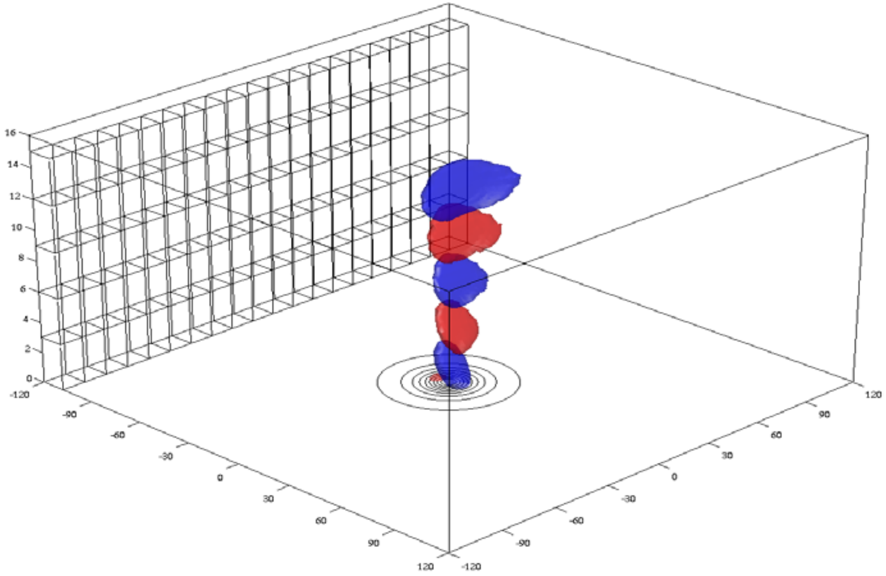
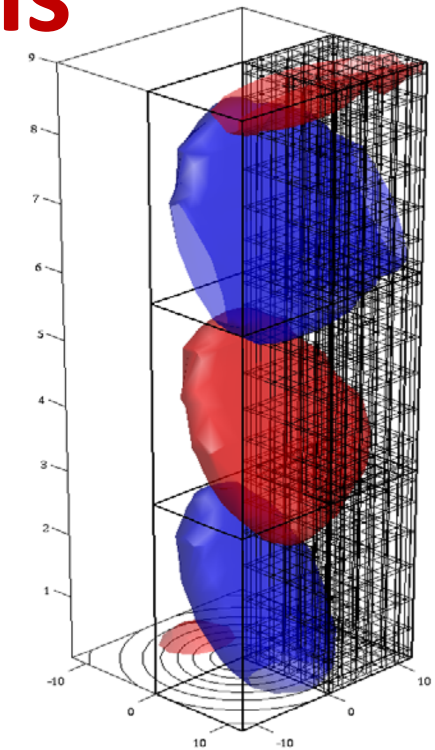
# A Multiscale Non-hydrostatic Atmospheric Model for Regional and Global Applications





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# Motivation

- Emerging need for next-generation models that are highly scalable and can be used across scales for Earth System Modeling applications.

- Our goal is to develop and evaluate a new Element Based Galerkin (EBG) modeling framework with the following capabilities:
  - Multi-scale non-hydrostatic dynamics (global-scale to mesoscale)
  - Flexible numerical methods
  - Highly scalable
  - Adaptive grids (e.g., statically and dynamically)
  - Adaptive time-stepping, as well as multi-rate time-integrators
  - Sub-grid scale physical parameterizations that are “scale-aware” for variable, unstructured, or adaptive grid applications
  - Flexible to enable earth system modeling (e.g., integrated, coupled..)

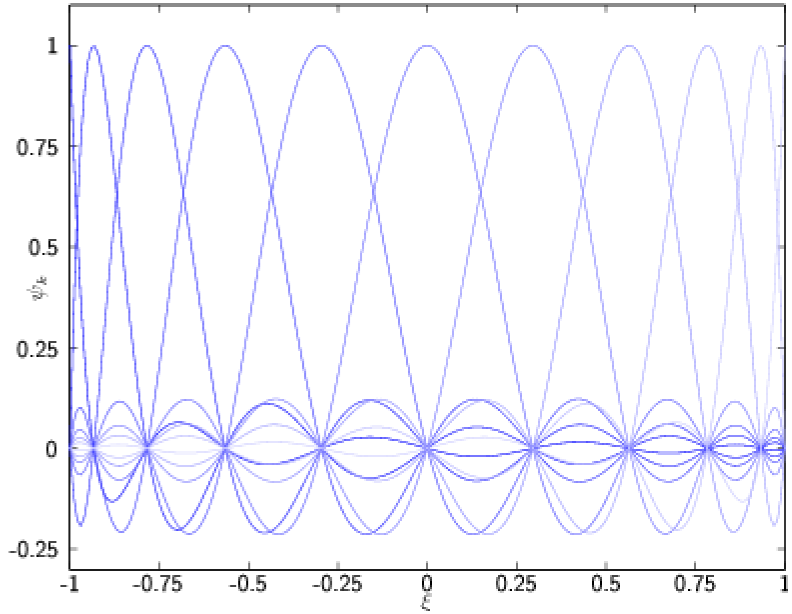
# Element Based Galerkin Method

## Background

Decompose the computational domain into **elements** in both horizontal and vertical direction (20 and 10, respectively in this 2D example).

Each element is transformed onto a canonical element [-1,1].

Within each element there are non-uniformly spaced interpolation (**nodal**) points (example for *N*=10, i.e., 10th order function).




Basis functions are defined on these points. Variables are constructed using a linear combination: $f_i(\boldsymbol{\xi}, t) = \sum_{k=1}^{N} \widehat{f}_i(t)\psi_k(\boldsymbol{\xi})$

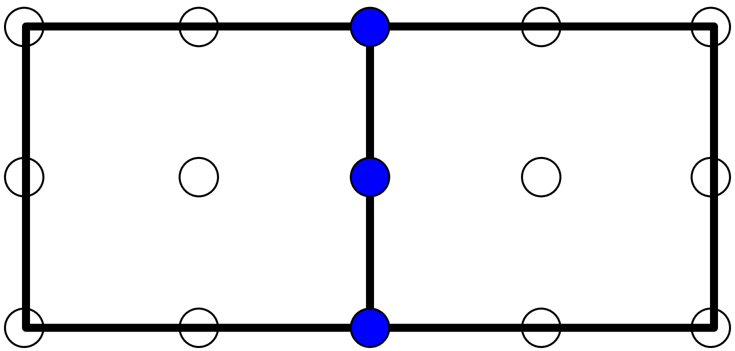
Solve the governing equation: $\frac{\partial \boldsymbol{q}}{\partial t} = F(\boldsymbol{q})$, where $\boldsymbol{q}(f_1, f_2, \ldots)$ is the solution vector

# Non-hydrostatic Unified Model of the Atmosphere (NUMA)

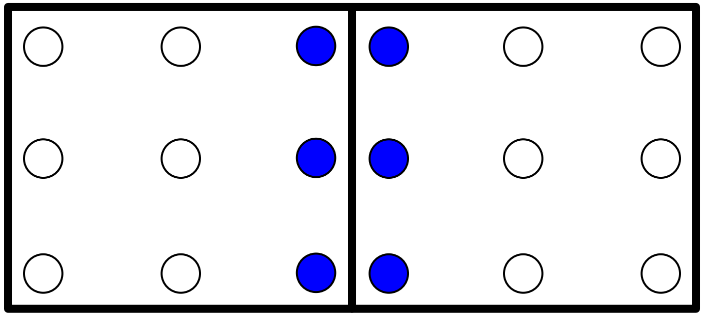
## Spatial discretization for Element Based Galerkin (EBG) methods

- Based on sharing of nodal points between adjacent elements

Continuous Galerkin (**CG**)



Discontinuous Galerkin (**DG**)



- Both methods are being developed within the **N**on-hydrostatic **U**nified **M**odel of the **A**tmosphere (**NUMA**) framework
- Both methods have excellent scalability characteristics because only minimal communication is needed

# NUMA Attributes


- Local and global conservation (e.g. mass, energy…)
- Highly accurate dynamical core
- Excellent scalability on massively parallel computers
- Geometric flexibility
- Dynamical core supports an array of time integrators, both fully explicit and implicit-explicit (IMEX)
- Dynamical core for global or limited area problems

# NUMA Design

## Unified Dynamics

- Resolutions of global models are rapidly approaching the nonhydrostatic scales.
- Both limited-area and global models can utilize the same equations.
- Common dynamical core for both models, flexibility for grids, forcing….

