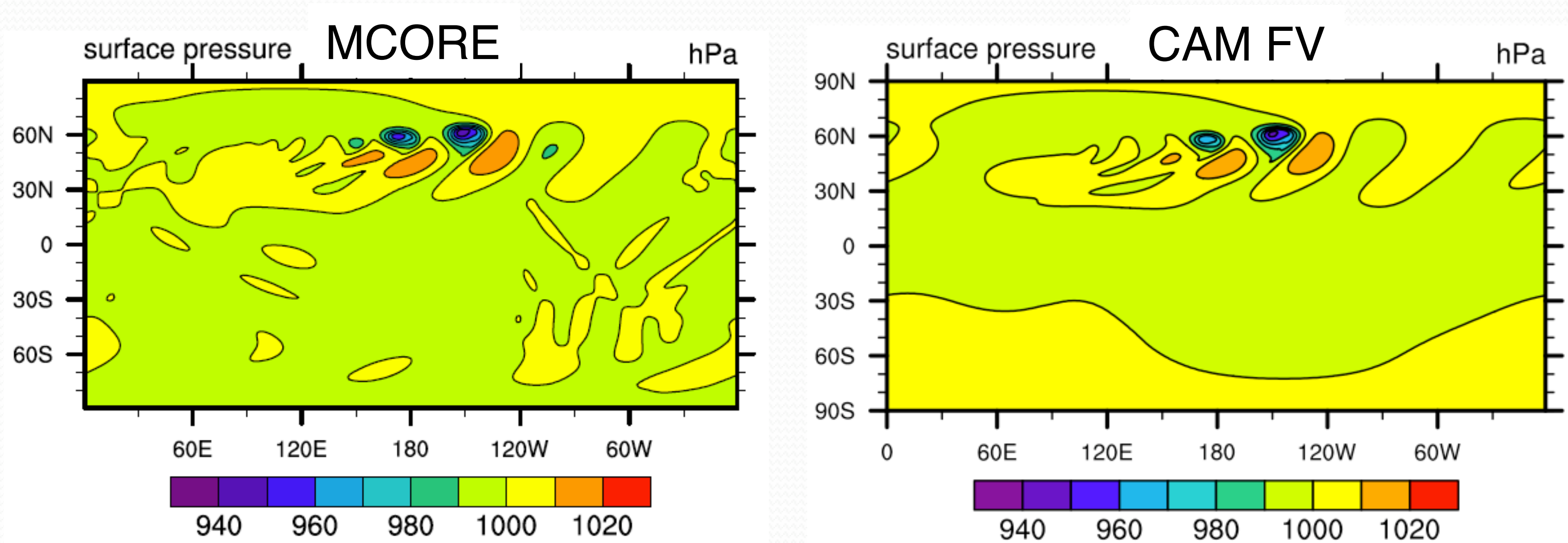
Snapshots of the Results: 3D channel

- Baroclinic wave in a periodic channel, similar to a baroclinic wave test (Jablonowski and Williamson, QJ (2006)) in spherical geometry



Snapshots of the Results on the Cubed Sphere: The High-Order Finite-Volume Dynamical Core MCore

