A Variable Resolution Global Ocean Model

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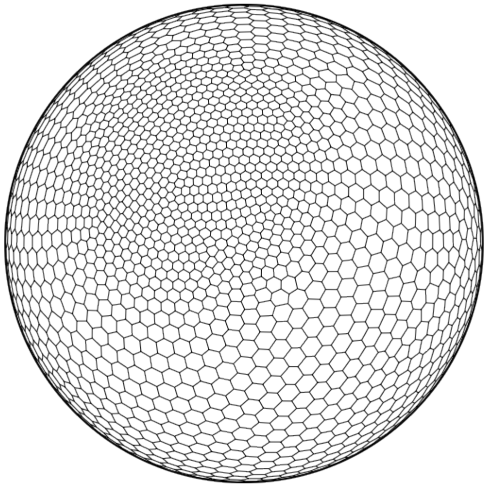
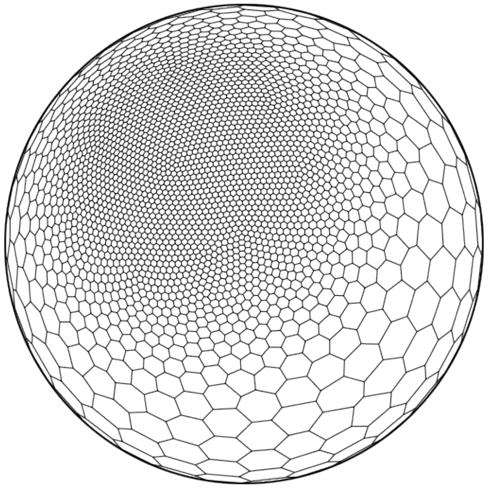
MPAS
Model for Prediction Across Scales

What is MPAS? Model for Prediction Across Scales

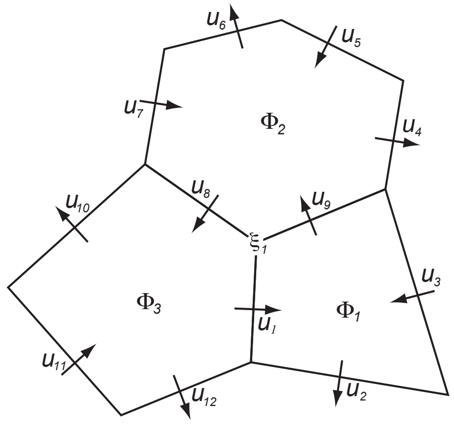
- MPAS is an unstructured-grid approach to climate system modeling.
- MPAS supports both quasi-uniform and variable resolution meshing of the sphere using quadrilaterals, triangles or Voronoi tessellations.
- MPAS is a software framework for the rapid prototyping of single-components of climate system models (atmosphere, ocean, land ice, etc.).
- MPAS offers the potential to explore regional-scale climate change within the context of global climate system modeling.
- 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)

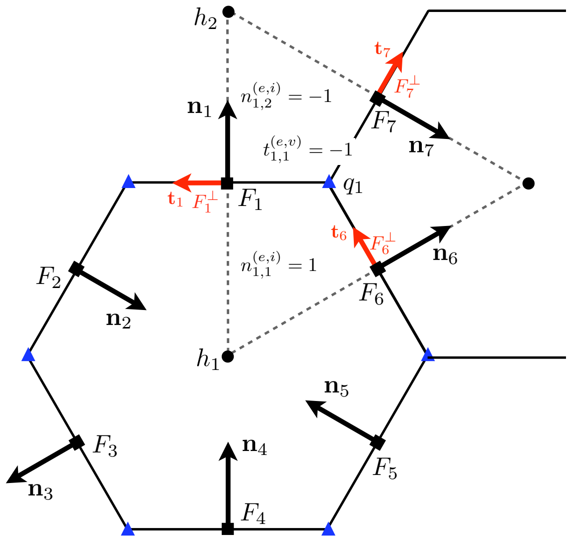




MPAS Numerics

- The numerical scheme developed by Thuburn et al. (2009) and Ringler et al. (2010) conserves mass, total energy and potential vorticity on these variable-resolution meshes.
- May run on grids with four, five, or six sided cells.
- C-grid staggering: velocity normals at cell edges
- Mass, geopotential, and kinetic energy are defined at cell centers.
- Vorticity and potential vorticity are defined at cell vertices.
- Code is “mesh-unaware”. That is, code is identical for Voronoi Tessellation, quad meshes, or any other grid configuration.





Ringler, T., J. Thuburn, J. Klemp and W. Skamarock, 2010: A unified approach to energy conservation and potential vorticity dynamics on arbitrarily structured C-grids, J. Comp. Physics, 229 3065–3090.

Thuburn, J., T. Ringler, J. Klemp and W. Skamarock, 2009: Numerical representation of geostrophic modes on arbitrarily structured C-grids, J. Comp. Phys, 228 (22), 8321-8335

MPAS Component Development Teams

MPAS-Ocean Team:

Todd Ringler, Mark Petersen, Mat Maltrud, Phil Jones, Chris Newman, Bob Higdon, Doug Jacobsen, Rob Lowrie, Jonathan Graham, Qingshan Chen

MPAS-Atmosphere Hydrostatic Team:

Bill Skamarock, Todd Ringler, Michael Duda, Sara Rauscher, Li Dong, Art Mirin, Chris Jeffery

MPAS-Atmosphere Non-Hydrostatic Team:

Bill Skamarock, Michael Duda, Laura Fowler and others in NCAR MMM

MPAS-Land Ice Team:

Bill Lipscomb, Steve Price, John Burkhart, Xylar Asay-Davis, Lili Ju, Max Gunzburger, Mauro Pereg

MPAS Development: Benefits of Collaboration

- **MPAS is a collaborative development between MMM at NCAR, COSIM at LANL, and others (e.g. LLNL)**
- **All developers share the same repository.**
- **Each component (atmosphere, ocean, etc) has its own modules for core-specific subroutines.**
- **All cores share common framework modules, which include:**
  - i/o and restart modules
  - time managers
  - grid initialization
  - parallelization, boundary updates, and block decomposition
  - support for registry file that automates variable declaration and input namelists
- **Improvements and bug-fixes from one core are transferred to other cores.**
- **MPAS components designed to be components of coupled climate models like CESM.**

Items Completed in MPAS-Ocean

- Choice of isopycnal or z-level vertical grids as namelist option
- Global ocean capability with land boundaries and bathymetry
- Del2 and del4 horizontal diffusion
- High-order horizontal advection for Voronoi tessellations
- Nonlinear equation of state (Jackett and McDougall)
- High-order vertical advection
- Pacanowski and Philander vertical mixing
- Implicit vertical mixing
- Split-explicit timestepping scheme has been implemented in a simplified prototype code and into MPAS-Ocean.
- MPAS-Ocean testing on quad meshes: Initial validation using POP
- Creation and testing of global uniform density Voronoi Tessellation grids, with topography: 120km, 60km, and 30km gridcell meshes.
- MPAS-Ocean testing on Voronoi Tessellation meshes: both uniform and variable density meshes.