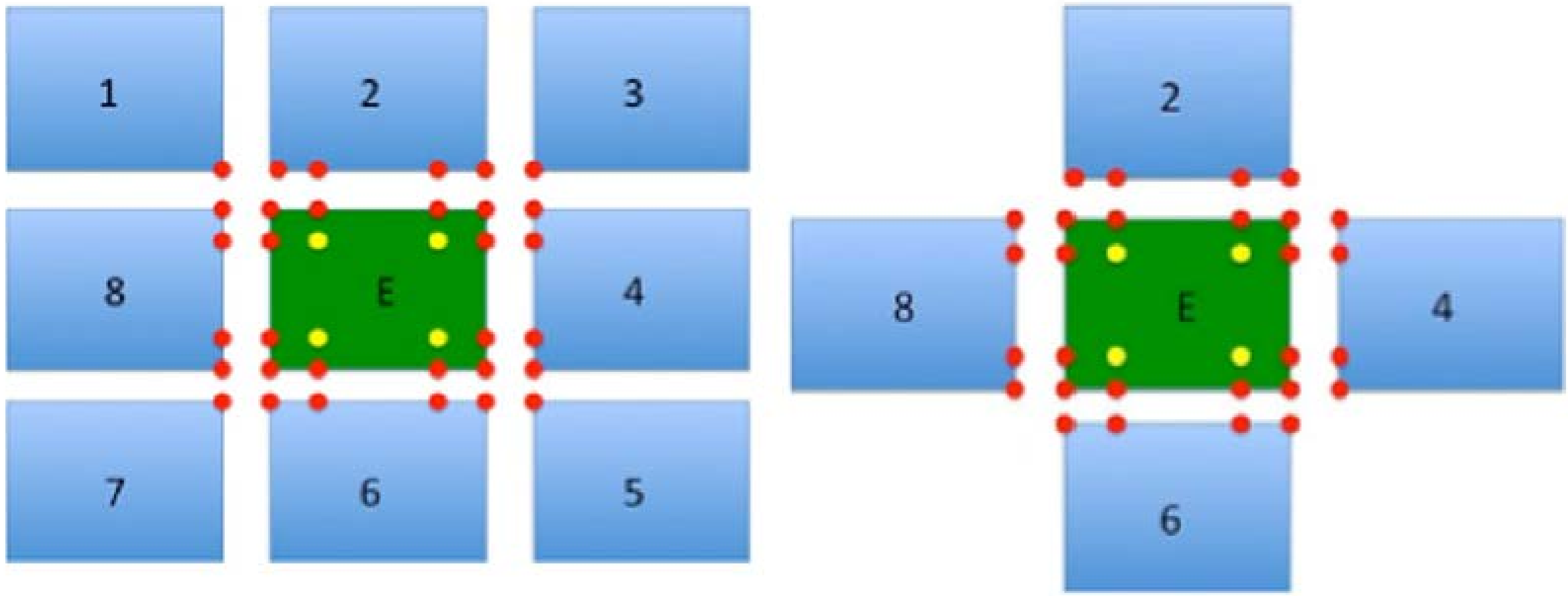
## Unified Numerics

- CG is more efficient for smooth problems at low processor counts.
- DG is more accurate for problems with sharp gradients and more efficient at high processor counts.
- Both EBGs utilize a common mathematical arsenal.
- NUMA allows the user to choose either CG or DG for the problem at hand.

## Unified Code

- Code is *modular*, with a common set of data structures.
- New time-integrators, grids, basis functions, physics, etc. may be swapped in and out.
- Code is portable: Successfully installed on Linux, Cray, IBM, Sun, Apple.
- 2D option available for prototypical and testing
- SVN code repository

# Computational Stencil for CG and DG

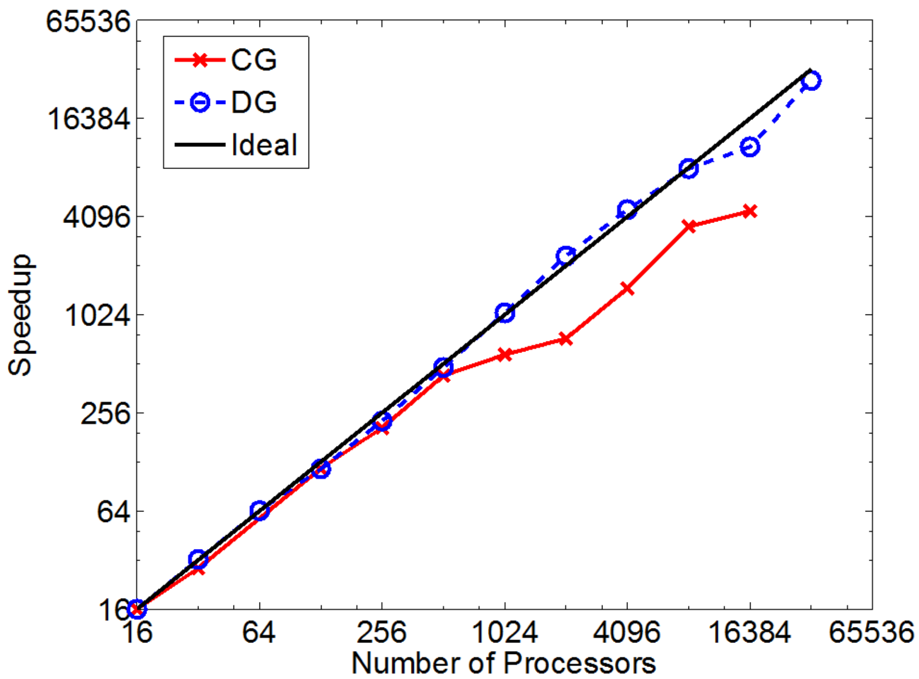


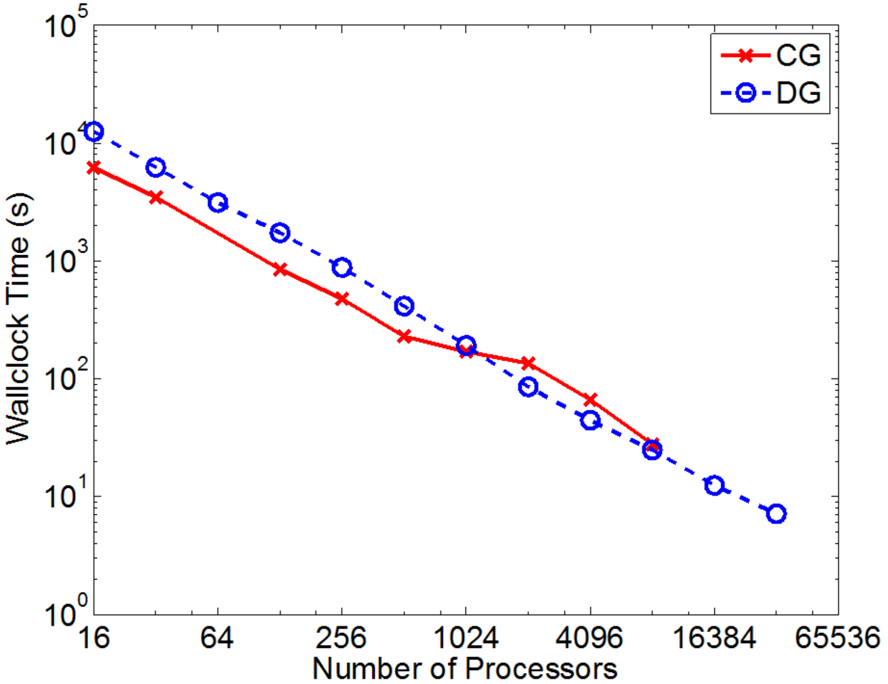

(a) CG stencil (b) DG stencil

- CG requires nodal information from 8 neighbors
- DG only requires information from its 4 face neighbors

Kelly and Giraldo (2012)