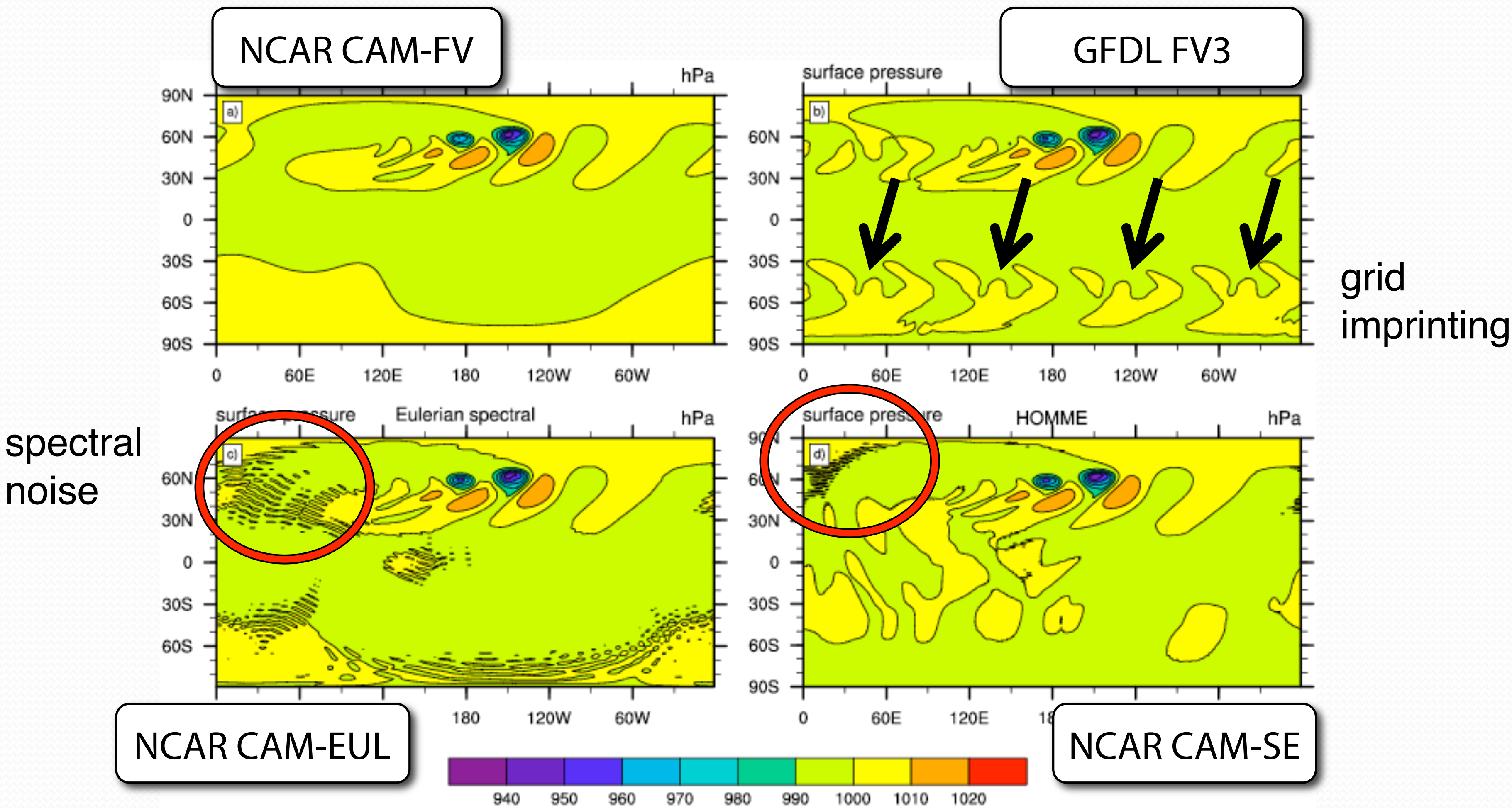
- Baroclinic wave test, surface pressure at day 9 (Jablonowski and Williamson, QJ (2006))



Sequence of high and low pressure systems

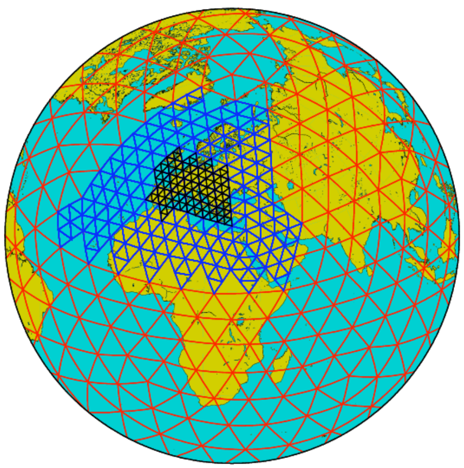
Snapshots of the Results: Intercomparisons

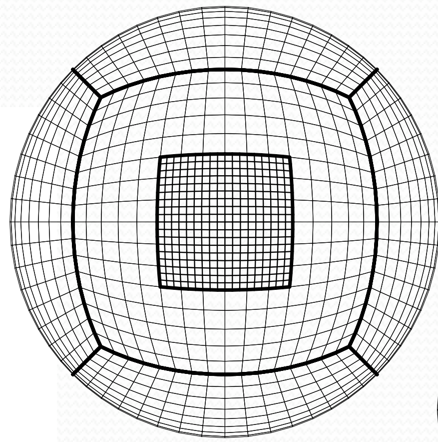
- Baroclinic wave test, day 9 (Jablonowski and Williamson, 2006)

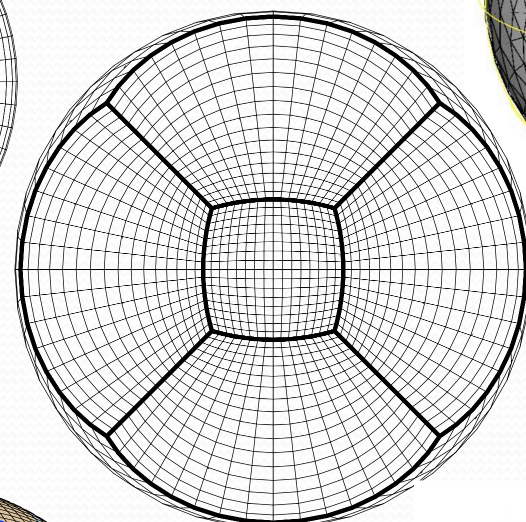


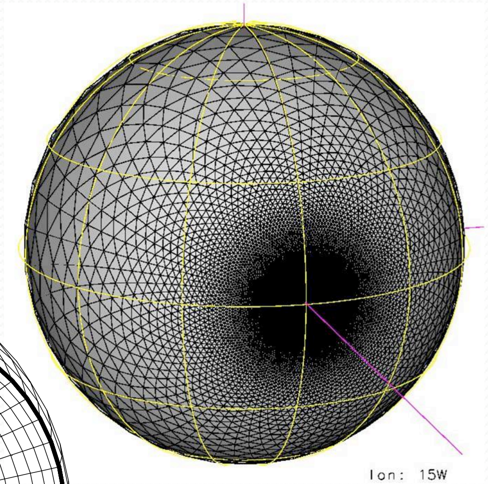
No grid imprinting or spectral ringing in MCore (previous slide)

