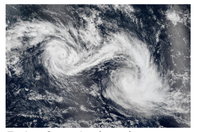
Assessing Adaptive Grid Refinement Techniques with the Chombo-AMR Shallow Water Model

Jared Ferguson[1], Christiane Jablonowski[1], Hans Johansen[2], Peter McCorquodale[2], and Phillip Colella[2]

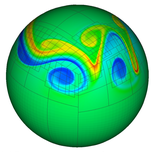
[1]Atmospheric, Oceanic, and Space Sciences, University of Michigan, and [2] Lawrence Berkeley National Laboratory (LBNL)

Introduction

- Current global climate and weather models are challenged by multi-scale intense atmospheric phenomena such as tropical cyclones and squall lines
- Adaptive mesh refinement (AMR):
  - Dynamically increases resolution locally over areas of interest when needed
  - Balances benefits of fine-scale resolution with increased computational burden
- Working to asses the effectiveness of AMR and various refinement strategies within the Chombo-AMR dynamical core using a series of 2D shallow water test cases
- Will use these refinement strategies in 3D-dycore simulations with simplified physics parameterization schemes



Pair of tropical cyclones (NASA's Earth Observatory)

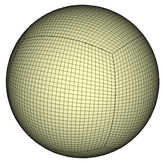


AMR grid example, barotropic instability test case

Model Description

Chombo-AMR Dynamical Core

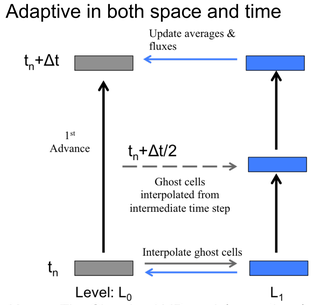
- Development led by Applied Numerical Algorithms Group (ANAG) at LBNL [MU2015] in collaboration with the University of Michigan
- Uses the Chombo framework library, an open-source toolkit for solving PDES on structured grids
- Multi-block grids on a cubed-sphere
- 4th-order finite-volume discretization of the shallow water equations
- Adaptive in both space and time



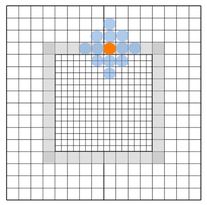
Above: A uniform c32 resolution cubed-sphere grid. The length of each panel edge is 32 grid cells.

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

Table: Equivalent grid spacing at the equator for cubed-sphere grid resolutions.



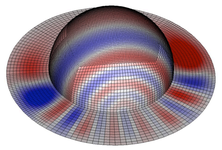
Above: The Chombo-AMR model uses the classical 4th order Runge-Kutta temporal discretization. Refined grid levels are sub-cycled in time.



Above: Grid cells are contained in a hierarchy of nested levels for different resolutions. Ghost cells (in grey) are calculated by interpolated stencils of nearby cells (light blue).

3D-Dycore Plans

- Non-hydrostatic model with a vertical time integrator that is implicit for vertical "wave" terms and option to use Strang-type or IMEX coupling approaches.
- Will implement a simplified physics parameterization scheme base on [RJ2012] and a more complex Kessler-type warm precipitation microphysics scheme
- Will use a variety of baroclinic wave, orographic precipitation, and idealized tropical cyclone test cases
- Goal is to asses the effectiveness of AMR and the affects of AMR and changing grid resolutions on the physics parameterizations

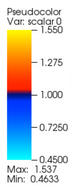


Above: AMR tracks the potential temperature gravity wave in a small planet gravity wave test. An example of dry atmospheric dynamical core tests currently being performed. Image created by E. English at LBNL.

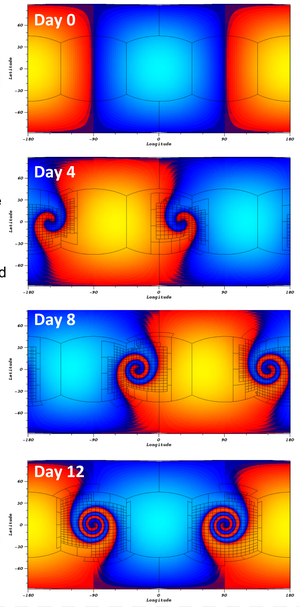
Shallow Water Test Cases

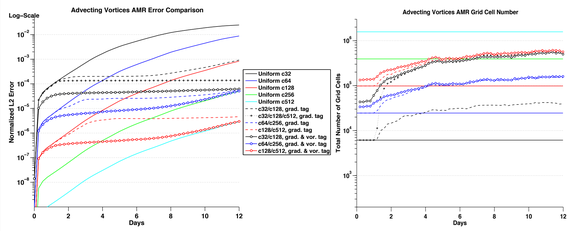
Spiral Advection

- Advection test case in which an initially smooth passive tracer is rolled up into tight spiral bands over a 12 day period (pictured right) [NJ2008]
- AMR is used on the sharp tracer gradients that develop.
- Error in AMR runs are comparable to those of uniform runs at the finest AMR resolution (e.g. the c32/c128 run's error is comparable to the uniform c128 run)
- AMR runs use a significantly lower number of grid cells



Right: Evolution of the tracer field in a 3 level (c32/c128/c512) AMR run. The black lines represent blocks of grid cells at the 3 levels.