# NUMA Scalability



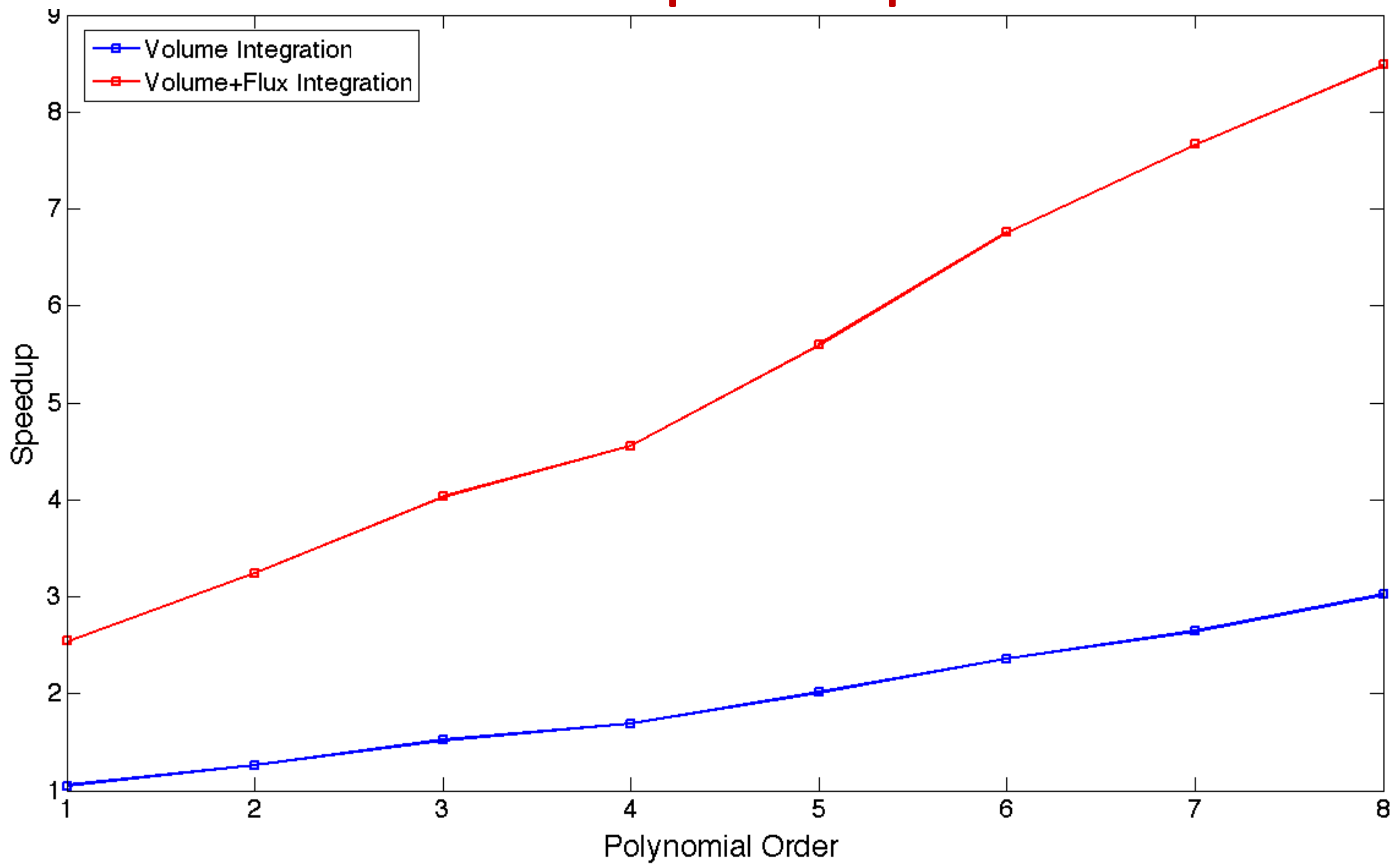




- Simulations performed with $h_x=h_y=h_z=32$, p=8
- Both methods scale well up to 8,000 processors.
- DG method scales up to 32,000 processors.
- Each processor contains only one single element which illustrates the fine-grain parallelism of both methods.

Kelly and Giraldo (2012)

# GPU-based Scalability of DG

## GPU Speedup

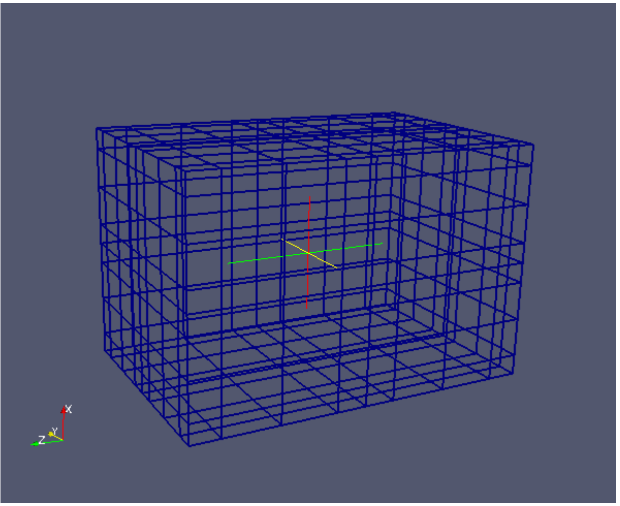



Multi-threading of the volume integrals (local operations) and the flux integrals (DG communication) leads to better performance on GPUs

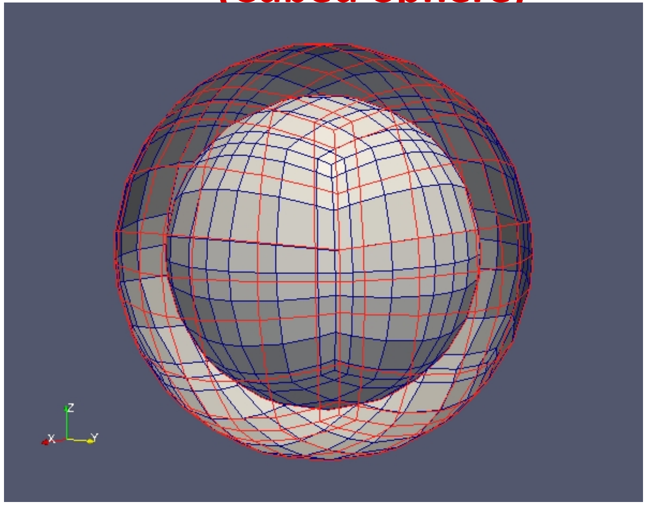
Gopalakrishnan and Giraldo (2012)