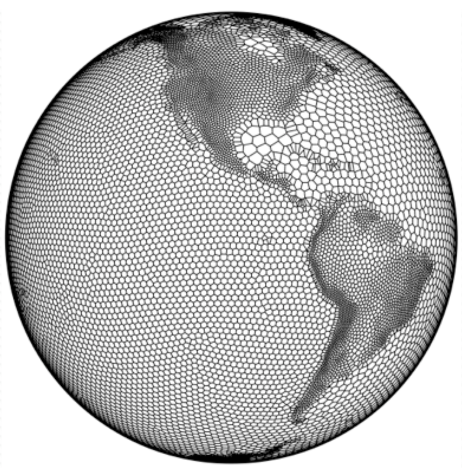
Variable-Resolution Modeling

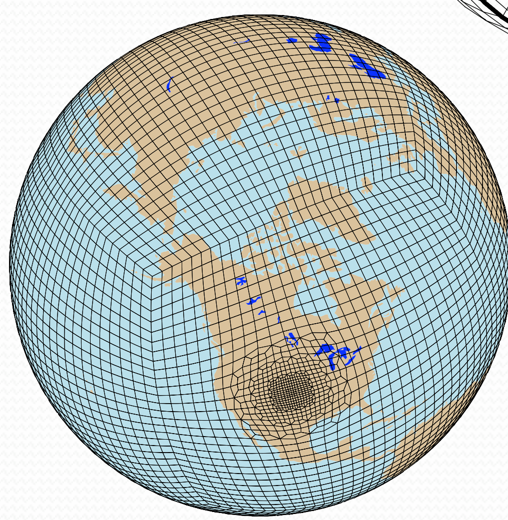


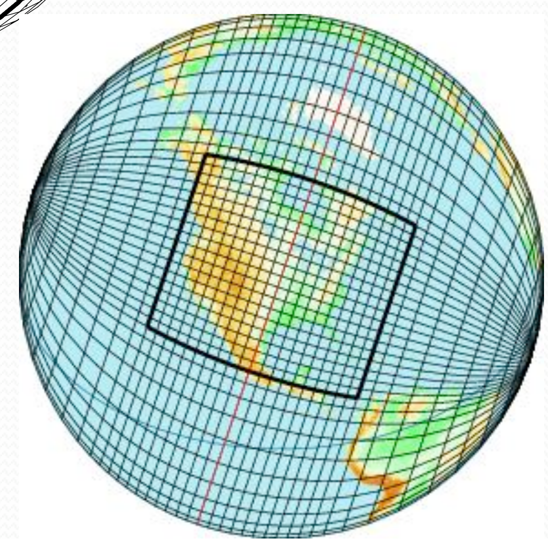






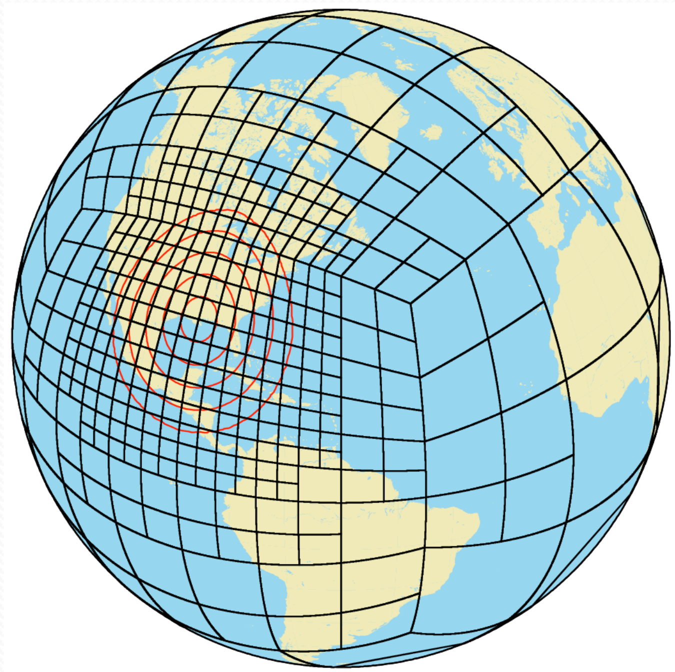






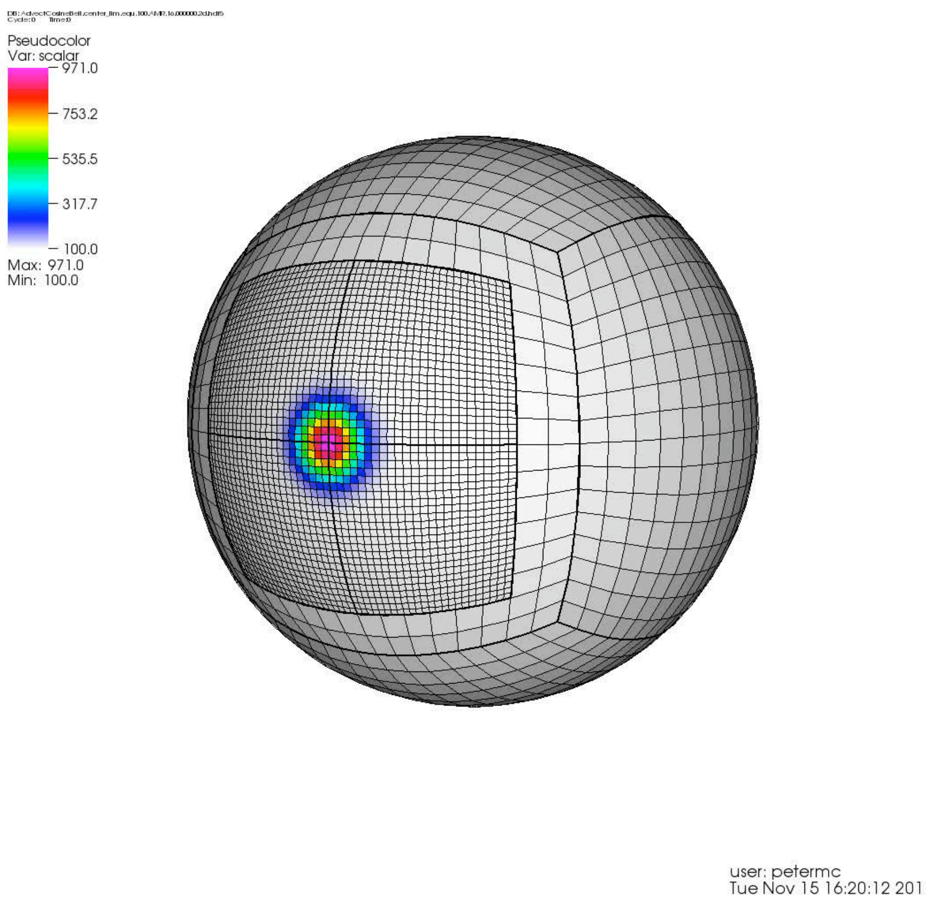
AMR and Variable-Resolution Modeling

- Our 3D dynamical core test results so far look promising, meanwhile we performed simplified tests with moisture
- We work with Phil Colella and Hans Johansen (LBNL) to pair high-order finite-volume methods with the adaptive mesh refinement library *Chombo* in order to support flexible (static and dynamically adaptive) cubed sphere grids
- First step is an AMR shallow water model on the cubed-sphere (fall this year)
- We need the 4th-order on uniform grids to comfortably drop down to 3rd-order at refinement boundaries