Vertical Grid: General formulation accommodates many grids

- **Z-Level vertical grid:**
  - top layer thickness *h* evolves freely to account for SSH changes
  - In lower layers, thickness equation used to compute *w*, and we set *dh/dt=0*
  - density computed from T & S at each timestep
- **Isopycnal vertical grid:**
  - layer thickness *h* is prognostic variable for full 3D array
  - no vertical advection between layers (no remapping at this time)
  - density is fixed for each layer for all time
- **z*, $\tilde{z}$ vertical grids, under development**
  - accommodates deviations from the vertical coordinate for SSH, internal gravity waves.

thickness

$$\frac{\partial h}{\partial t} + \nabla \cdot (h\mathbf{u}) + \frac{\partial}{\partial z}(hw) = 0,$$

momentum

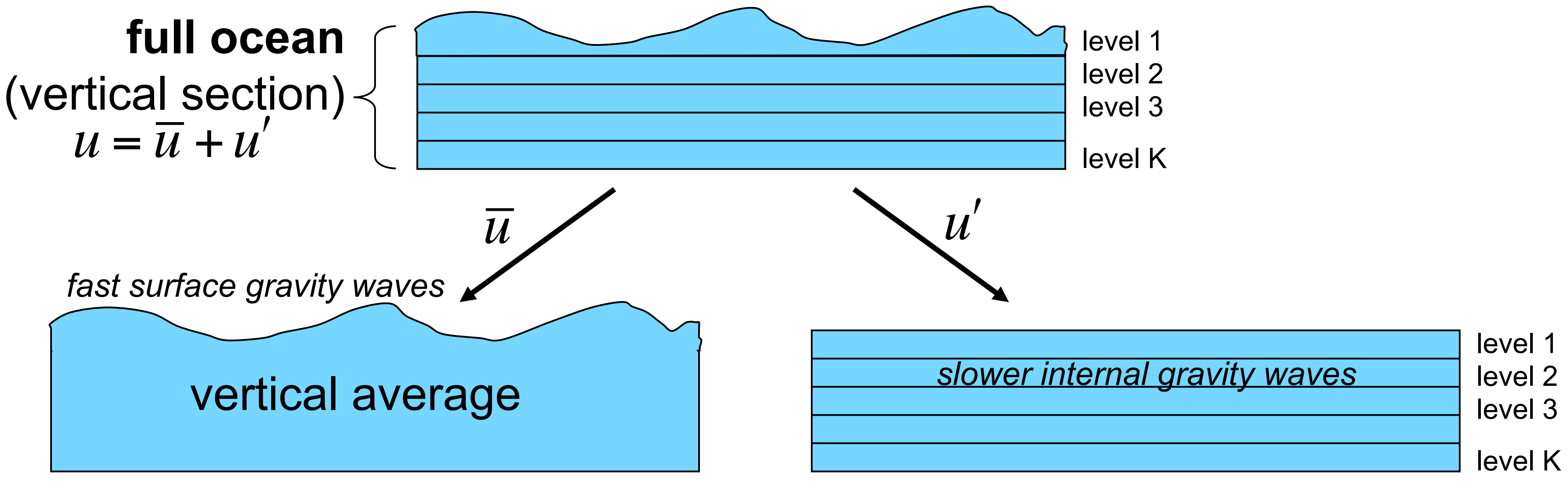
$$\frac{\partial \mathbf{u}}{\partial t} + q(h\mathbf{u}^{\perp}) + w\frac{\partial \mathbf{u}}{\partial z} = -\frac{1}{\rho_0}\nabla p - \frac{\rho}{\rho_0}\nabla\Phi - \nabla K + \nu_h(\nabla\delta + \mathbf{k}\times\nabla\eta) + \frac{\partial}{\partial z}\left(\nu_v\frac{\partial \mathbf{u}}{\partial z}\right),$$

tracer

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

Split-Explicit Timestepping

- **Split timestepping used for computational efficiency**



full ocean
(vertical section)
$u = \overline{u} + u'$

level 1
level 2
level 3
level K

$\overline{u}$

u'

fast surface gravity waves

vertical average

slower internal gravity waves

level 1
level 2
level 3
level K

$\overline{u}$ **barotropic part**

- 2D: single layer
- time step: explicit subcycling

u' **baroclinic part**

- 3D: multiple layers
- one explicit time step
- vertical mean = 0

Split-Explicit Time Stepping

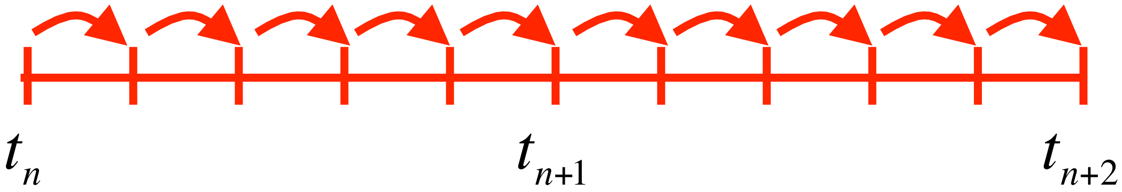
- **Baroclinic** system (3-D) explicit with long timestep

Splitting and coupling based on state at t_n

Predicted baroclinic:
u'_{n+1}
G barotropic tendencies

- **Barotropic** system (2-D) explicitly subcycled

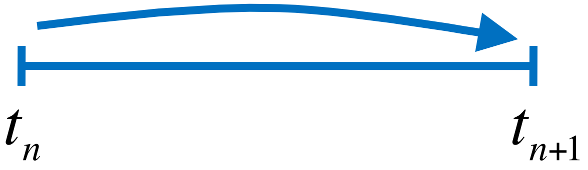
Based on state at t_n and forced by G



Time averaged velocities, SSH
$\overline{u}^*, \eta^*$

- **Tracer, density, pressure** update

flux tracers using
$u'^* + \overline{u}^*$



Predicted tracers, density:
$\varphi_{n+1}, \rho_{n+1}$

Split-Explicit Time Stepping

Timing tests, using periodic channel domain.

Maximum allowable timestep, seconds:

Grid cell size:	**80km**	**40km**	**20km**	**10km**
Runge-Kutta 4	300s	150s	75s	38s
Split Explicit	10,000s	5000s	2000s	1000s
Ratio	33	33	27	26