# NUMA Grid Mesh Examples

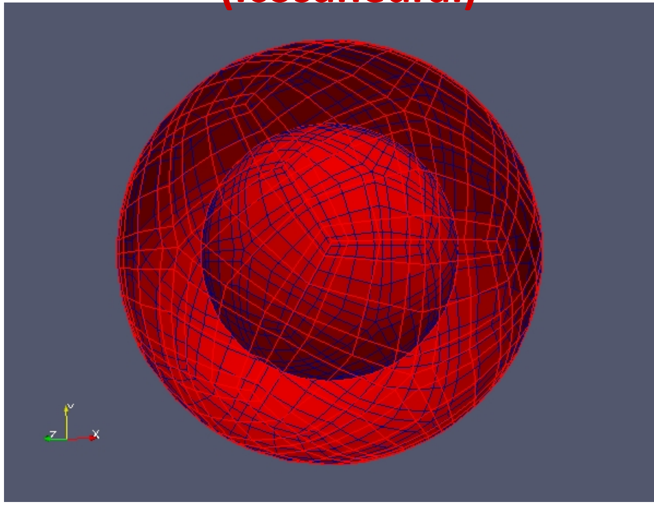
**Mesoscale Modeling Mode**

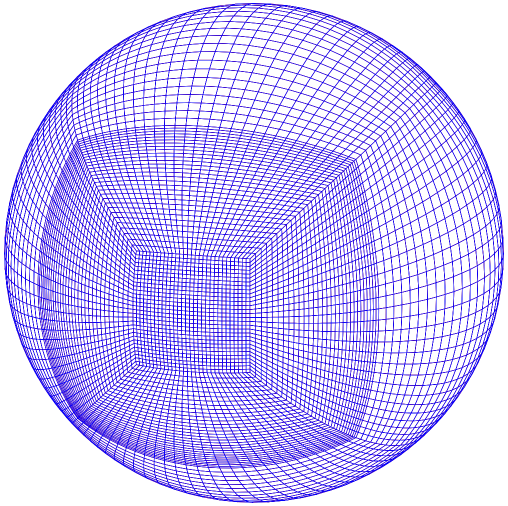



**Global Modeling Mode (Cubed-Sphere)**

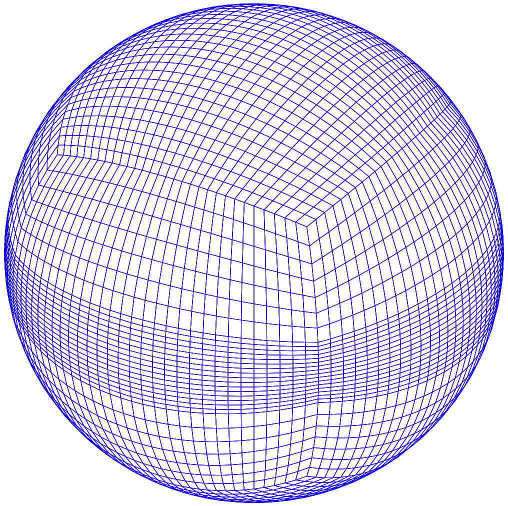



**Global Modeling Mode (Icosahedral)**



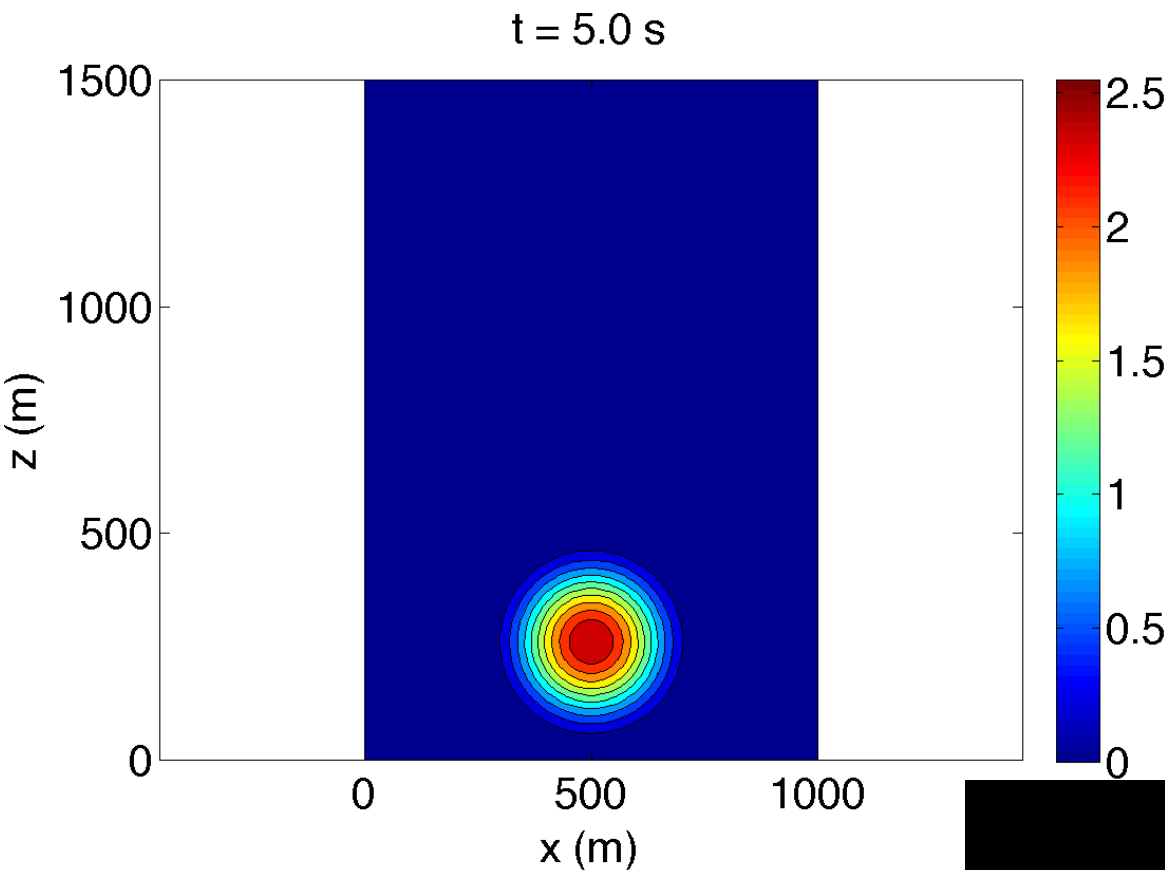
**Telescoping Grid**



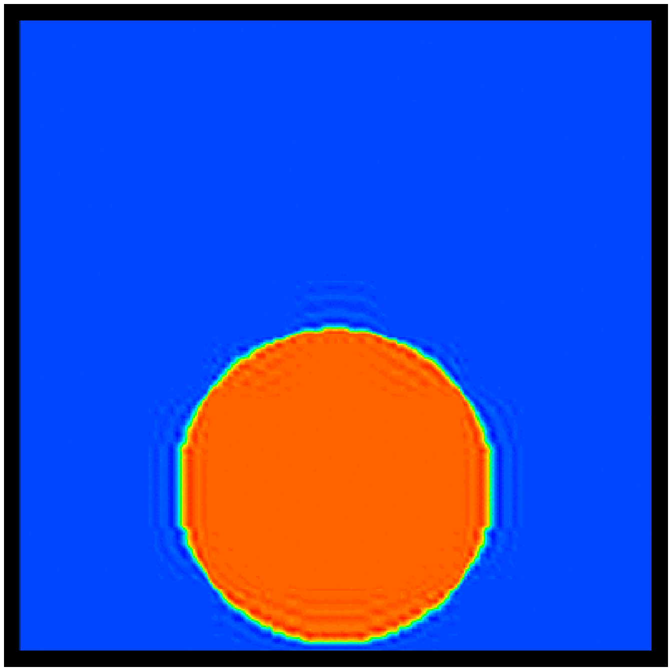
**ITCZ Grid**

# Basic Test Cases

## Smooth Bubble (3D)

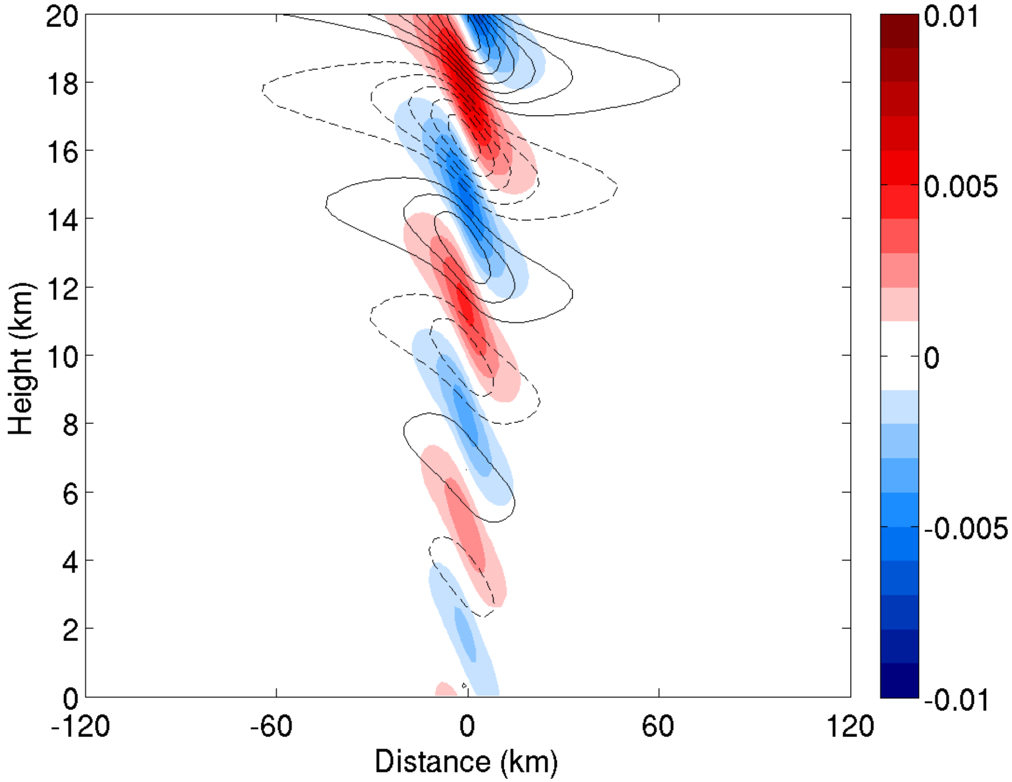