Adaptive Mesh Refinement on Cubed-Sphere Grids

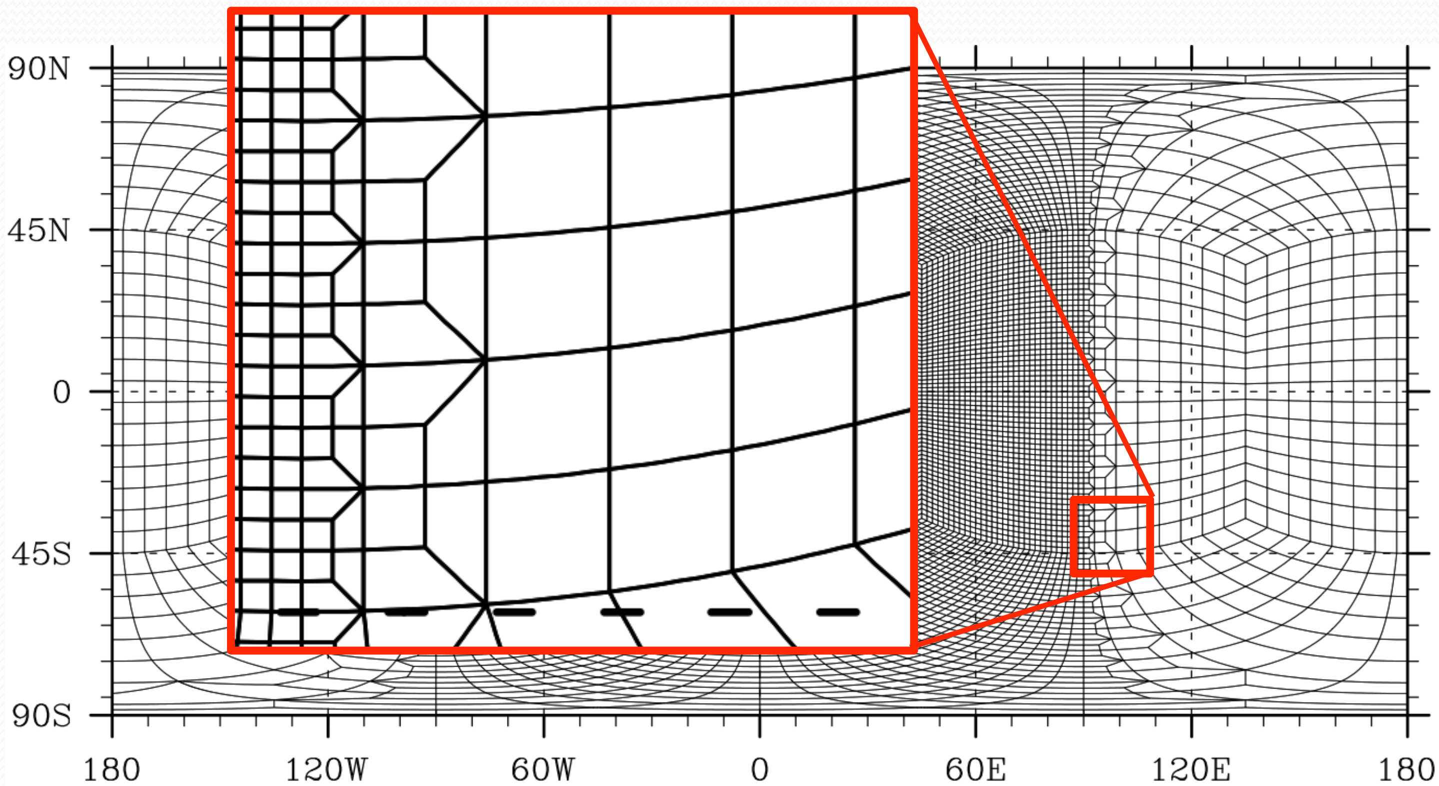
Animation of an advected tracer tracked by an AMR grid



Source: Hans Johansen, Phil Colella (LBNL)

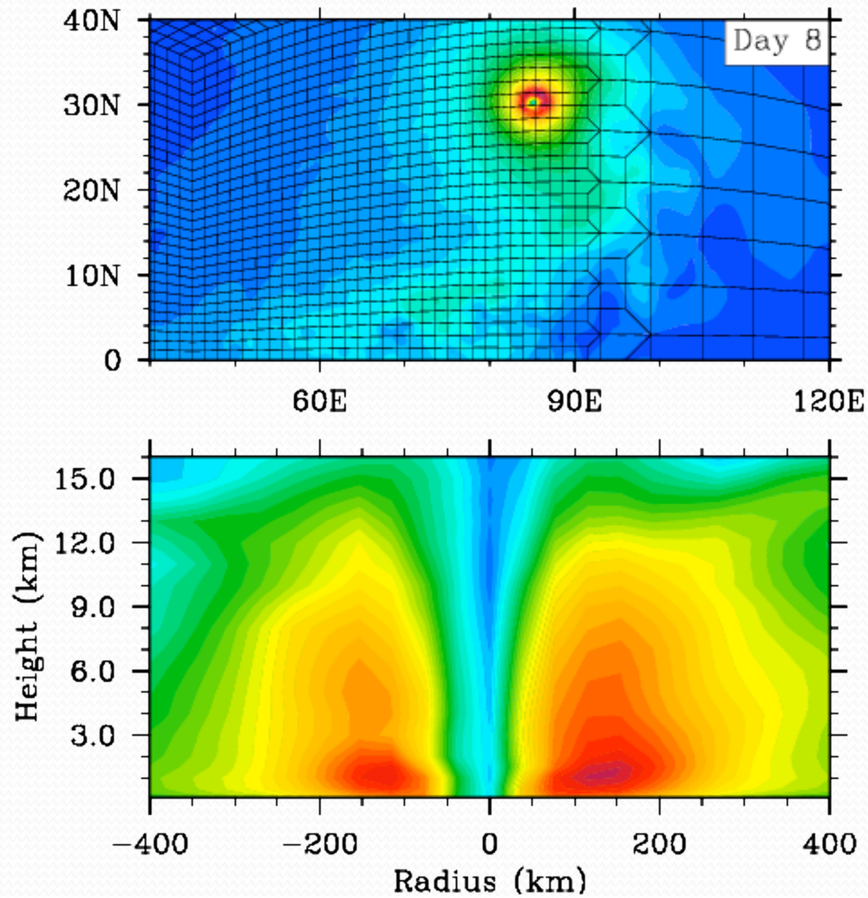
Static Mesh Adaptations

- Collaboration with Mark Taylor (Sandia Labs) and Michael Levy (NCAR)
- Conforming mesh adaptations in the DoE/NCAR Spectral Element (SE) dynamical core



Idealized Tropical Cyclone Simulations with the Community-Atmosphere Model (CAM-SE)