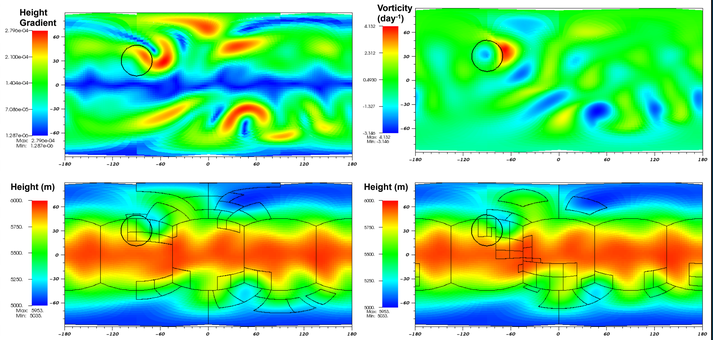




Above: Global normalized L2 error over time comparison for uniform runs and 2 and 3 level AMR runs tagging on the tracer gradient or a combination of tracer gradient and vorticity magnitude **(Left)**. Total number of grid cells (log-scale) over time in each run **(Right)**.

Mountain Wave

- Shallow water test case which consists of a zonal flow over an isolated mountain that induces large-scale Rossby-waves [WD1992]
- Ideal for testing a variety of AMR refinement criteria: vorticity, height gradient, topography, or a combination
- Can compare the variations in refined areas under different tagging criteria

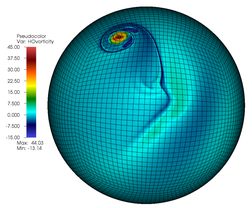


Top: Height gradient on day 15. Black circle represents location of mountain.
Bottom: Height field on day 15 in a c32/c128 AMR run refining over areas of large height gradient.

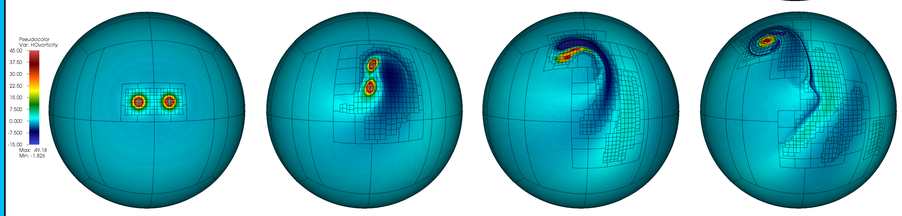
Top: Vorticity on day 15.
Bottom: Height field on day 15 in a c32/c128 AMR run refining over areas of high vorticity. The adaptive blocks are outlined in black.

Merging Vortices

- In this shallow water test, an isolated pair of symmetric vortices interact
- Depending on their size, strength, and separation distance. they either merge together or repel each other simulating the 'Fujiwhara effect'
- Pictured below is the vorticity profile of merging vortices in a 3 level (c64/c256/c1024) AMR run using a vorticity magnitude refinement criterion



Left: Day 4 comparison between high resolution uniform c1024 run (**Top)** and an 3 level c64/c256/c1024 run **(Bottom)**. The AMR technique enables highly accurate simulations of the moving storms and captures the fine-scale details of the rotational flow with its associated band structure and large-scale wave train in the lee of the merged cyclone.

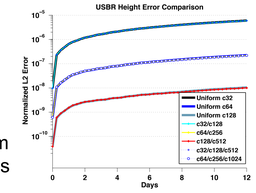


Day 0 Vorticity Profile **Day 1 Vorticity Profile** **Day 2 Vorticity Profile** **Day 4 Vorticity Profile**

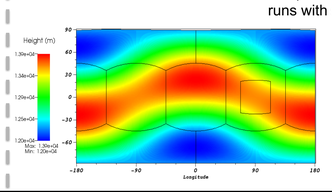
Note: The adaptive blocks are outlined in black.

Unsteady Solid Body Rotation (USBR)

- Shallow water test case which consists of a smooth flow (pictured right) forced by simple orography for 12 days [LH2007]
- Serves as a "Do No Harm Test", i.e. refinement does not increase error



Above: Normalized L2 error comparison between uniform runs and runs with static refinement patches.



Left: The USBR total height field. The flow completes a revolution once per day.

Acknowledgements and References

Thanks to my collaborators at LBNL, whose code was used for these simulations. The code was developed with funding from DoE Office of Science, BER and ASCR.

[LH2007] Läuter, M., D. Handorf, and K. Dethloff, 2005: Unsteady analytical solutions of the spherical shallow water equations. Journal of Computational Physics, 210, 535–553 .
[NJ2008] Nair, R. D. and C. Jablonowski, 2008: Moving vortices on the sphere: A test case for horizontal advection problems. American Meteorological Society, 136 (2), 699–711.
[MU2015] McCorquodale, P., P.A. Ullrich, H. Johansen and P. Colella. (2015) "An adaptive multiblock high-order finite-volume method for solving the shallow-water equations on the sphere" Submitted to Comm. Appl. Math. Comp. Sci. (Under Revision).
[RJ2012] Reed, K. A. and C. Jablonowski, 2012: Idealized tropical cyclone simulations of intermediate complexity: a test case for AGCMs. Journal of Advances in Modeling Earth Systems, 4 (2), 1942–2466.
[WD1992] Williamson, D. L., J. B. Drake, J. J. Hack, R. Jakob, and P. N. Swartrauber, 1992: A standard test set for numerical approximations to the shallow water equations in spherical geometry. Journal of Computational Physics, 102, 211–224.

Conclusions

AMR techniques show promising results in the 2D shallow water tests:

- Able to achieve similar errors to uniform runs with significantly fewer grid cells
- AMR grid does not degrade large scale smooth flows
- Multiple possible refinement criteria
- Able to resolve localized fine-scale features accurately

Future Work: Begin similar analysis using the full 3D Chombo-AMR with the simplified physics parameterization schemes discussed. Focus will be on assessing the dependence of these sub-grid parameterizations on the resolution and grid structure in AMR runs using idealized tropical cyclones and other test cases.