## (Non-Smooth) Robert Bubble



**Density Current w/50 m resolution and 10th order polynomials**

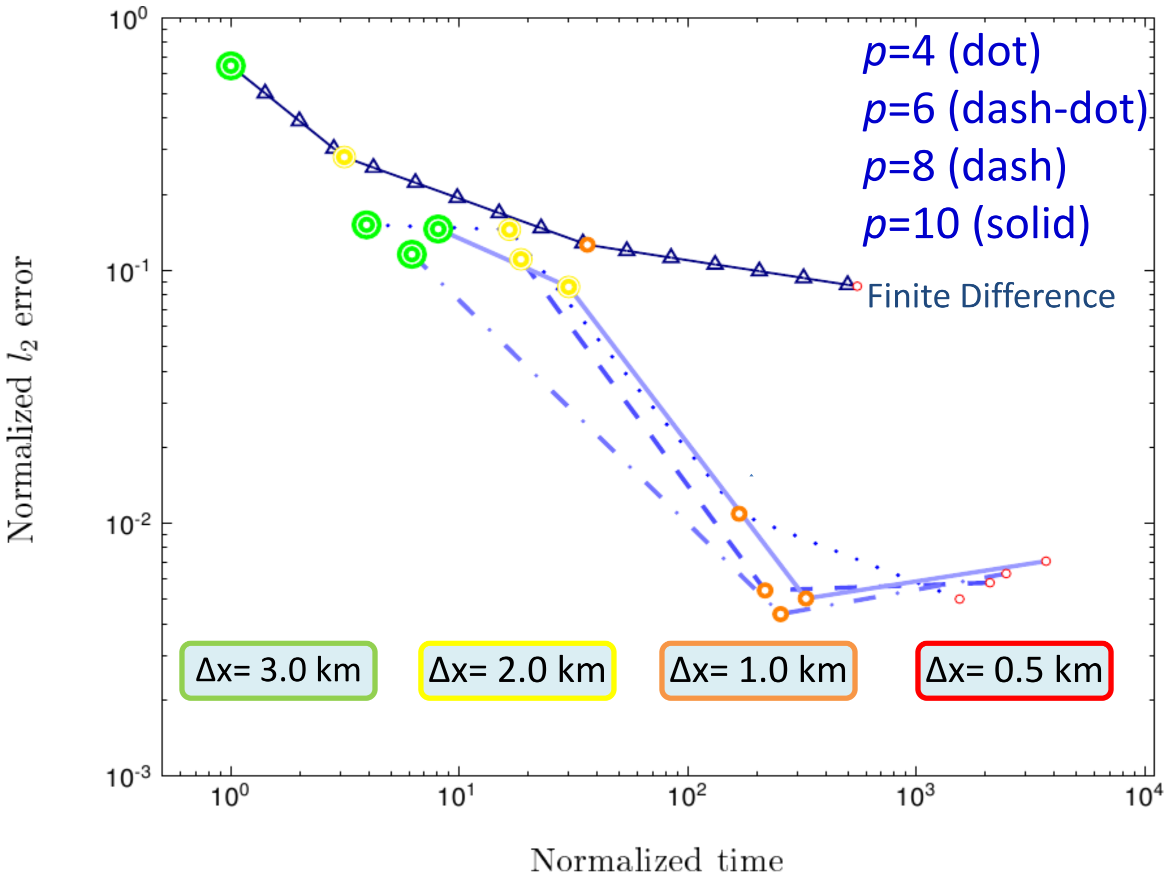
# 2-D Linear Hydrostatic Wave




- Vary number of elements (h) & polynomial order (p)
- p range: 4-10
- h-range: 6-120
- $\Delta x$ : 200 m – 10 km

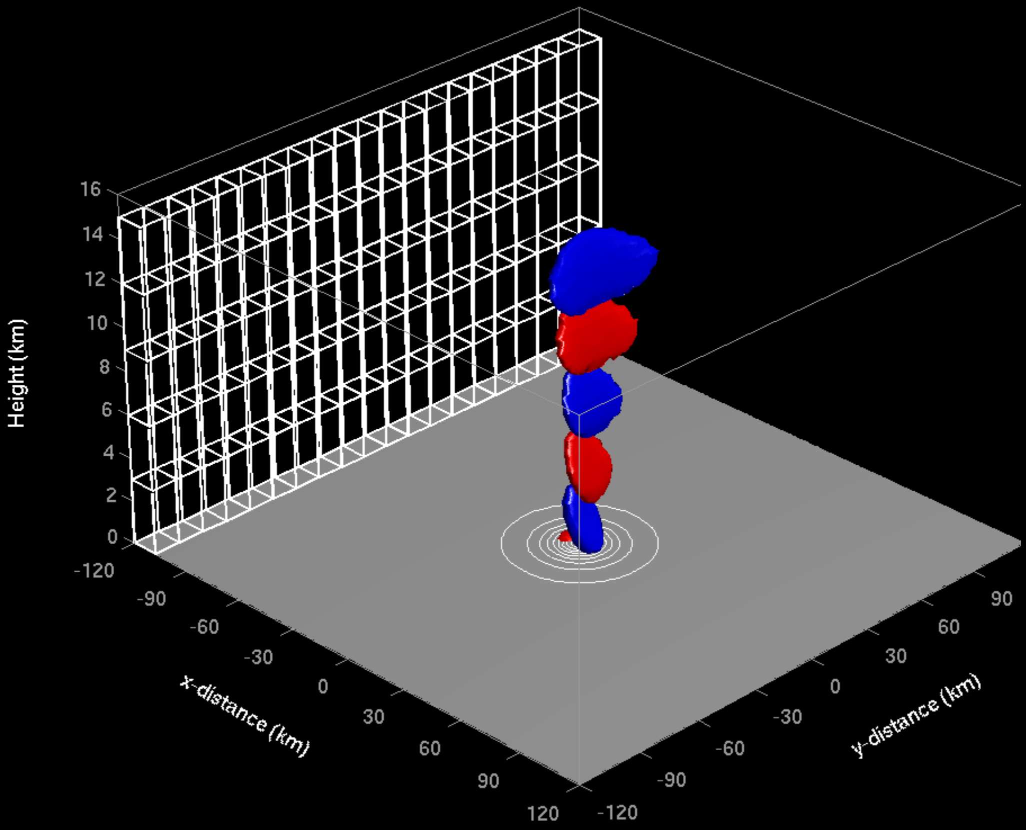
Compare SE model with analytic solution and evaluate the accuracy, computational cost and convergence.