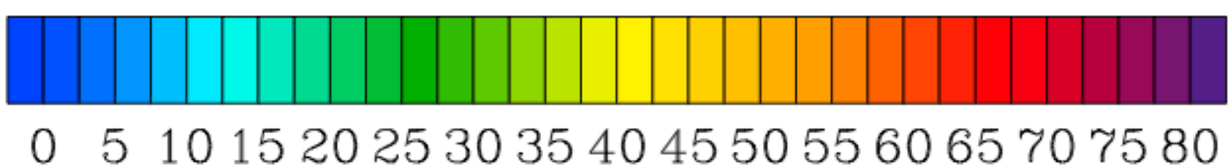
Initial vortex:
v = 20 m/s
RMW = 250 km,
Reed and Jablonowski, MWR (2011)



After 8 days: 850 hPa wind speed (m/s)

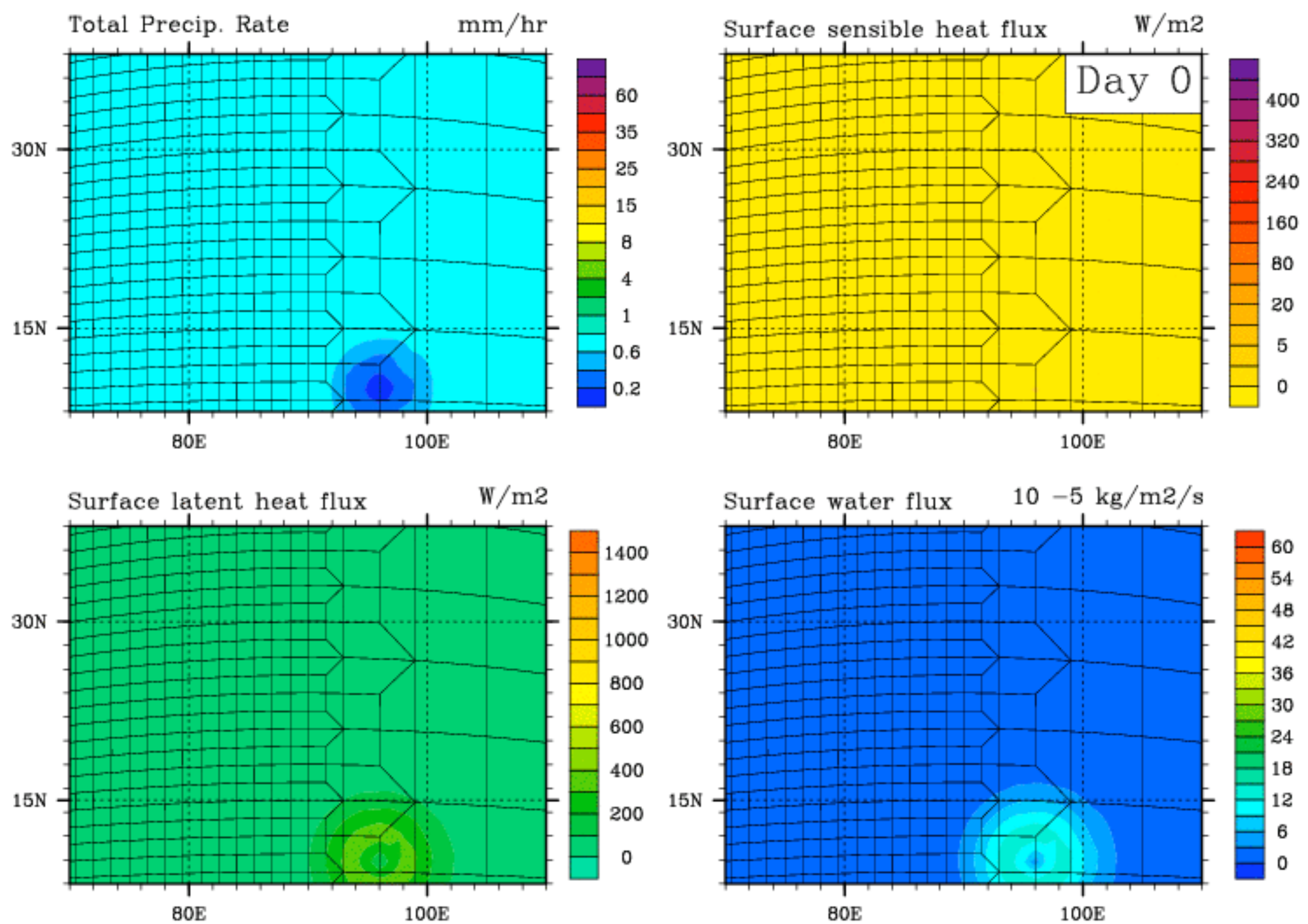
Latitude-height cross section wind speed (m/s)

Zarzycki and Jablonowski (2012)