Wall clock time, seconds, to run for ten model days

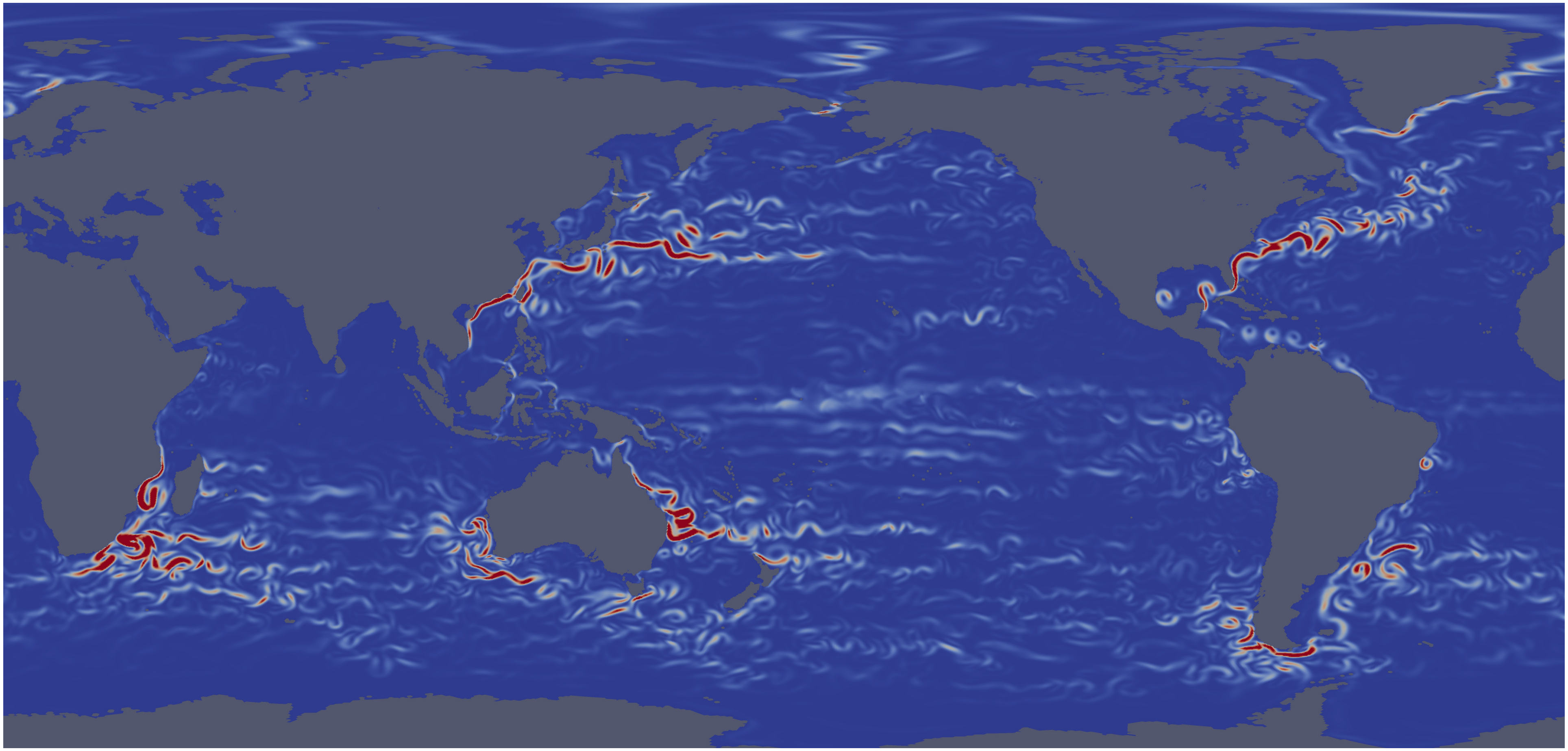
Grid cell size:	**80km**	**40km**	**20km**	**10km**
Runge-Kutta 4	420s	940s	2040s	7750s
Split Explicit	12s	59s	153s	560s
Speed-up factor	35	16	13	14
Number procs	16	16	64	128

MPAS-Ocean Testing and Validation

- Global uniform density Voronoi Tessellation grids (hexagons), with topography: 120km, 60km, and 30km gridcell meshes.
- Global variable density Voronoi Tessellation grids.
- Global quadrilateral grids identical to standard POP grids for direct comparison: 3°, 1°, 0.1° gridcell meshes.
- Double Gyre wind-driven basin
- Periodic channel, wind-driven, idealization of Antarctic Circumpolar Current.
- Split-explicit time stepping validation:
  - Test barotropic subcycling with single layer basin with surface waves
  - Test baroclinic timestep by filtering out barotropic mode in basin domain
- Standard Shallow Water Test Case Suite

MPAS-Ocean Testing and Validation: Global runs

- Global uniform density Voronoi Tessellation grids (hexagons), with topography: 120km, 60km, and 30km gridcell meshes.

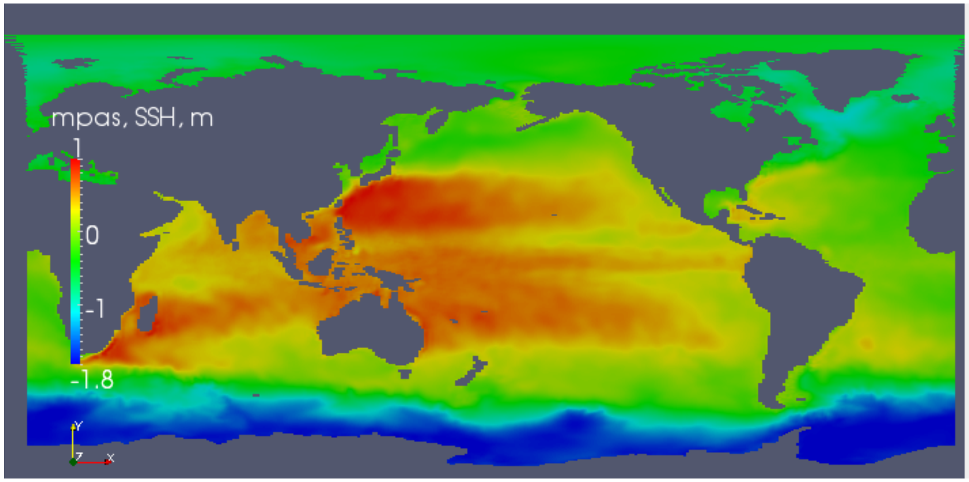


Kinetic energy after five years for the 30km grid. These simulations used z-level mode with realistic bathymetry, third order horizontal and vertical advection, Richardson-number based implicit vertical mixing, and hyper-diffusion and hyper-viscosity in the horizontal. The ocean was initialized with Levitus mean climatology, and is forced by yearly mean NCEP winds. The top layer includes a restoring tendency for temperature and salinity.

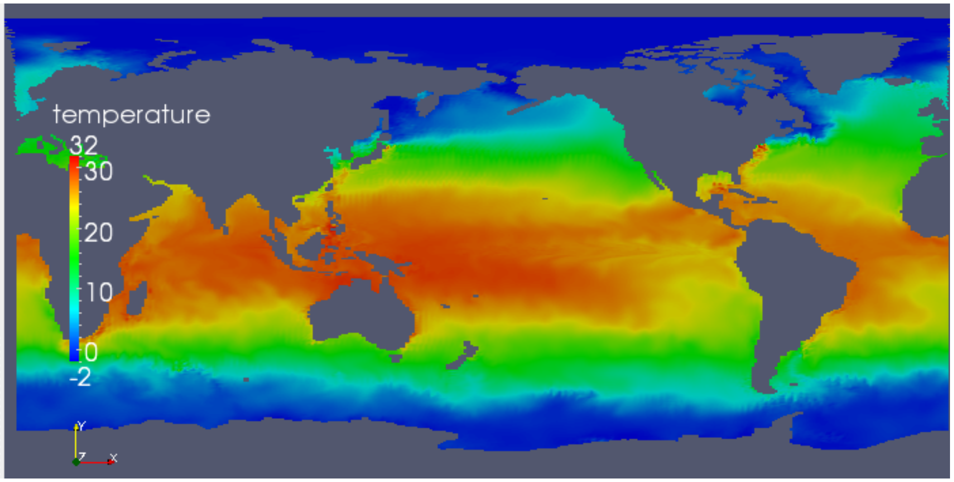
MPAS-Ocean Testing and Validation: POP Comparison

- Global quadrilateral grids identical to standard POP grids for direct comparison: 3°, 1°, 0.1° gridcell meshes. Shown: 1° after 40 days.