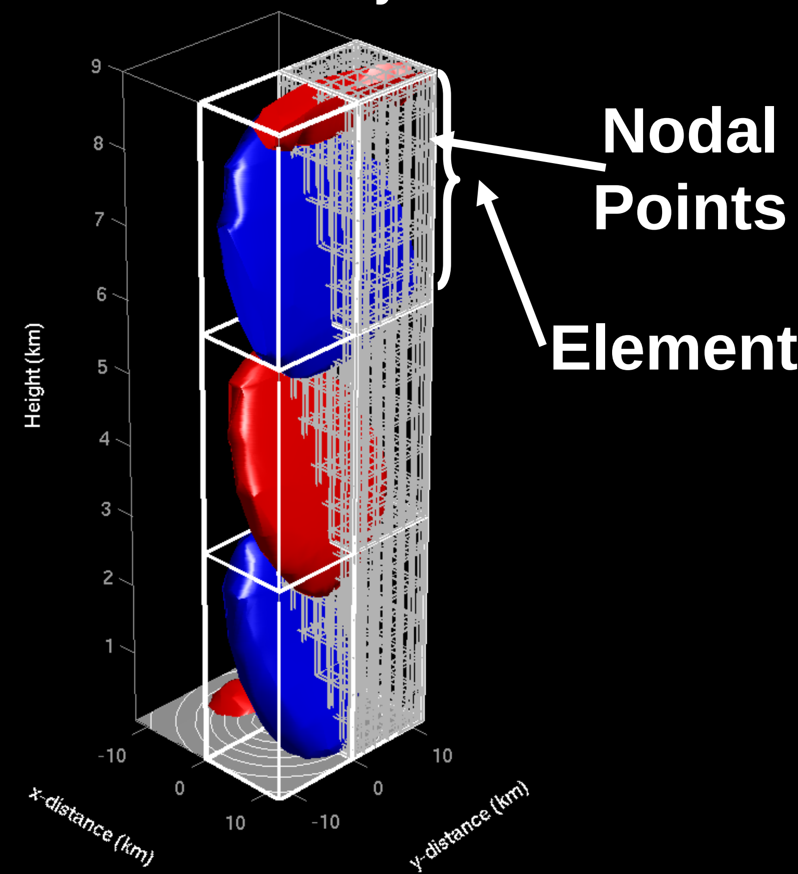
# 2-D Linear Hydrostatic Wave




***Efficacy***, defined as accuracy over cost, favors CG (NUMA), even in this serial implementation.

# 3-D Linear Hydrostatic Wave

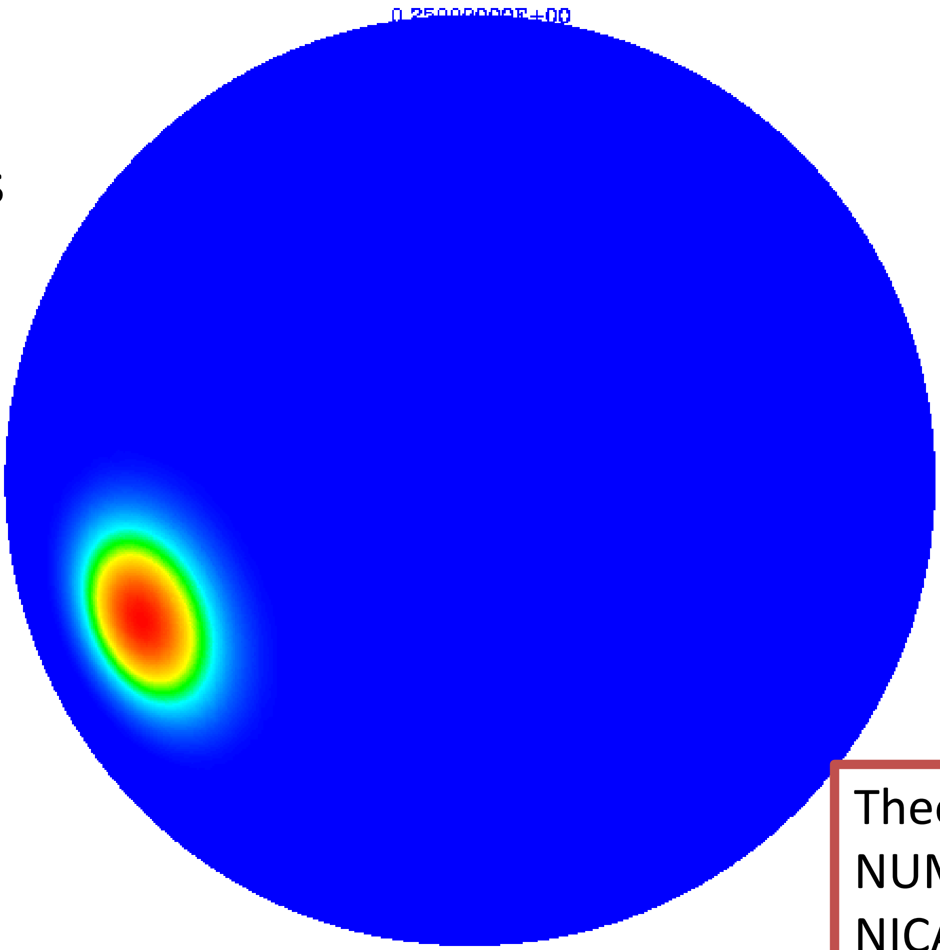



3-D linear hydrostatic wave test is nearly identical to the analytic solution for both CG and DG applications.

# 3-D Acoustic (Lamb) Wave Propagation

Potential Temperature for T=[0,12] hours

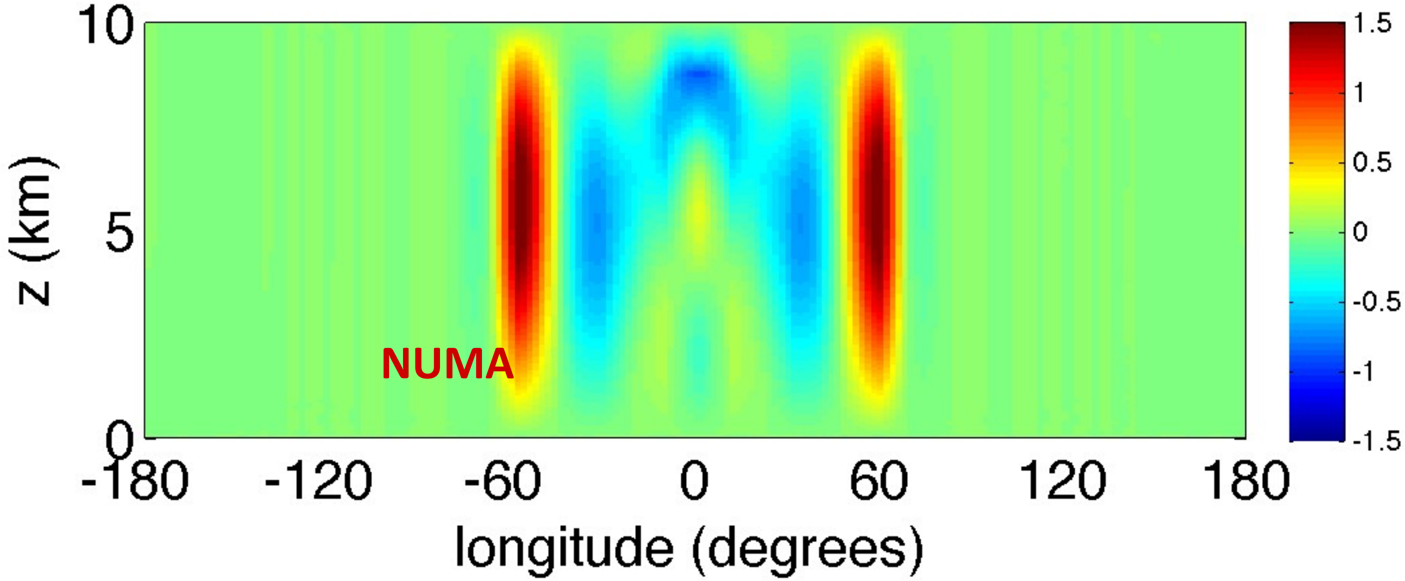


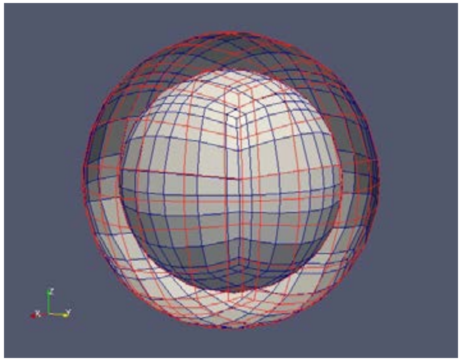
Theory=347 m/s,
NUMA model=347 m/s,
NICAM model = 338 m/s

3D acoustic (Lamb) wave propagation test case agrees well with theoretical expectations.

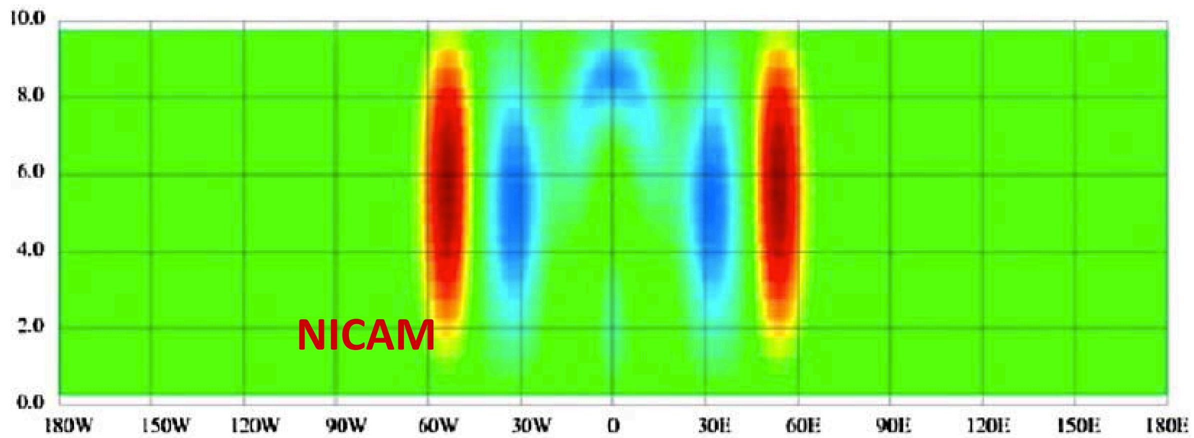
# Inertia-Gravity Wave Propagation

**(N=0.01, T=48 hours)** θ` (K)



**Grid**




Theory=32 m/s,
NUMA model=33 m/s,
NICAM model = 33 m/s

3D intertia-gravity wave test case agrees well with theory.

