The Global Nonhydrostatic Atmospheric Model MPAS: Preliminary results from uniform and variable-resolution mesh tests

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MPAS - Model for Prediction Across Scales

Based on unstructured centroidal Voronoi (hexagonal) meshes using C-grid staggering and selective grid refinement.

Jointly developed, primarily by NCAR and LANL/DOE, for weather, regional climate, and climate applications

MPAS infrastructure - NCAR, LANL, others.
MPAS - Atmosphere (NCAR)
MPAS - Ocean (LANL)
MPAS - Ice, etc. (LANL and others)
Primary drivers for global dynamical core development

(1) Scalable solvers needed for the new computer architectures.
(2) Nonhydrostatic global atmospheric models needed for cloud-permitting simulations ($\Delta x \sim \text{kms}$).

Newton Institute, PDEs on the sphere, major core development efforts:
(1) FV methods on icosahedral (hexagonal) meshes.
(2) FV, SE, and DG methods on the cubed sphere.
Most of these models are using horizontally-explicit integration techniques to facilitate scaling to $10^5$-$10^6$ processors or application to accelerators.
MPAS: C-Grid Spherical Centroidal Voronoi Meshes

Unstructured mesh
Mesh generation uses a density function.
Uniform resolution – traditional icosahedral mesh.

Centroidal Voronoi
Mostly hexagons, some pentagons and 7-sided cells.
Cell centers are at cell center-of-mass.
Lines connecting cell centers intersect cell edges at right angles.
Lines connecting cell centers are bisected by cell edge.

C-grid
Solve for normal velocities on cell edges.

Equations
Fully compressible
nonhydrostatic equations
(explicit simulation of clouds)

Solver Technology
Integration scheme similar to WRF.
WRF-NRCM physics
Nonhydrostatic formulation

Equations

• Prognostic equations for coupled variables.
• Generalized height coordinate.
• Horizontally vector invariant eqn set.
• Continuity equation for dry air mass.
• Thermodynamic equation for coupled potential temperature.

Time integration scheme

As in Advanced Research WRF - Split horizontally-explicit vertically-implicit Runge-Kutta (3rd order)

Variables:
\( (U, V, \Omega, \Theta, Q_j) = \tilde{\rho}_d \cdot (u, v, \tilde{\eta}, \theta, q_j) \)

Vertical coordinate:
\( z = \zeta + A(\zeta) h_s(x, y, \zeta) \)

Prognostic equations:
\[
\frac{\partial V_H}{\partial t} = -\frac{\rho_d}{\rho_m} \left[ \nabla_z \left( \frac{p}{\zeta} \right) - \frac{\partial z_H p}{\partial \zeta} \right] - \eta k \times V_H
\]
\[
- v_H \nabla_z \cdot V - \frac{\partial \Omega v_H}{\partial \zeta} - \rho_d \nabla_z K - eW \cos \alpha - \frac{uW}{r_e} + F_{V_H},
\]
\[
\frac{\partial W}{\partial t} = -\frac{\rho_d}{\rho_m} \left[ \frac{\partial p}{\partial \zeta} + g\tilde{\rho}_m \right] - (\nabla \cdot vW) \zeta
\]
\[
+ \frac{uU + vV}{r_e} + e(U \cos \alpha - V \sin \alpha) + F_W,
\]
\[
\frac{\partial \Theta_m}{\partial t} = - (\nabla \cdot V \theta_m) \zeta + F_{\Theta_m},
\]
\[
\frac{\partial \tilde{\rho}_d}{\partial t} = - (\nabla \cdot V) \zeta,
\]
\[
\frac{\partial Q_j}{\partial t} = - (\nabla \cdot V q_j) \zeta + \rho_d S_j + F_{Q_j},
\]

Diagnostics and definitions:
\[
\theta_m = \theta [1 + (R_v/R_d)q_v]
\]
\[
p = p_0 \left( \frac{R_d \zeta \Theta_m}{\tilde{\rho}_d} \right)^\gamma
\]
\[
\frac{\rho_m}{\rho_d} = 1 + q_v + q_c + q_r + \ldots
\]
Variable Resolution Meshes

Applications: Regional climate, weather prediction
(address problems with one-way nesting)

Static refinement: Obvious next step for applications

Smooth conforming meshes: Motivations
(i) unstructured mesh looks the same everywhere
(ii) preserve the accuracy of the numerics
(iii) minimize wave-reflection problems
at mesh density transitions
Voronoi meshes will allow us to cleanly incorporate both downscaling and upscaling effects (avoiding the problems in traditional grid nesting) and to assess the accuracy of the traditional downscaling approaches used in regional climate and NWP applications.
Domain Decomposition for Parallel Processing

A global 30 km mesh broken into 2562 blocks

Close-up of block decomposition showing ghost cell data that indicates interblock communication
(from Todd Ringler)
Simulation rate given for the dynamical core only
• 8 scalars w/positive-definite advection
• 41 vertical levels
• All runs on a Cray XT5m (lynx)
• MPI parallelism only; no OpenMP yet

NB: Very little optimization has been performed so far besides an attempt to remove any unnecessary halo updates.