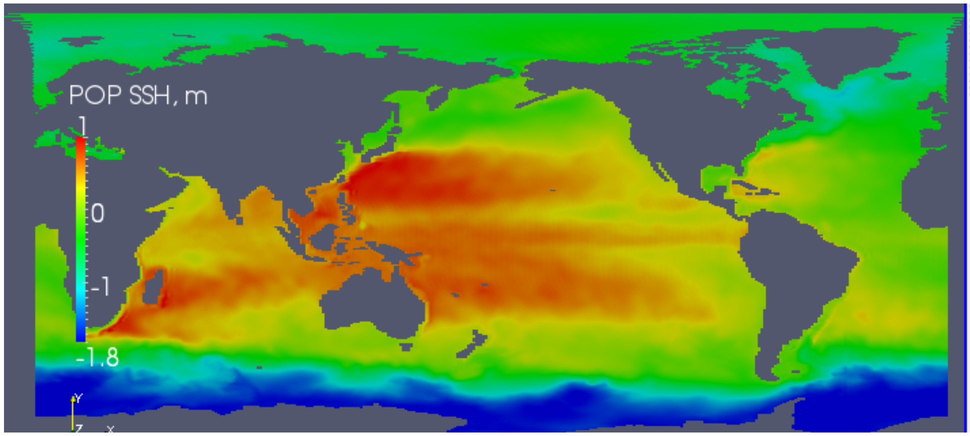
MPAS-Ocean SSH



MPAS-Ocean SST



POP SSH



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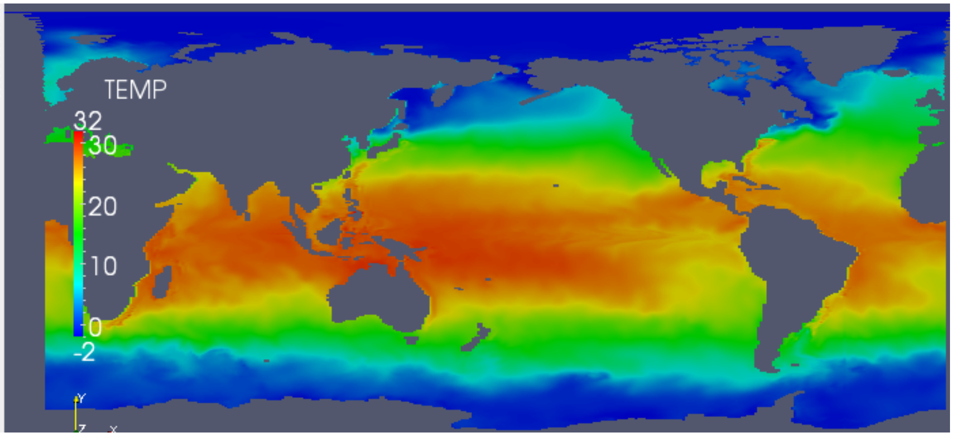
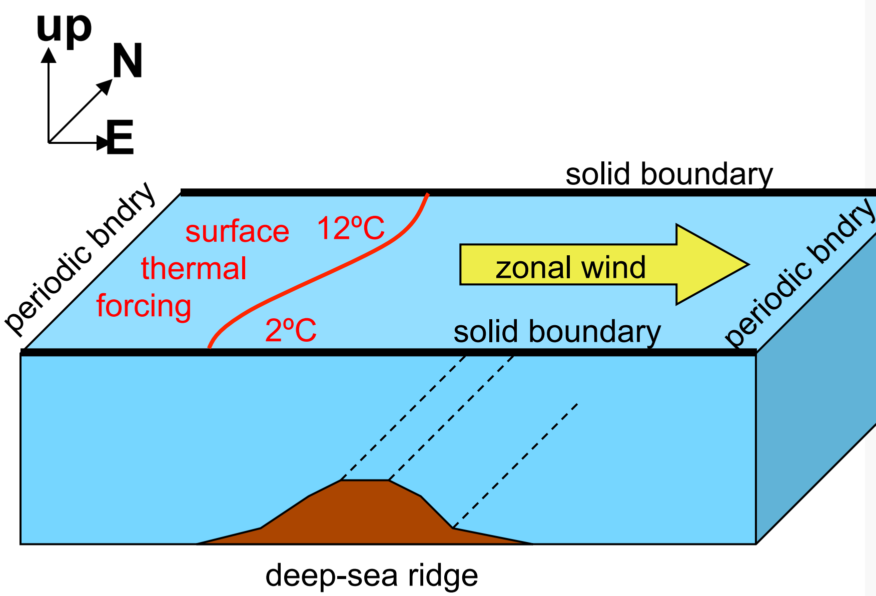


MPAS-Ocean Testing and Validation

- Periodic channel, wind-driven, idealization of Antarctic Circumpolar Current.