# Incorporation of Physical Processes

**Physical parameterization implementation**

- Interface for basic differential operators (gradient, divergence, curl, laplacian), with analytic derivatives as opposed to FD method
- Fortran module **mod_interface.f90**

Include the module and relevant operator(s)

Call the relevant operator

Example

```
subroutine stability(n,q)

use mod_grid,only: npoin
use mod_constants,only: gravity
use mod_interface,only: compute_gradient

implicit none

real :: n(npoin),q(npoin)
real :: dthetadz(npoin),grad_q(3,npoin)

call compute_gradient(q,grad_q)
dthetadz=grad_q(3,:)
n=sqrt(gravity/theta*dthetadz)

end
```

# Incorporation of Physical Processes

## Surface Fluxes, Boundary Layer, Vertical Diffusion

- Surface roughness $z_0$
- Friction velocity $u_*$
- momentum, sensible, latent heat fluxes
- Test cases: evolution of well mixed PBL (Ekman spiral), sea-breeze, wave breaking

## Microphysics

- Port the 2D code to 3D (warm, Kessler-type)
- Upgrade to involve ice species
- Test cases: 2D and 3D squall line, storm-splitting

## Cumulus parameterization

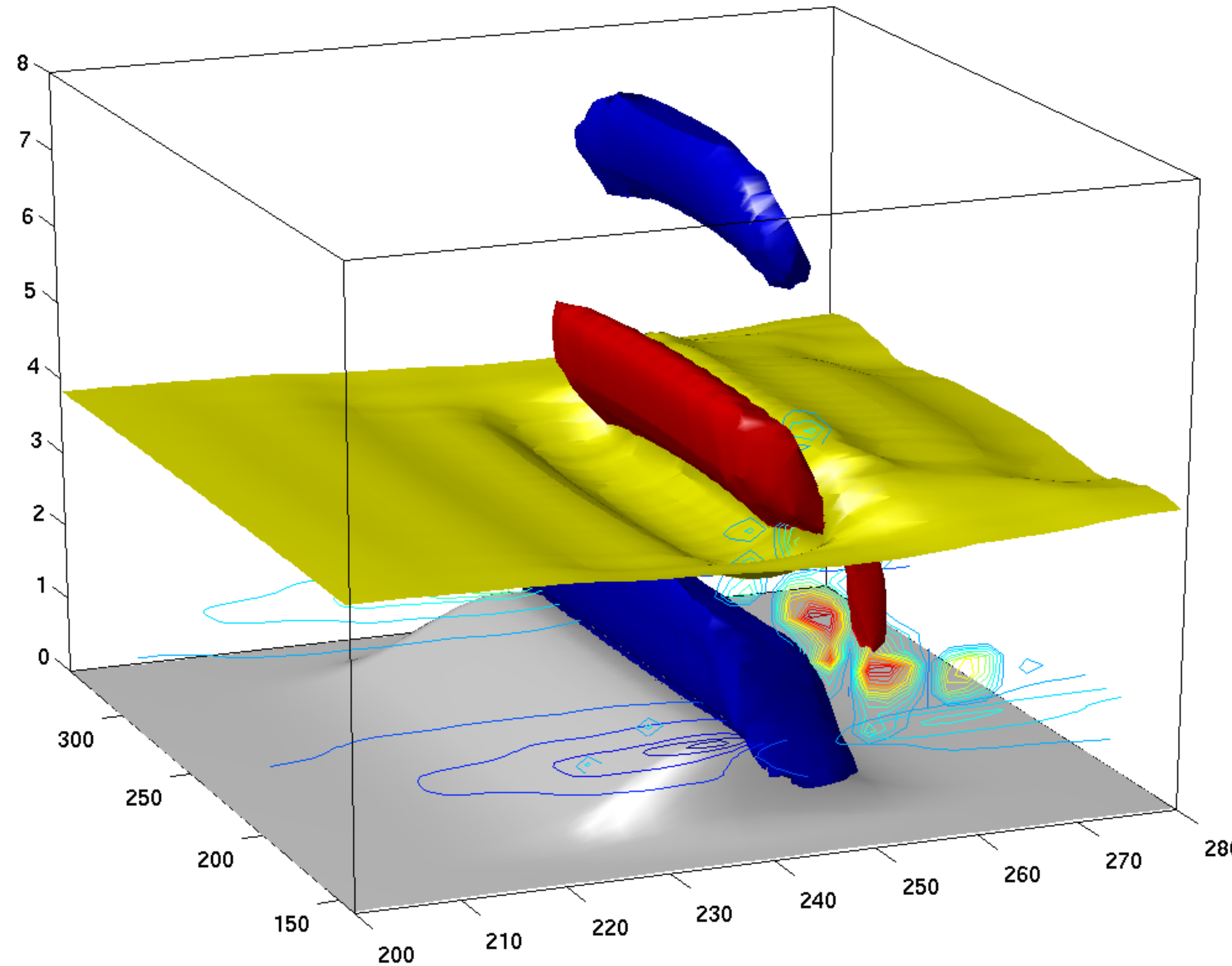
- Invoked when nodal spacing is above a predetermined threshold value
- Shallow/Deep
- Scale-aware parameterization to avoid abrupt transitions
- Test cases: large scale (global), moist baroclinic instability

## Radiation

- Test cases: convective-radiative equilibrium, tropical belt

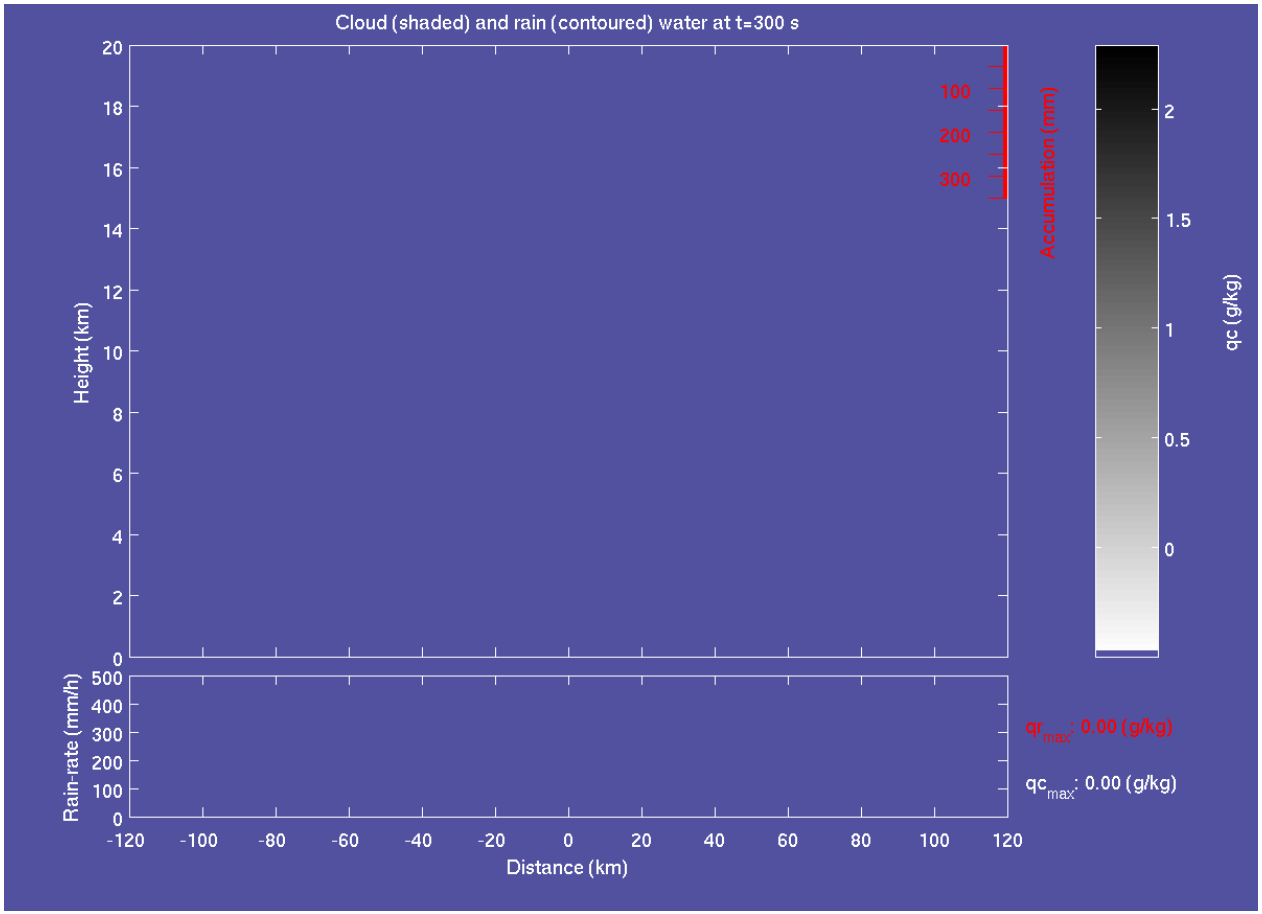
# 3-D Non-Linear Gravity Wave

$\vartheta$=290 K (yellow)
w=+2 $ms^{-1}$ (red)
w=-2 $ms^{-1}$ (blue)
v(z=1 km), c.i. 2.5 $ms^{-1}$
$K_m$(y=190 km), c.i. 2.5 $m^2s^{-1}$
topography (gray)




3D nonlinear gravity wave with wave overturning and vertical mixing.

