Ocean Modeling I

Ocean Modeling Basics and Overview of CESM Ocean Models

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Outline

1) General ocean modelling considerations

- Challenges for ocean modeling
- Ocean properties
- Governing equations
- Boundary conditions
- Horizontal/vertical discretization

2) Parallel Ocean Program version 2 (POP2)

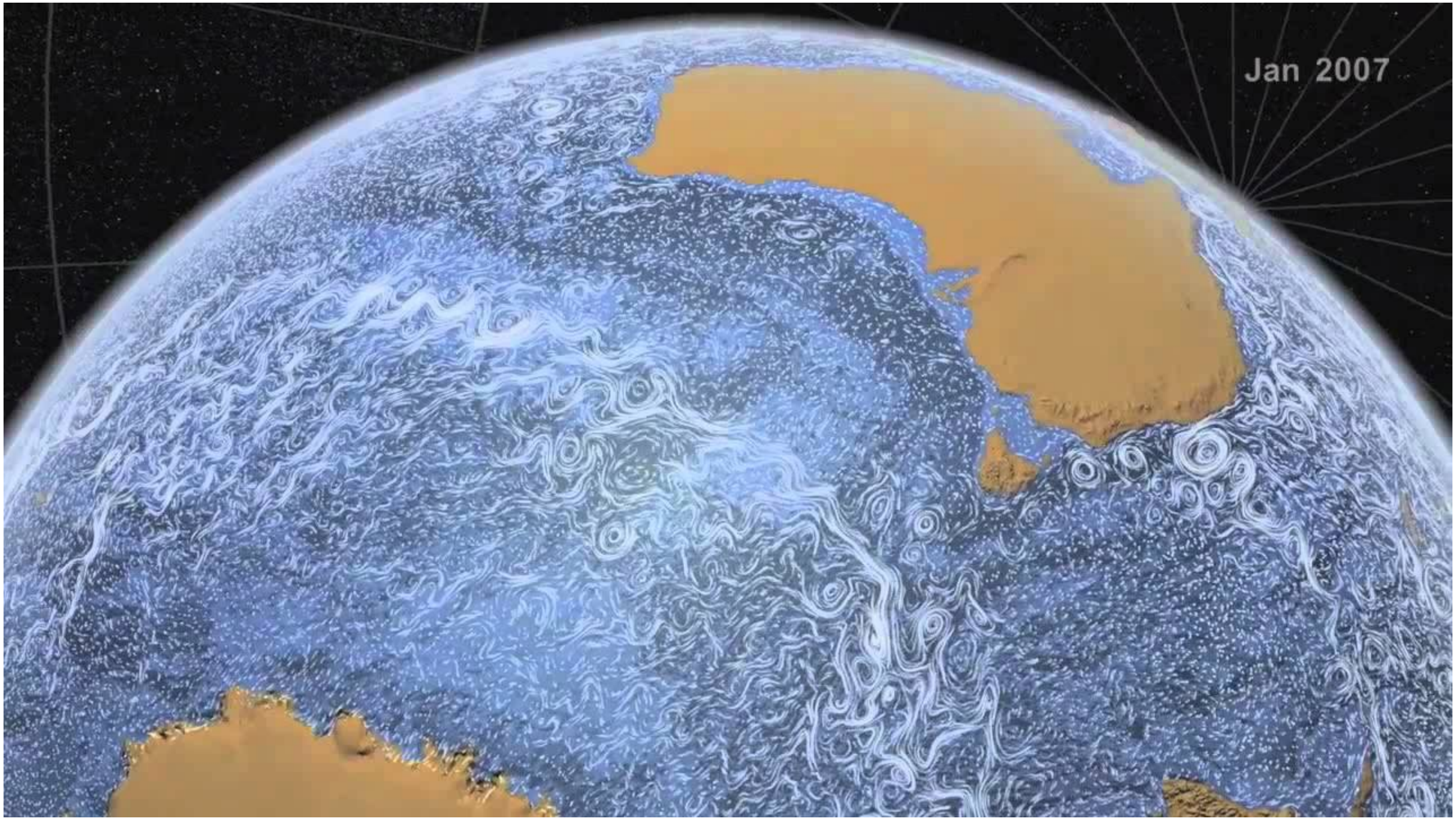
3) Modular Ocean Model version 6 (MOM6)

4) Helpful resources

Ocean Modeling Challenges: irregular domain

1st order challenges from a numerical perspective:

