Status of MPAS-O

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What is MPAS?

1. MPAS is an unstructured-grid approach to climate system modeling.

2. MPAS supports both quasi-uniform and variable resolution meshing of the sphere using quadrilaterals, triangles or Voronoi tessellations.

3. MPAS is a software framework for the rapid prototyping of single-components of climate system models (atmosphere, ocean, land ice, etc.).

4. MPAS offers the potential to explore regional-scale climate change within the context of global climate system modeling. Multiple high-resolution regions are permitted.

5. MPAS is currently structured as a partnership between NCAR MMM and LANL COSIM, where we intend to distribute our models through open-source, 3rd-party facilities (e.g. Sourceforge).
MPAS Component Development Teams

**MPAS-Ocean Team:**
Todd Ringler, Mark Petersen, Mat Maltrud, Chris Newman, Bob Higdon, Doug Jacobsen, Rob Lowrie, Jonathan Graham, Qingshan Chen

**MPAS-Atmos Hydrostatic Team:**
Bill Skamarock, Todd Ringler, Michael Duda, Sara Rauscher, Li Dong, Art Mirin, Chris Jeffery

**MPAS-Atmos Non-Hydrostatic Team:**
Bill Skamarock, Michael Duda, Laura Fowler and others in MMM

**MPAS-Land Ice Team:**
Bill Lipscomb, Steve Price, John Burkhart, Xylar Asay-Davis, Lili Ju, Max Gunzburger, Mauro Perego

All model components share a majority of their source code, are built from the same Makefile and will likely be used within the CESM.
A summary of the MPAS-O capabilities

Choice of isopycnal or z-level vertical coordinate at runtime.
Configurable with idealized or real-world boundary/forcing at runtime.
Can run on quad grids (i.e. POP meshes) or Voronoi tessellations.
Can run in quasi-uniform mode or with an arbitrary number of high-resolution regions.
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Can run in quasi-uniform mode or with an arbitrary number of high-resolution regions.

High-order reconstruction for horizontal and \textit{vertical transport}.
Laplacian and/or bi-harmonic mixing of velocity and tracers.
Nonlinear equation of state (Jackett and McDougall).
Pacanowski and Philander Richardson Number based vertical mixing.
Implicit solve for vertical mixing.
Two-time level, split-explicit time-stepping scheme (implemented and being tested).
Exact tracer conservation.

(\textit{Items} discussed on following slides.)
High-Order Vertical Tracer Advection

Vertical tracer advection requires tracer values at vertical cell edge. Four methods are available to interpolate tracer values to cell interface:

\[
\frac{\partial h\phi}{\partial t} + \nabla \cdot (h\phi \mathbf{u}) + h \frac{\partial}{\partial z} (h\phi w) = \nabla \cdot (h \kappa_h \nabla \phi) + h \frac{\partial}{\partial z} \left( \kappa_v \frac{\partial \phi}{\partial z} \right)
\]

\[
\frac{\partial}{\partial z} (h \phi w) = \phi^\text{top}_k w^\text{top}_k - \phi^\text{top}_{k+1} w^\text{top}_{k+1}
\]

Four methods are available to interpolate tracer values to cell interface:

- **Linear**
- **3rd order stencil**
- **4th order stencil**
- **Cubic spline**

Weights and stencils are shown in the figure.
Richardson-Number based Vertical Mixing with an Implicit Solver

Pacanowski-Philander vertical mixing

Based on Richardson Number, so viscosity and tracer diffusion increase with vertical shear and weaker stratification.

Implicit vertical mixing

Allows mixing to occur stably at fast timescales without constraining the model time step.

Operator splitting used on explicit and implicit tendency terms in the momentum and tracer equations.

\[
\frac{\partial h\varphi}{\partial t} + \nabla \cdot (h\varphi \mathbf{u}) + \frac{\partial}{\partial z} (h\varphi w) = \nabla \cdot (h\kappa_h \nabla \varphi) + h \frac{\partial}{\partial z} \left( \kappa_v \frac{\partial \varphi}{\partial z} \right)
\]

solve explicitly
\[\text{solve implicitly}\]

The modular computation of vertical mixing coefficients allows for an easy migration to KPP or other vertical turbulence closure scheme.
Design and Implementation of a two-time level, split-explicit scheme

removes barotropic component from baroclinic system.
Design and Implementation of a two-time level, split-explicit scheme

update baroclinic velocity $u_n'$, $G$

RHS based on mid-time state

slow mode

$\Delta t = t_{n+1} - t_n$

removes barotropic component from baroclinic system.
Design and Implementation of a two-time level, split-explicit scheme

update baroclinic velocity $t_n$

RHS based on mid-time state $\Delta t = t_{n+1} - t_n$

$u'_{n+1}, G$

removes barotropic component from baroclinic system.

update barotropic state $t_n, G$

$\bar{u}_{n+1/2}, \eta_{n+1/2}$

$\delta t = \Delta t / m$
Design and Implementation of a two-time level, split-explicit scheme

- **update baroclinic velocity**
  - \( t_n \)  
  - RHS based on mid-time state  
  - \( u'_{n+1}, G \)  
  - \( \Delta t = t_{n+1} - t_n \)
  - removes barotropic component from baroclinic system.