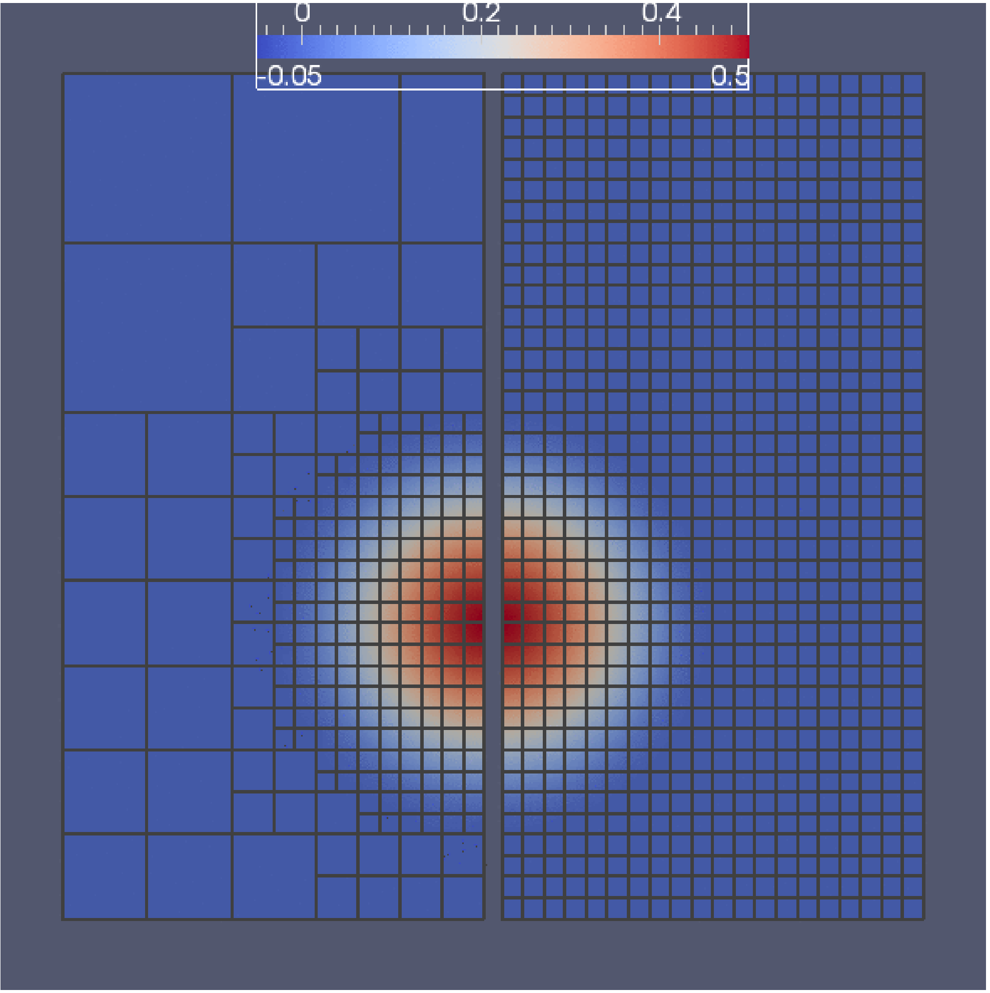
# 2-D Squall Line Test Case

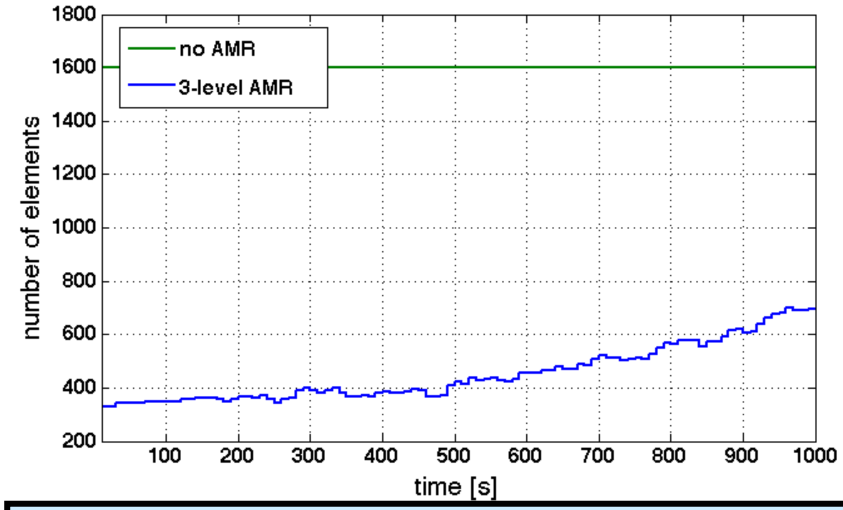



- Implementation of Kessler microphysics.
- Variable nodal spacing has no negative impact.

*Gabersek, Giraldo, Doyle, MWR (2012)*

# Non-conforming Adaptive Mesh Refinement




- Non-conforming adaptive mesh refinement capability can increase efficiency.
- Possible applications: tropical cyclones, dispersion, urban, coastal, severe storms, topographic flows....

*Kopera and Giraldo JCP (2013)*

# Summary and Future Directions

## NUMA Development and Evaluation:

- Attributes
  - ✓highly accurate dynamical core
  - ✓excellent scalability on massively parallel computers
  - ✓geometric flexibility
  - ✓flexible dynamical core for global or local area problems
- Extensive testing and evaluation already performed
- Possible next generation model for U.S. Navy, candidate for ESPC.
- Prototype for Korea’s next-generation global model
- NUMA selected by Argonne National Lab as flagship application for PETSc (winner of prestigious DoE Lawrence Award).

## Future Directions:

- Incorporation of full physics for global and mesoscale applications
- Coastal ocean model version of NUMA
- Coupling to waves, ice, ocean


QUESTIONS?

# NUMA Collaborators

## Model Development

- Michal Kopera, Applied Math, Naval Postgraduate School
- Andreas Müller, Applied Math, Naval Postgraduate School
- Shiva Gopalakrishnan, Indian Institute of Technology (Bombay)
- Jim Kelly, Exa Corporation

## Physical Parameterization and Coupling

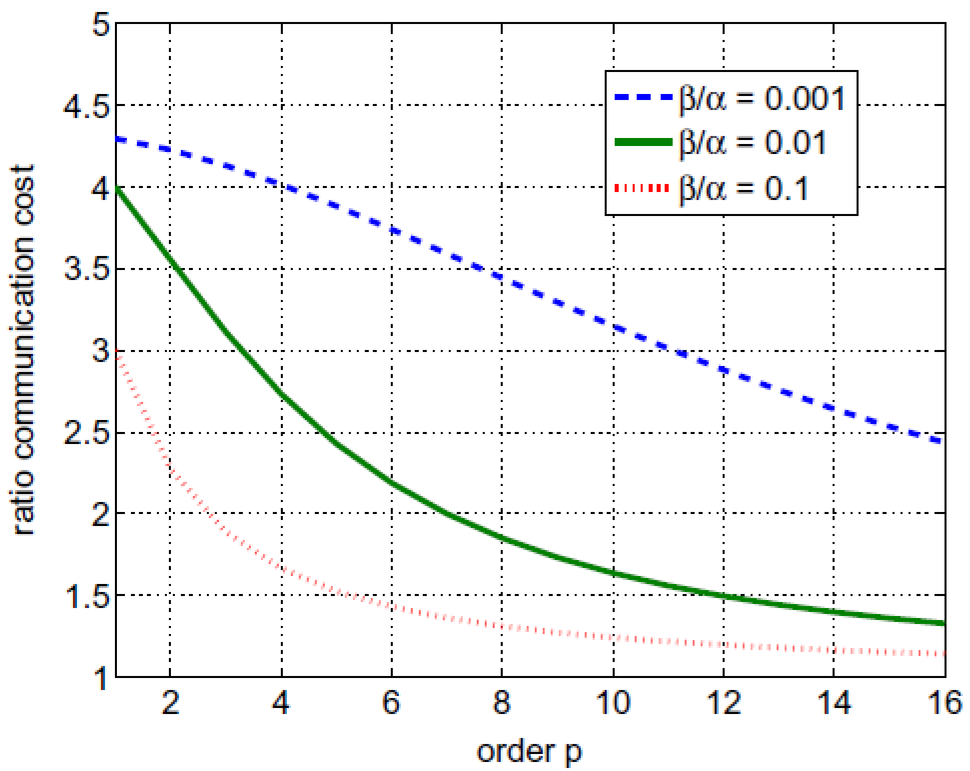
- Naval Research Laboratory (Monterey)
- Simone Marras, Barcelona Supercomputing Center

## Time-Integrators

- Emil Constantinescu, Argonne National Laboratory
- Dale Durran, University of Washington

## Preconditioners

- Carlos Borges, Applied Math, Naval Postgraduate School
- Les Carr, Applied Math, Naval Postgraduate School




The Ratio of communication costs $C_{CG}/C_{DG}$ plotted for transfer rate/latency ratios $\beta/\alpha = 0.1, 0.01$ and $0.001$ for polynomial orders $N$