up
N
E

solid boundary

periodic bndry

surface thermal forcing

12ºC

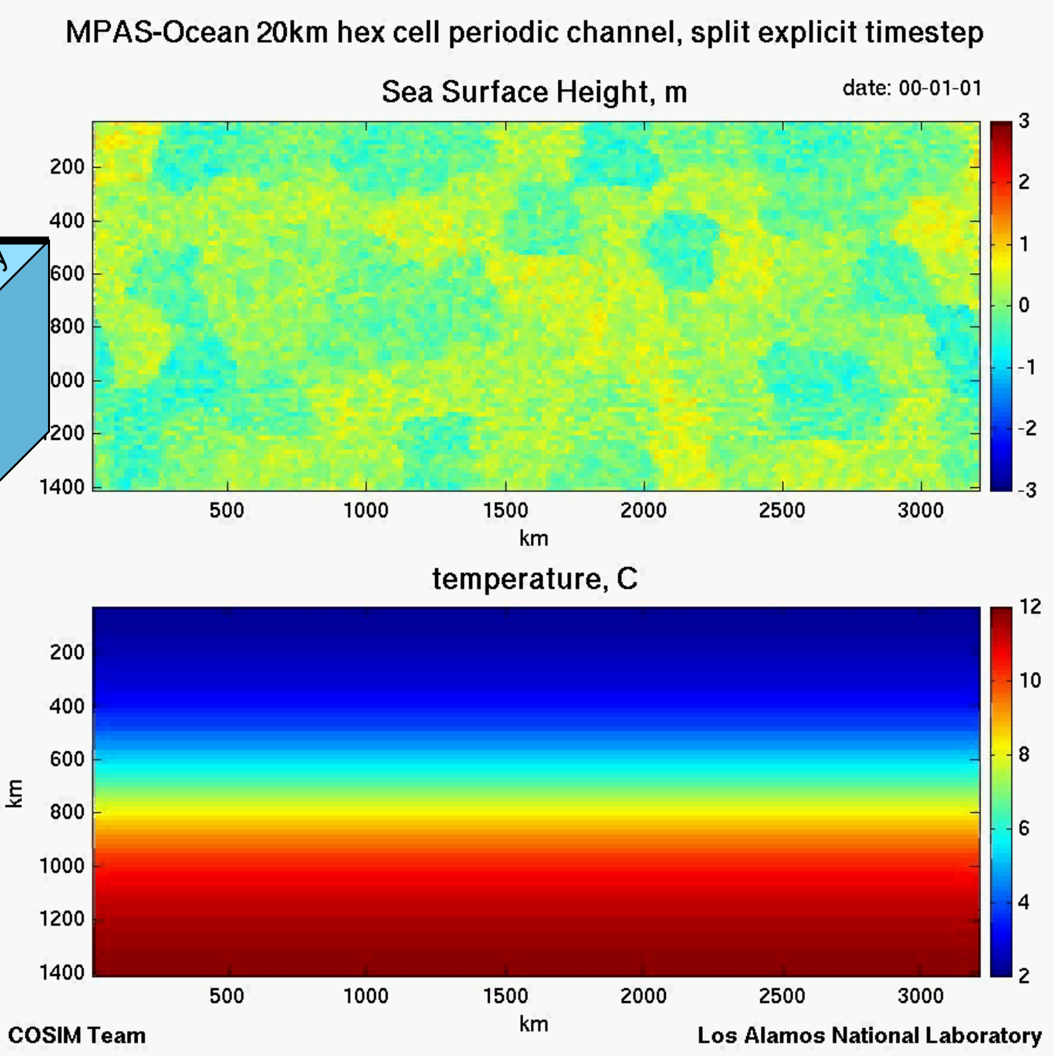
2ºC

zonal wind

solid boundary

periodic bndry

deep-sea ridge



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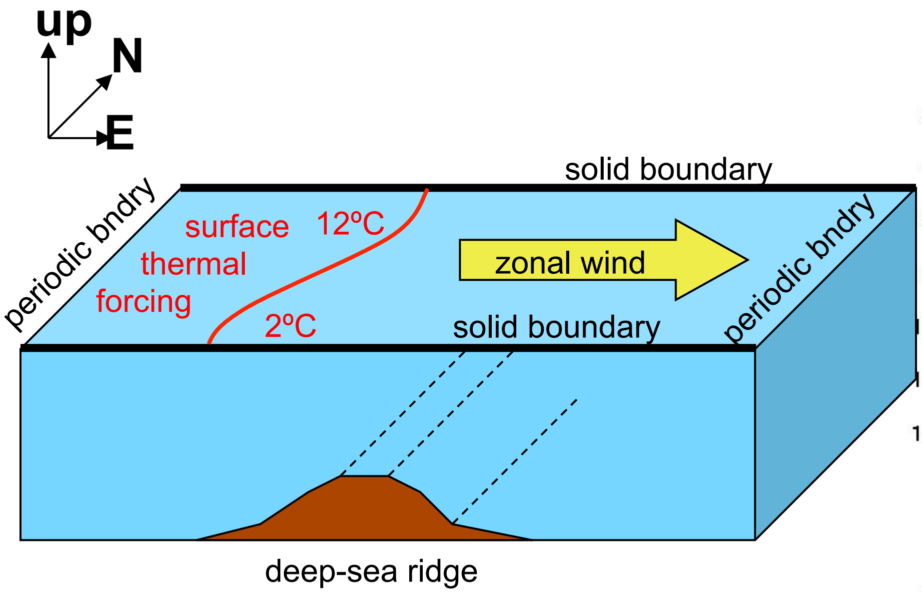
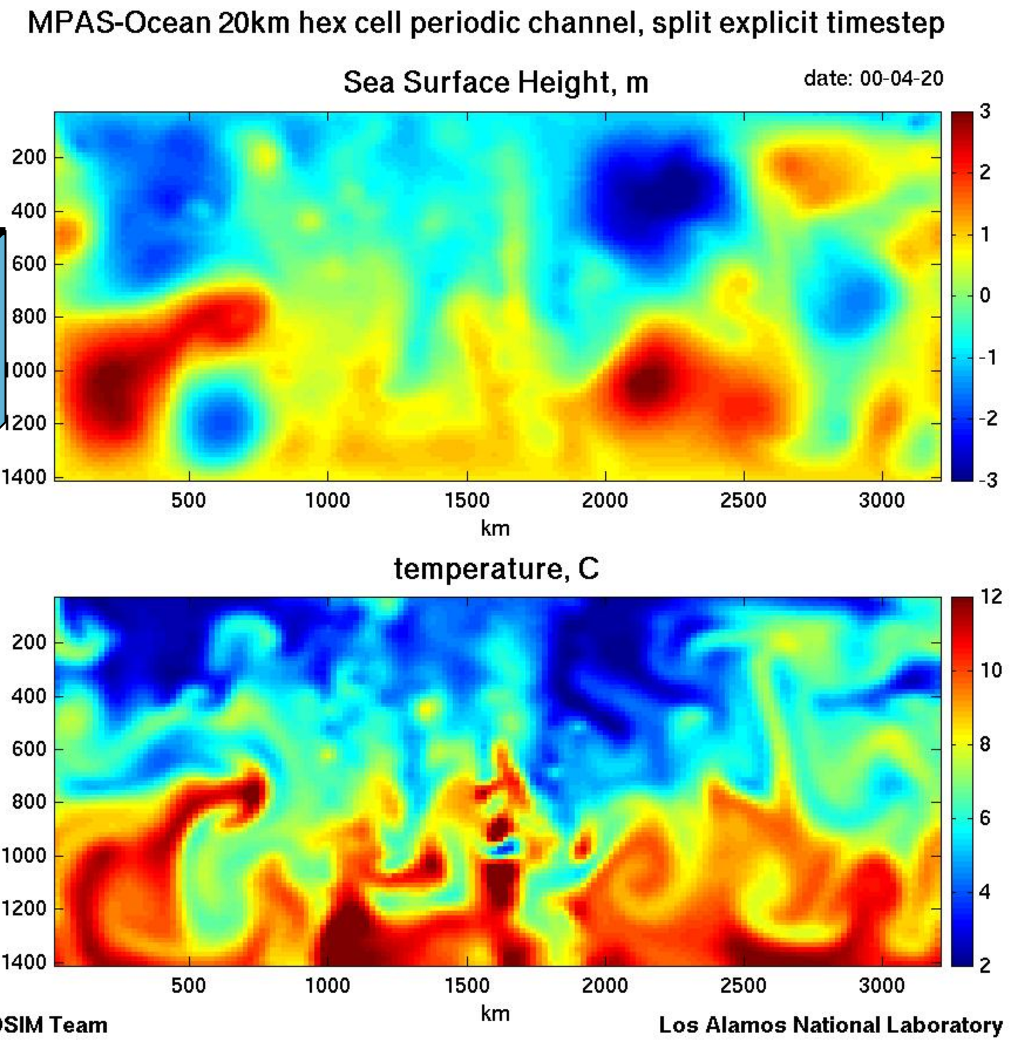
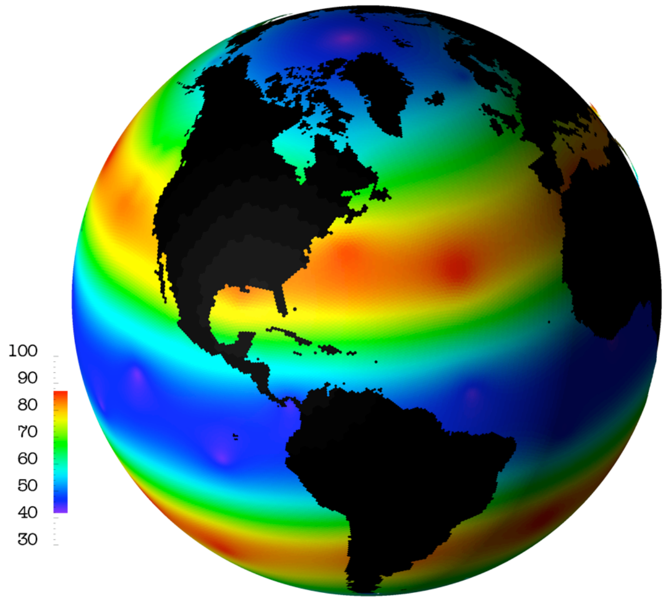