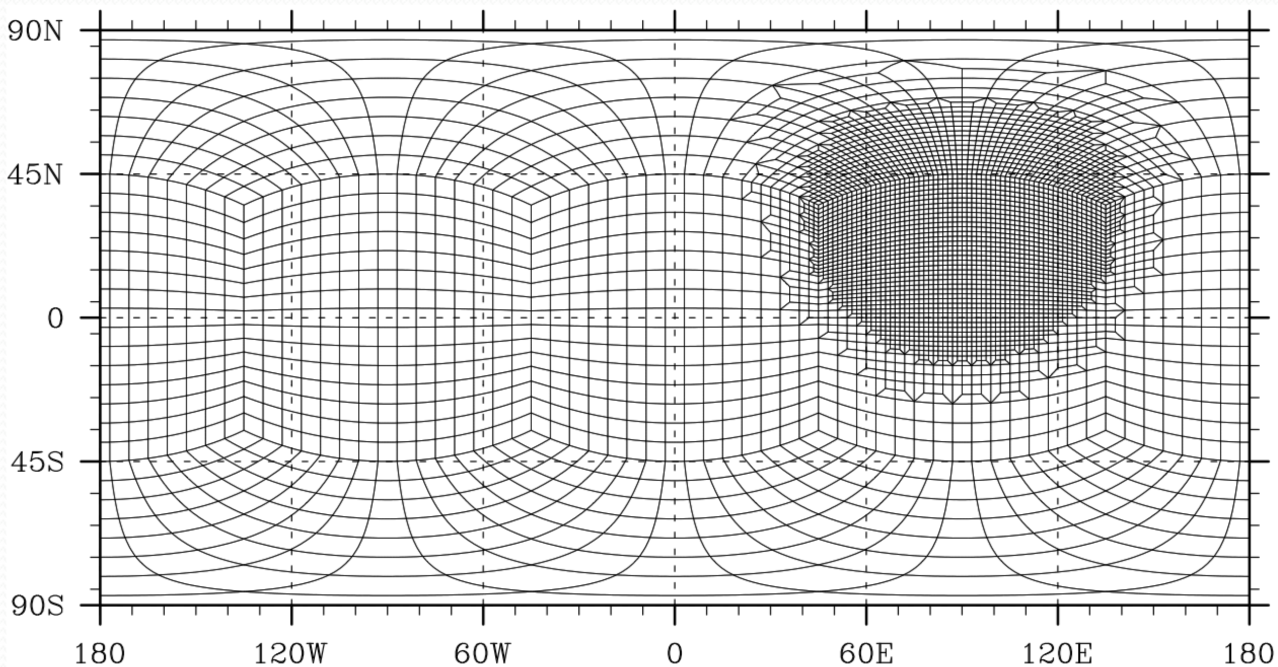
Evaluations: Cyclones in the Transition Region

No reflections of the tropical cyclone at refinement boundaries, smooth transition