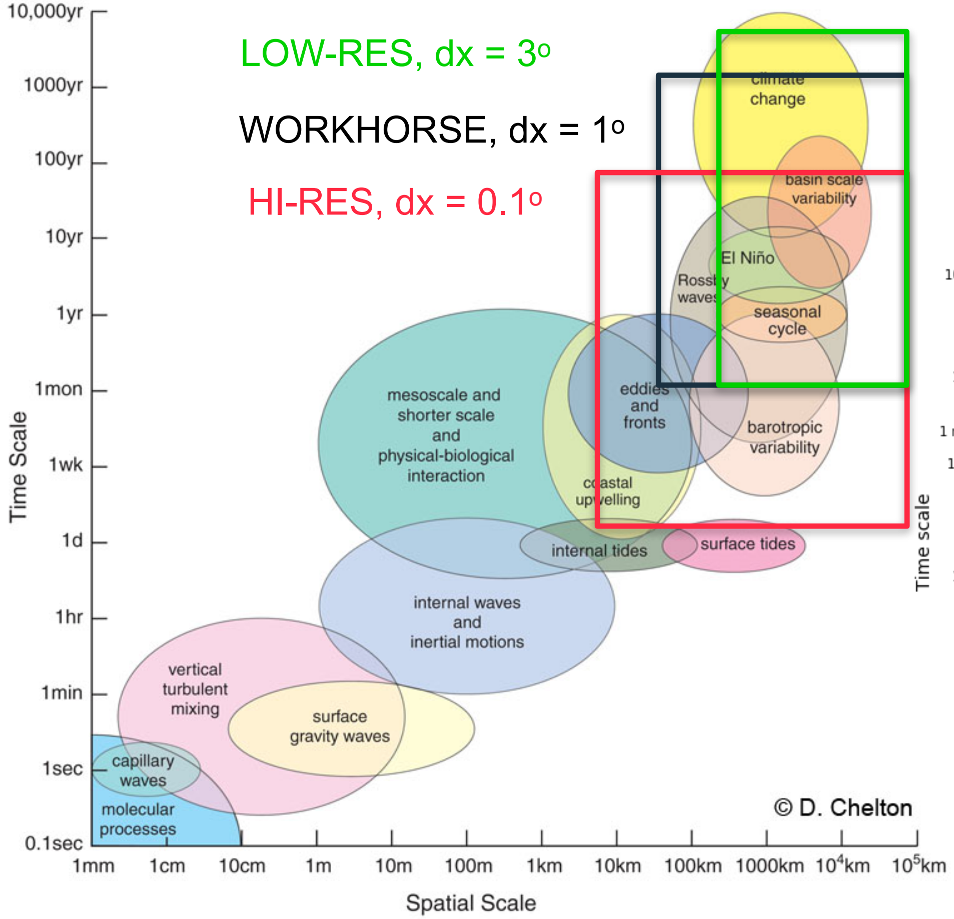
- Highly irregular domain; land boundary exerts strong control on ocean dynamics.



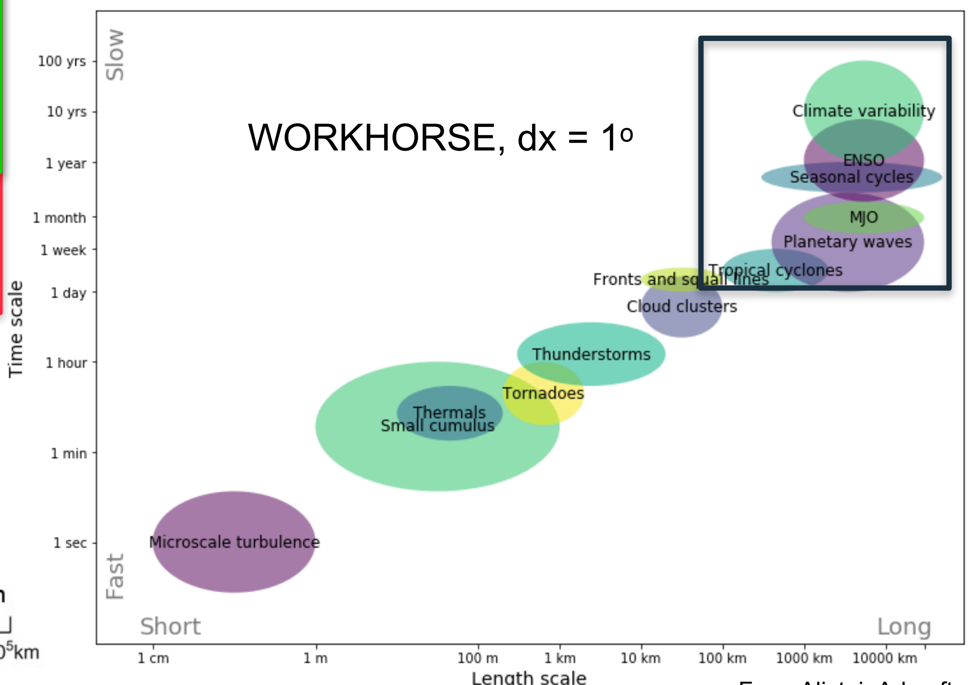
Perpetual Ocean; Credit: MIT/NASA-JPL ECCO2