- **update barotropic state**
  - \( t_n, G \)  
  - \( \delta t = \Delta t/m \)

- **update tracers**
  - \( u'_{n+1/2} + \bar{u}_{n+1/2} \)  
  - \( \phi_{n+1}, \rho_{n+1} \)  
  - \( \Delta t = t_{n+1} - t_n \)
Design and Implementation of a two-time level, split-explicit scheme

- Update baroclinic velocity \( t_n \)
- RHS based on mid-time state
- \( u'_{n+1}, G \)
- \( \Delta t = t_{n+1} - t_n \)
- Removes barotropic component from baroclinic system.

- Update barotropic state \( t_n, G \)
- Fast mode
- \( \bar{u}_{n+1/2}, \eta_{n+1/2} \)
- \( \delta t = \Delta t/m \)

- Update tracers \( u'_{n+1/2} + \bar{u}_{n+1/2} \)
- Slow mode
- \( \varphi_{n+1}, \rho_{n+1} \)
- \( \Delta t = t_{n+1} - t_n \)

Estimate mid-time state and repeat or move to next time step.
Design and Implementation of a two-time level, split-explicit scheme

Estimate mid-time state and repeat or Move to next time step

A few nice properties of this approach:
1. Only need time-level n information.
2. Can run with or without the splitting (runtime choice).
3. Maintain exact tracer conservation.
4. Splitting approach is same for z-level or layer model.
At that last OMWG, focus was on variable resolution capability of MPAS-O.

R60km: local grid resolution

R60kmNA: local grid resolution

See example of this same variable resolution approach in CAM at Sara Rauscher’s poster.
The focus over the last development period has been on real-world, quasi-uniform simulations at 120 km, 60 km and 30 km resolutions.

nominal 120 km, 60 km and 30 km horizontal resolutions
z-level model, 40 levels (same as POP gx1v3)
topography taken from ETOPO, no smoothing, depth >= 2 levels
initial conditions for T and S from annual mean WOCE global climatology
time-invariant wind stress forcing from annual mean NCEP 1958-2000
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2nd-order, two-time level, predictor-corrector, unsplit time stepping
(dt=200 s, 100 s and 50 s for 120 km, 60 km and 30 km resolutions)
3rd-order reconstruction for horizontal transport
3rd-order reconstruction for vertical transport
Jackett and McDougall EOS
vertical diffusivity/viscosity based on Pacanowski and Philander with implicit solve.
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The simulations use bi-harmonic dissipation on u and tracers
(visc = 1.0e14 m^4/s, 2.5e13 m^4/s and 5.0e12 m^4/s)
restoring to WOCE annual mean T and S with 45 day time scale
Global 30 km Simulation: Snap-Shot of Surface Kinetic Energy

start of year 3
Global 30 km Simulation: Snap-Shot of Surface Kinetic Energy

There are many promising aspects of this simulation .... all of which might disappear as we integrate the model longer.
Global 60 km Simulation: Sea-Surface Height

Time mean SSH, Year 3, contour interval = 0.15 m, peak-to-peak amplitude= 3.0 m.
Comparison of the 120 km and 60 km simulations.
MPAS-POP comparison
Equatorial Undercurrent at 140W

black: POP x1 (30 km at equator)
red: MPAS 60 km (60 km at equator)
Overall, this figure does a great job of summarizing where we are at with MPAS-O. The raw features are present, sometimes with tantalizing hints of promise, but often without the fidelity of a highly polished model.
MPAS-POP comparison
Computational Efficiency

For a given simulation, we want to minimize wall clock time. We can reduce wall clock time by increasing the scaling efficiency and by reducing the computational time per degree of freedom. We have shown previously that model scales well out to at least 1000 processors.
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64 processors, MPAS @ 120 km, POP @ x1
MPAS-POP comparison
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MPAS is currently 6x slower than POP (caveats abound here). This is due to the following:
1. Have not invested any time in computational efficiency.
2. Use of derived data types and pointers (expect 2x improvement here).
3. Use of unstructured grids.

Our goal over the next six months is to bring MPAS on par with POP.
Plans for the next six-month cycle:

1. Finish testing and evaluation of two-time level, barotropic-baroclinic splitting scheme.

2. We plan to bring two manuscripts to the December meeting.
   Manuscript #1: Exploring a Multi-Resolution Approach for Global Ocean Modeling
   Manuscript #2: A Comparison of MPAS-O to POP

3. MPAS-wide optimization.

4. Facilitate/Coordinate/Participate in the design of general CESM/COM software interfaces to allow the use of unstructured-mesh dynamical core(s). (Note: This is already done on the CESM/CAM side.)

5. Finish implementation of Prather-like, method-of-moments, horizontal transport scheme. (This scheme will be available across the MPAS framework.)

6. Begin design of Gent-McWilliams mixing schemes.
Thanks!