MPAS-Ocean Testing and Validation: Variable Resolution

Control Simulation

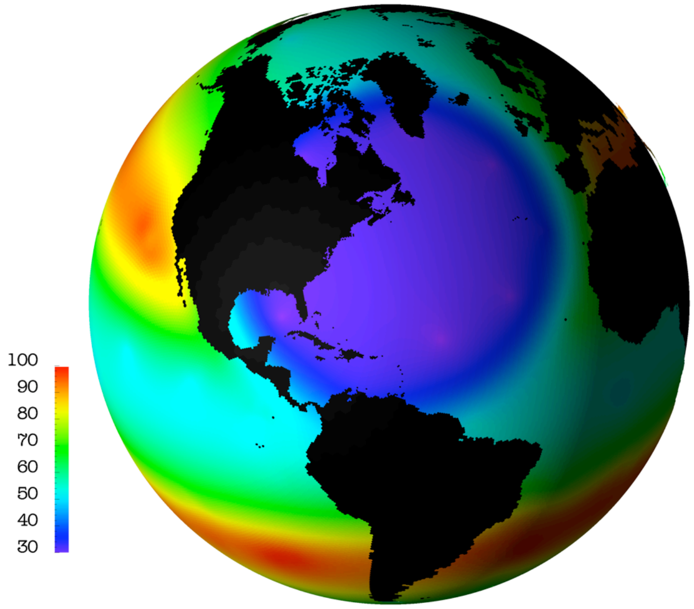
local grid resolution



total number of cells: 115K
equatorial and polar resolution: 40 km
subtropical resolution: 85 km

North Atlantic High Resolution

local grid resolution

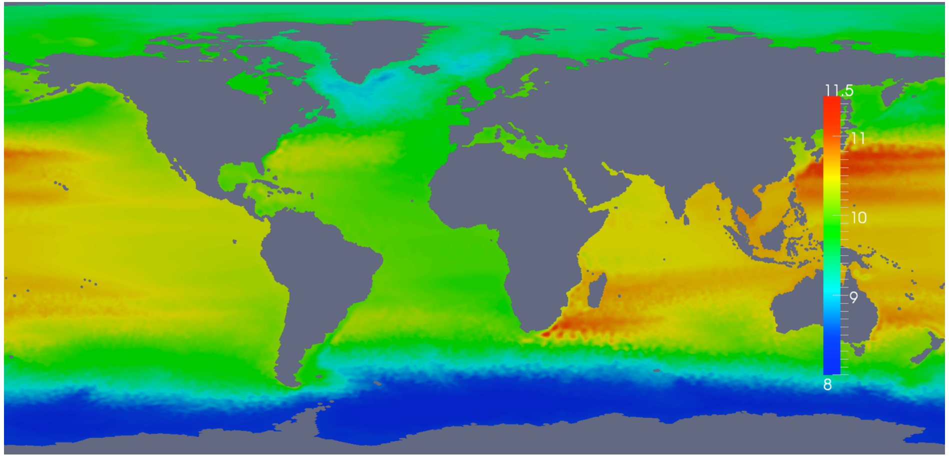


total number of cells: 115K
equatorial and polar resolution: 50 km
subtropical resolution:100 km
North Atlantic resolution: 30 km

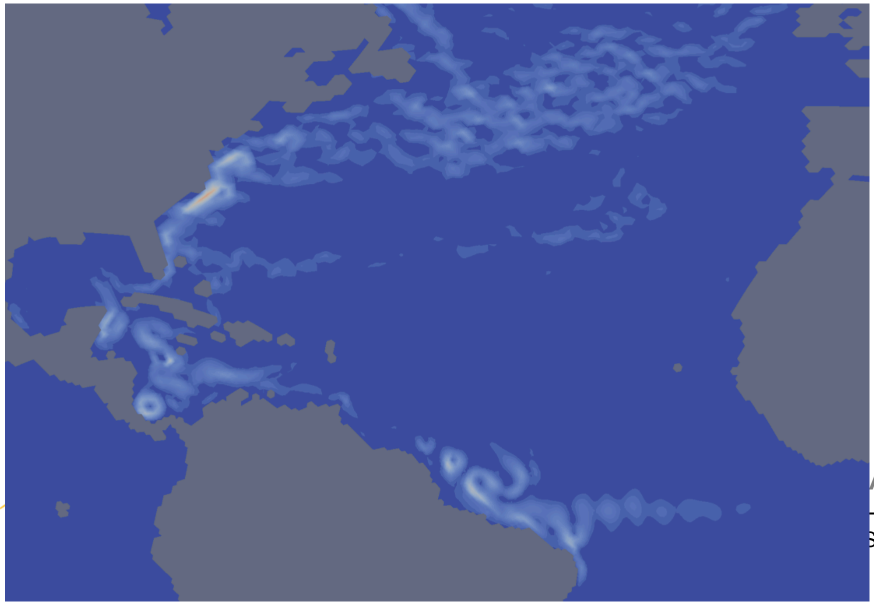
MPAS-Ocean Testing and Validation: Variable Resolution