120-km simulations:
• 40962 grid cells
• 93% efficiency on 240 cores (relative to 8 cores)
• 79% efficiency on 504 cores
• 63% efficiency on 912 cores

60-km simulations:
• 163842 grid cells
• 98% efficiency on 504 cores (relative to 24 cores)
• 91% efficiency on 912 cores

Weak-scaling extrapolation:
60 km – 912 cores (91%)
30 km – 3,648 cores
15 km – 14,592 cores
7.7 km – 58,368 cores
3.8 km – 233,472 cores
1.9 km – 933,888 cores

Preliminary MPAS-ANH Scaling Results
Preliminary MPAS-Ocean Scaling Results

Hydrostatic ocean model

(1) Explicit RK4 integration
(2) Timesplit
Model for Prediction Across Scales: MPAS

**Global simulation tests**

Baroclinic waves

Convection on a Cartesian plane

Supercell thunderstorms

- W contours at 1, 5, and 10 km (c.i. = 3 m/s)
- 30 m/s W surface shaded in red
- Rainwater surfaces - transparent shells
- Surface temperature shaded on baseplane
- 500 meter mesh
Model for Prediction Across Scales: MPAS

Global variable-resolution moist baroclinic waves

Squall-lines on a Cartesian plane using a variable-resolution mesh
GOES-W, 2010-10-25, 0 UTC, vapor channel
Remnants of TS Richard

Mountain waves

Tornadic thunderstorms
MPAS Forecast Tests

Current MPAS Physics:
- WSM6 cloud microphysics
- Kain_Fritsch or Tiedtke convection
- Monin-Obukhov surface layer
- YSU pbl, Noah land-surface
- RRTMG lw and sw or CAM radiation.

MPAS mesh (4x finer than below), 41 levels

Δx = 15 km
Δx = 60 km

Western Pacific refinement
MPAS Forecast Tests

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MPAS mesh (4x finer than below), 41 levels

Eastern Pacific refinement

Δx = 15 km  Δx = 60 km
Variable Resolution Mesh Tests

$\Delta t$ is constant on the variable-resolution mesh.

Smagorinsky: \[ K_h = c_s^2 l^2 |Def| \]

$l^2$ scales with $\Delta x^2$

Viscosity and hyper-viscosity formulations:

\[ K_2 \nabla_\zeta^2 \phi \quad K_2 \text{ scales with } \Delta x^2 \]

\[ K_4 \nabla_\zeta^2 (\nabla_\zeta^2 \phi) \quad K_4 \text{ scales with } \Delta x^4 \]

Locally 2$\Delta$ waves are damped at same rate.
20 October 2010
5 day accumulated precipitation (mm)

CFSR (~ 40 km)

MPAS (60 km)
uniform resolution
Smagorinsky

MPAS (60-15 km)
variable resolution
Western Pacific ref.
Smagorinsky,
($\Delta x^2$ scaling)
MPAS (60 – 15 km mesh)
Western Pacific refinement
15 October initialization
Smagorinsky, \( \Delta x^2 \) scaling
MPAS (60 – 15 km mesh)
Eastern Pacific refinement
21 October initialization
Smagorinsky, $\Delta x^2$ scaling
MPAS (60 – 15 km mesh)  
Eastern Pacific refinement  
21 October initialization

East-Pac mesh (\(\Delta x = 60-15 \text{ km}\))  
Smagorinsky, \(\Delta x^2\) scaling

East-Pac mesh (\(\Delta x = 60-15 \text{ km}\))  
Smagorinsky, \(\Delta x^2\) scaling;  
background \(K_4 = 2 \times 10^{10} \text{ m}^4\text{s}^{-1}\)  
(15 km mesh value, \(\Delta x^4\) scaling)
Summary

Preliminary results show adequate scaling for both ocean and atmospheric cores. (MPI-only configuration)

Variable-resolution mesh simulations in both idealized and full-physics NWP configurations suggest that the smooth mesh transitions are viable for applications.

The model filters, appropriately scaled by the mesh density, appear to be behaving properly.

Current and future work:

- Further optimization (MPI, OpenMP implementation).
- I/O (PIO) testing and development.
- Parameterizations (physics) need attention (scale-aware physics).
- Continued testing, hydrostatic – nonhydrostatic regime mesh transition.
- Applications.