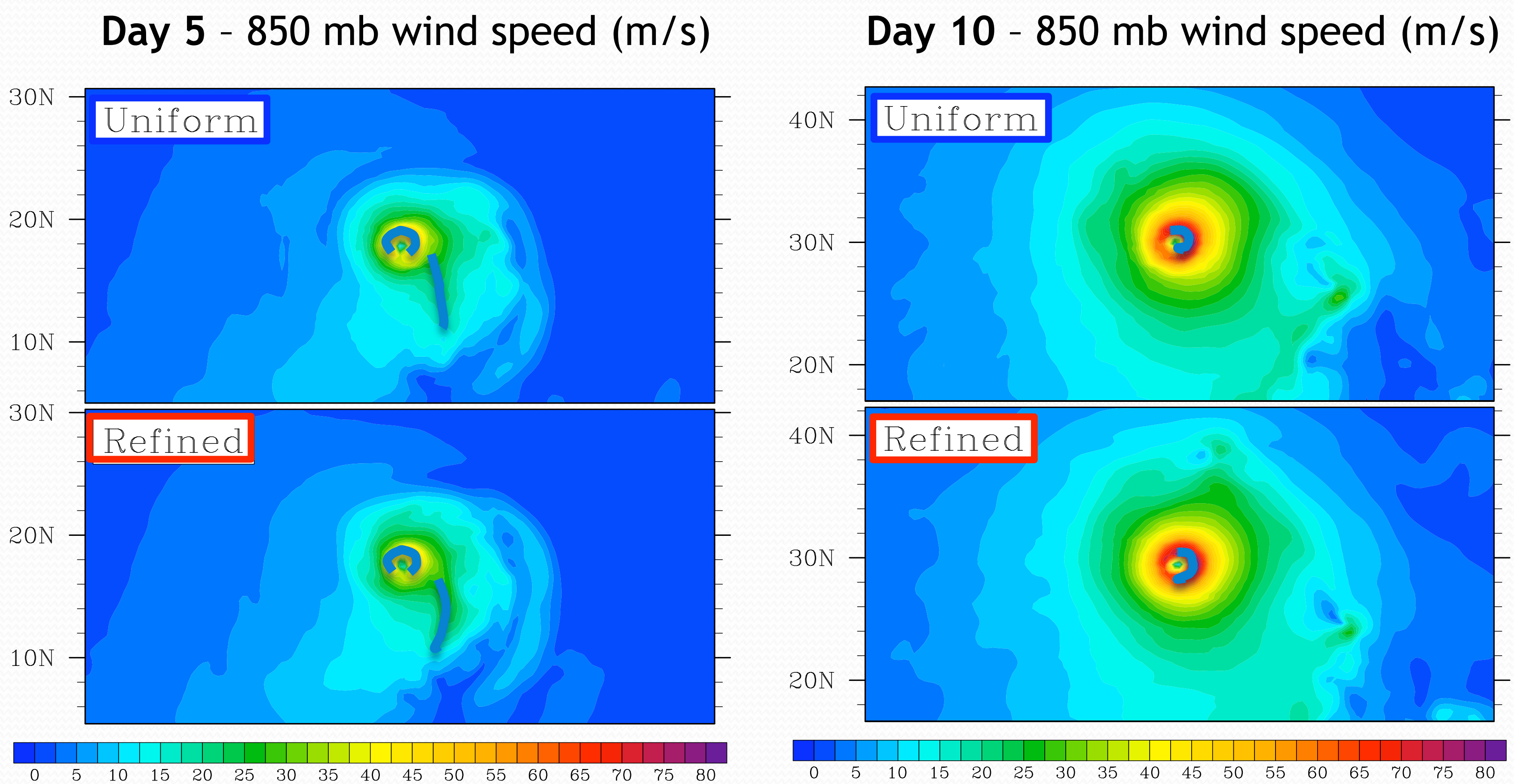


Comparing "uniform" to "refined" meshes

- Compare idealized cyclone in A) traditional uniform ne60 (~0.5°) mesh to a B) ne15 mesh (~2°) with a 4x refined area (ne60, ~0.5°)
- Smaller refined region than hemisphere: analogous to size of north Pacific ocean



Comparing “uniform” to “refined” meshes



Almost identical results, significant computational savings in variable-resolution simulations (factor 5 speed-up)

Objective Dynamical Core Evaluations: Dynamical Core Model Intercomparison Project (DCMIP) in August 2012 (NCAR, Boulder, CO)

- A community effort towards **standard evaluations** of dynamical cores, supported by cyber-infrastructure

Organizers: Christiane Jablonowski (lead), Paul Ullrich, James Kent, Kevin Reed (UM), Mark Taylor (Sandia), Peter Lauritzen, Ram Nair (NCAR)

http://earthsystemcog.org/projects/dcmip-2012/

Goals of the DCMIP and its Summer School

- Explore new test cases designed for **hydrostatic** and **non-hydrostatic** dynamical cores on the sphere, for both **shallow** and **deep atmosphere** models
- Examples: small-Earth, unsteady exact solutions, 3D mountain waves, moist baroclinic waves, moist simple-physics (tropical cyclones), dry tropical cyclones
- Special focus on non-hydrostatic models and high resolutions
- Provide standard diagnostics for model evaluations
- Multi-model ensemble assessments, uncertainty quantification
- Establish standard test suite that is relevant to atmospheric phenomena and reveals important characteristics of the numerical schemes
- 18 atmospheric modeling groups from the international community participated

DCMIP Modeling Mentors

R. Bleck, T. Smirnova, S. Sun
D. Dazlich, R. Heikes, C. Konor
T. Dubos, Y. Meurdesoif
M. Duda, W. Skamarock
T. Frisius
A. Gassmann
M. Giorgetta
M. Gross
L. Harris
J. Kent
J. Klemp, S.-H. Park
J. Lee
S. Malardel
T. Melvin
H. Miura, R. Yoshida
A. Qaddouri
K. Reed
D. Reinert
L. Silvers
M. Taylor
R. Walko, M. Otte

Summary

- We push the frontiers of
  - dynamical core modeling for weather and climate applications by developing physically consistent fluid dynamics solvers based on high-order finite-volume methods
  - variable-resolution modeling by exploring dynamic and static mesh adaptations, e.g. based on the AMR library Chombo
  - objective dynamical core evaluations via new test cases. We provide leadership for international model intercomparisons.

Variable Resolution Modeling: There are many Open Questions and Challenges

- Will there be artificial effects at refinement boundaries? If yes, how do we deal with them?
- I expect vertical refinements to be a real challenge
- Adaptive grids will require a major effort concerning scale-aware physics routines, lots of opportunities to team up with scientists at the Lawrence Berkeley National Laboratory, NCAR and at other institutions.
- How does the computational cost of the high-order finite-volume dynamical core compare to other nonhydrostatic dynamical cores?

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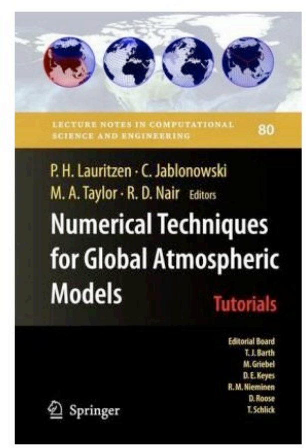

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