Control Simulation

Top layer thickness, day 1600

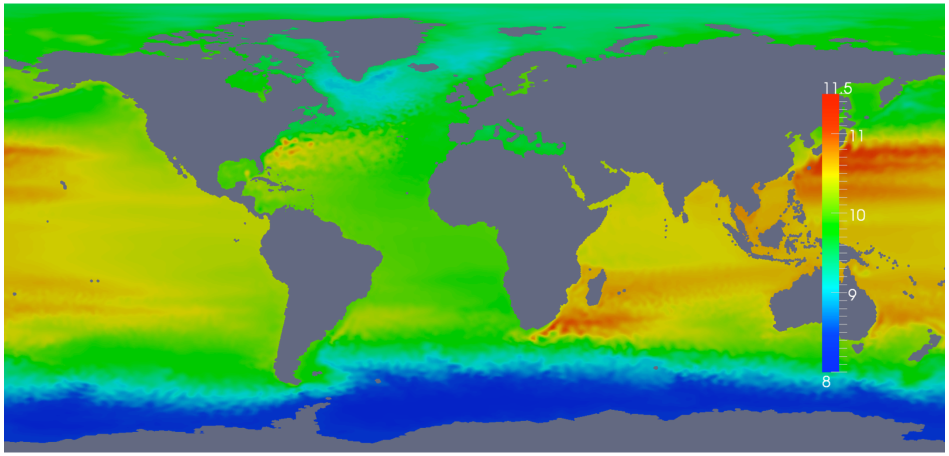


Kinetic Energy

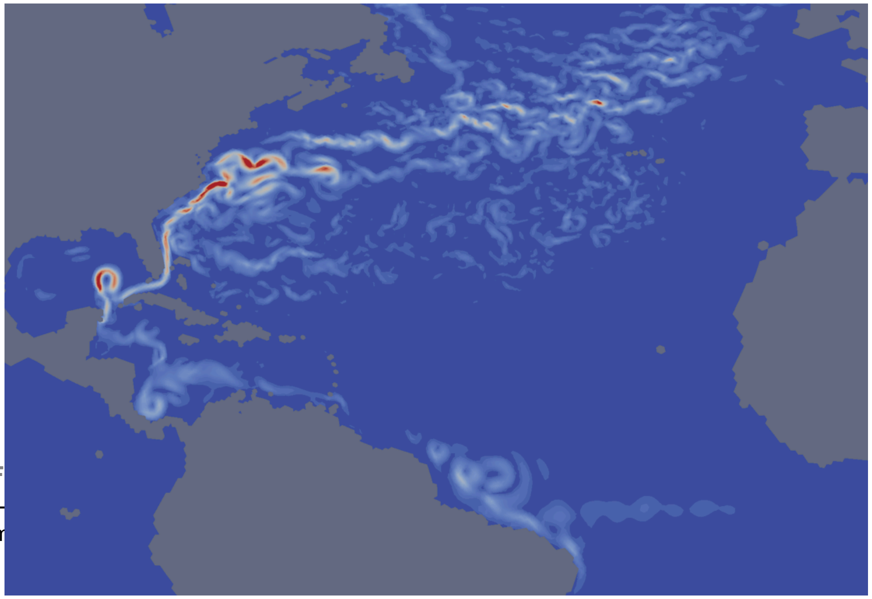


North Atlantic High Resolution

Top layer thickness, day 1600



Kinetic Energy



MPAS Development: Software Engineering Practices

- **Goal: A transparent, well-planned and documented design and code-writing process.**
- **We use Requirements and Design Documents and Reviews:**
  - R&D document is written and reviewed for each major code improvement.
  - Code developed on repository branch
  - Branch reviewed by other team members, compared with R&D Document before committing to the trunk.
- **R&D Documents form a history of code modifications, and first draft for the MPAS-Ocean Reference Manual.**

Conclusions

- **MPAS-Ocean is a functioning variable-resolution ocean dynamical core.**
- **Major functionality is now in place, including:**
  - Choice of z-level or isopycnal mode
  - High order vertical and horizontal advection
  - Split-explicit time stepping, with a speed-up of 14 over fourth-order Runge-Kutta
- **MPAS-Ocean goals for next 6 months:**
  - Peer-reviewed publications introducing MPAS-ocean
  - Develop a community of early users to test MPAS-Ocean
  - Profile performance, scaling, and efficiency improvements
  - z* and $\tilde{z}$ adaptive vertical grids.
  - Add additional standard parameterizations, like KPP vertical mixing
- **MPAS-Ocean goals, longer term:**
  - Coupling to CESM
  - Parameterization development for variable resolution grids.
  - Development of sea ice and land ice MPAS components

MPAS-Ocean z-level mode initial validation with POP

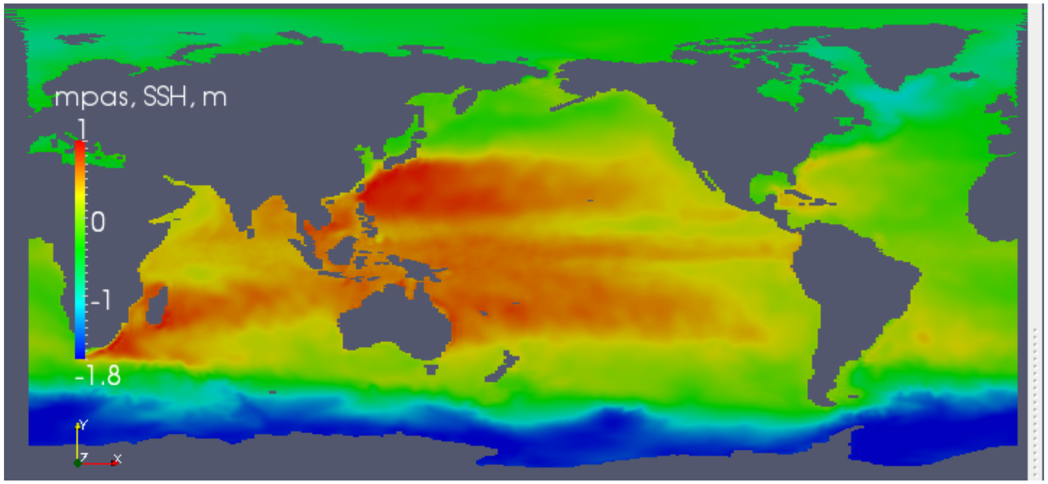
- **MPAS-Ocean on quad grid and bathymetry identical to POP gx3v2, gx1v3, and 0.1 dipole grids.**
- **Levitus climatological mean initial temperature and salinity**
- **NCEP 1958-2000 annual mean wind stress**
- **No surface forcing or restoring of temperature and salinity**
- **Horizontal mixing: del2, constant coefficient viscosity (1.0e3 m^2/s) and diffusion (1.0e2 m^2/s).**
- **Vertical mixing: constant coefficient viscosity (2.5e-5 m^2/s) and diffusion (2.5e-5 m^2/s).**
- **Jacket & McDougall equation of state**

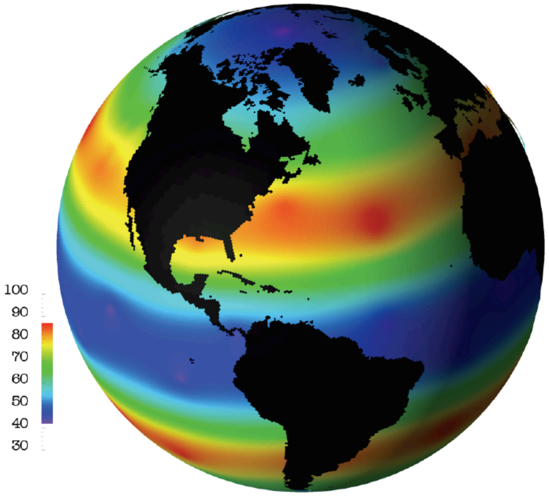
Efficiency

- **Array structure**
  - POP: TRACER(i, j, k, tracer_index, time_index, iblock) *hor. neighbors in cache*
  - MPAS: tracers(tracer_index, k, iCell, time_index) *tracers & column in cache*
  - Indirect array references for neighbors in MPAS.
  - MPAS includes no land cells.
  - In MPAS, adding tracers and vertical levels will not add much computational time.
- **We have done no profiling on MPAS-Ocean yet, so large gains may be possible.**
- **Major task is to include timesplitting to lengthen baroclinic steps**
- **Assuming longer timestep in split mode, MPAS-Ocean is currently 5-10 times slower than POP.**

Visualization Tools for Unstructured Grids

- POP’s structured horizontal grid makes for easy plotting in Ferret and Matlab.
- MPAS unstructured grids required additional tools to convert NetCDF output files to plotable formats
- At LANL, we made conversion tools for Paraview .vtk format in:
  - spherical projection
  - latitude-longitude projection
  - combined POP/MPAS output for direct comparison
- NCAR staff is creating unstructured visualization tools for NCL.





