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

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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..)
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., 10\(^{th}\) order function).

Basis functions are defined on these points. Variables are constructed using a linear combination:

\[
\overline{f}_i(\xi, t) = \sum_{k=1}^{N} \hat{f}_i(t) \psi_k(\xi)
\]

Solve the governing equation: \(\frac{\partial \mathbf{q}}{\partial t} = F(\mathbf{q})\), where \(\mathbf{q}(f_1, f_2, \ldots)\) 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 Non-hydrostatic Unified Model of the Atmosphere (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
 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)
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) $t = 5.0 \text{ s}$

(Non-Smooth) Robert Bubble

Density Current w/50 m resolution and 10th order polynomials
Compare SE model with analytic solution and evaluate the accuracy, computational cost and convergence.

- Vary number of elements (h) & polynomial order (p)
  - p range: 4-10
  - h-range: 6-120
  - $\Delta x : 200 \text{ m} - 10 \text{ km}$
Efficacy, defined as accuracy over cost, favors CG (NUMA), even in this serial implementation.
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)

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

3D inertia-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`

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
```

Include the module and relevant operator(s)

Call the relevant operator
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

$\theta = 290\, \text{K (yellow)}$

$w = +2\, \text{ms}^{-1} \text{ (red)}$

$w = -2\, \text{ms}^{-1} \text{ (blue)}$

$v(z=1\, \text{km}), \text{c.i. } 2.5\, \text{ms}^{-1}$

$K_m(y=190\, \text{km}), \text{c.i. } 2.5\, \text{m}^2\text{s}^{-1}$

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)
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 $N$. 