High-Order Vertical Tracer Advection

- **Vertical tracer advection,** $\frac{\partial}{\partial z}(h\varphi w) = \varphi_k^{top} w_k^{top} - \varphi_{k+1}^{top} w_{k+1}^{top}$ **requires tracer values at vertical cell edge.**
- **Four methods are available to interpolate tracer values to cell interface:**

linear **3rd order stencil** **4th order stencil** **cubic spline**

$$\frac{\partial h\varphi}{\partial t} + \nabla\cdot(h\varphi\mathbf{u}) + \underbrace{\frac{\partial}{\partial z}(h\varphi w)}_{\text{vertical advection}} = \nabla\cdot(h\kappa_h\nabla\varphi) + h\frac{\partial}{\partial z}\left(\kappa_v\frac{\partial\varphi}{\partial z}\right)$$

Vertical Mixing

- **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.

$$\frac{\partial h\varphi}{\partial t} + \underbrace{\nabla\cdot(h\varphi\mathbf{u}) + \frac{\partial}{\partial z}(h\varphi w) = \nabla\cdot(h\kappa_h\nabla\varphi)}_{\text{solve explicitly}} + \underbrace{h\frac{\partial}{\partial z}\left(\kappa_v\frac{\partial\varphi}{\partial z}\right)}_{\text{solve implicitly}}$$

  - Implicit solve is conducted after explicit time step.

$$\left(1 - \Delta t\frac{\partial}{\partial z}\left(\kappa_v\frac{\partial}{\partial z}\right)\right)\varphi^{n+1} = \frac{\widetilde{(h\varphi)}^{n+1}}{h^{n+1}} \longleftarrow$$

new provisional value
from explicit solve

How do POP and MPAS-Ocean differ in these tests?

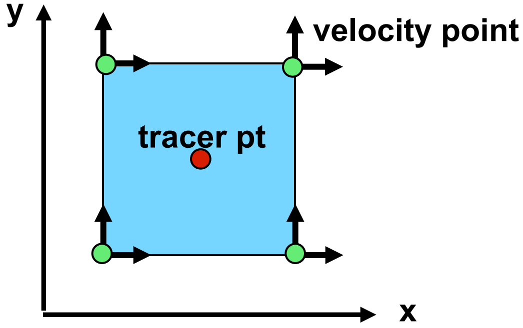
- **Time stepping and time splitting**
  - POP: Barotropic/Baroclinic implicit/explicit splitting, leap-frog timestep

    60 minute timestep for 1° grid
  - MPAS-Ocean: no splitting, explicit 4th-order Runga-Kutta timestep

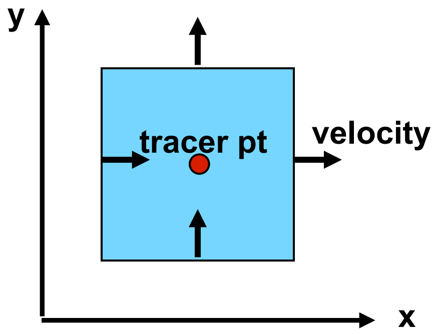
    1 minute timestep for 1° grid

- **Grid:**

POP uses a B-grid:
Velocities on corners

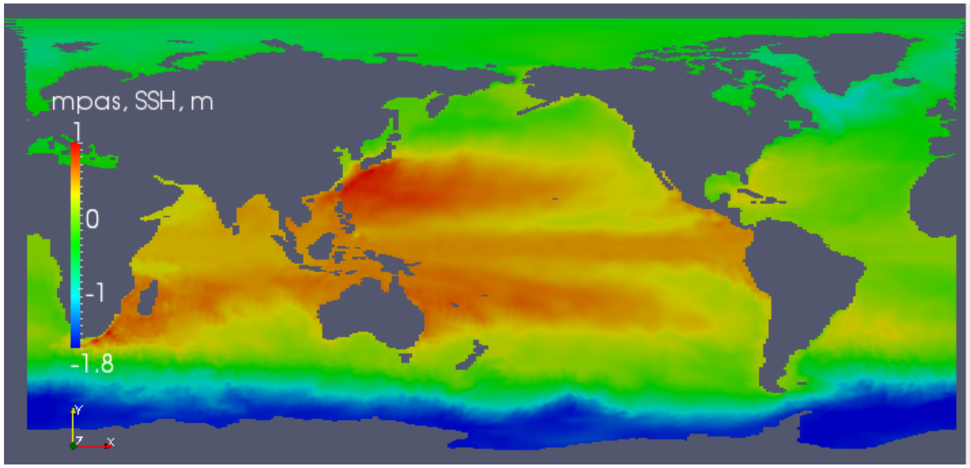


MPAS uses a C-grid:
Velocities on edges

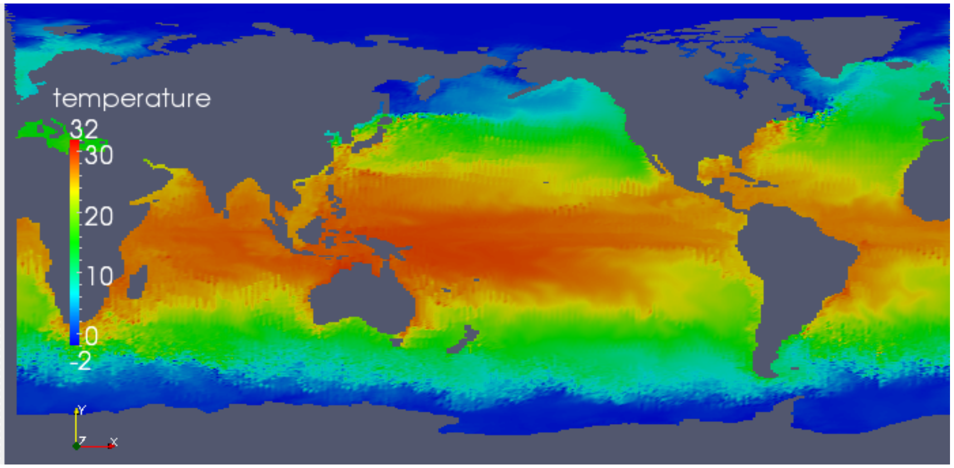


POP/MPAS-Ocean Comparison, 1° grid, 165 days

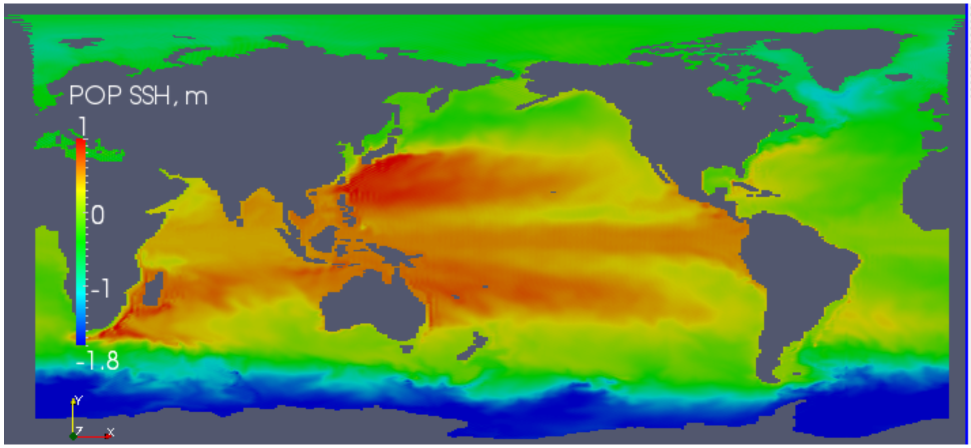
mpas SSH



mpas SST



POP SSH



POP SST