Ocean Modeling Challenges: Spatial vs. Temporal Scales

Ocean



Atmosphere

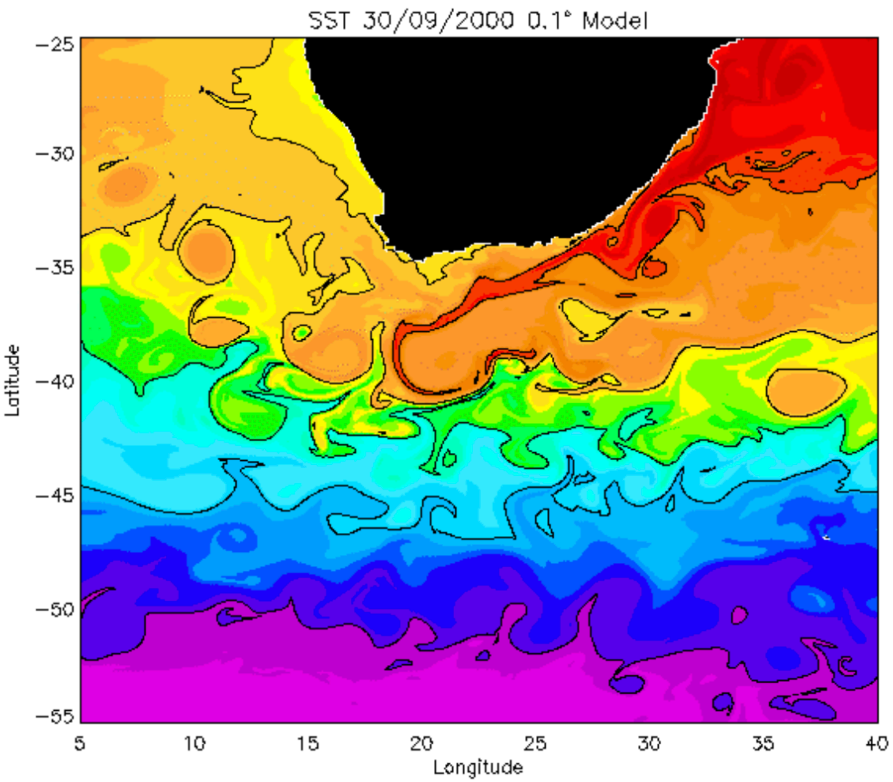


From Alistair Adcroft

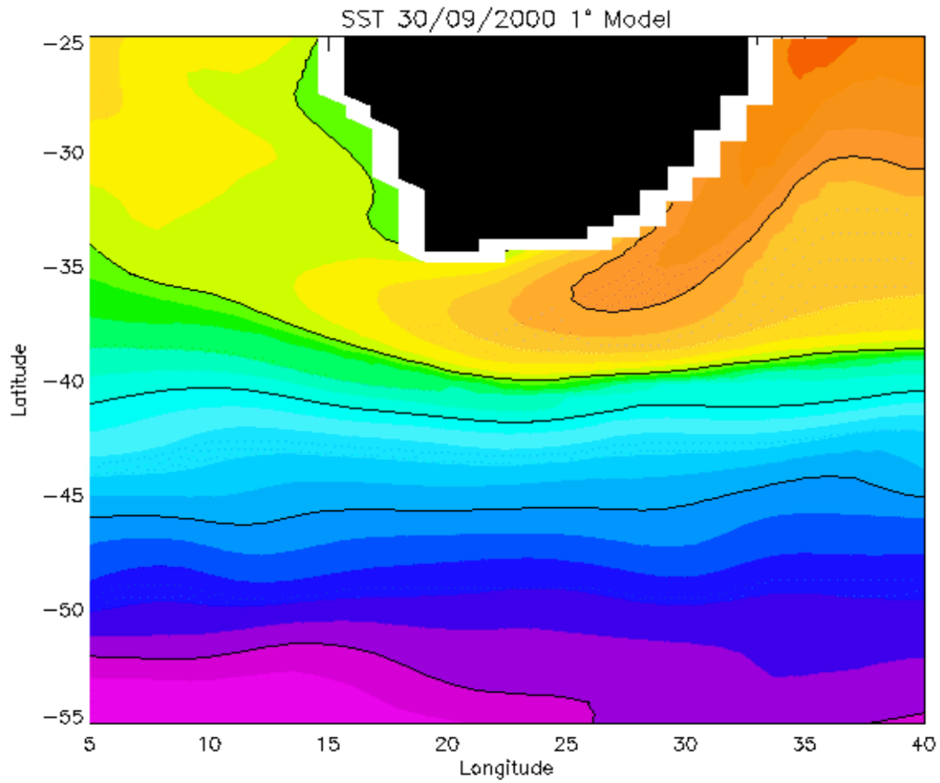
- Ocean models simulate the **climate**
- ATM. models simulate the **weather**

Ocean Modeling Challenges: Spatial Scales

Δx = 0.1 degree



Δx = 1.0 degree

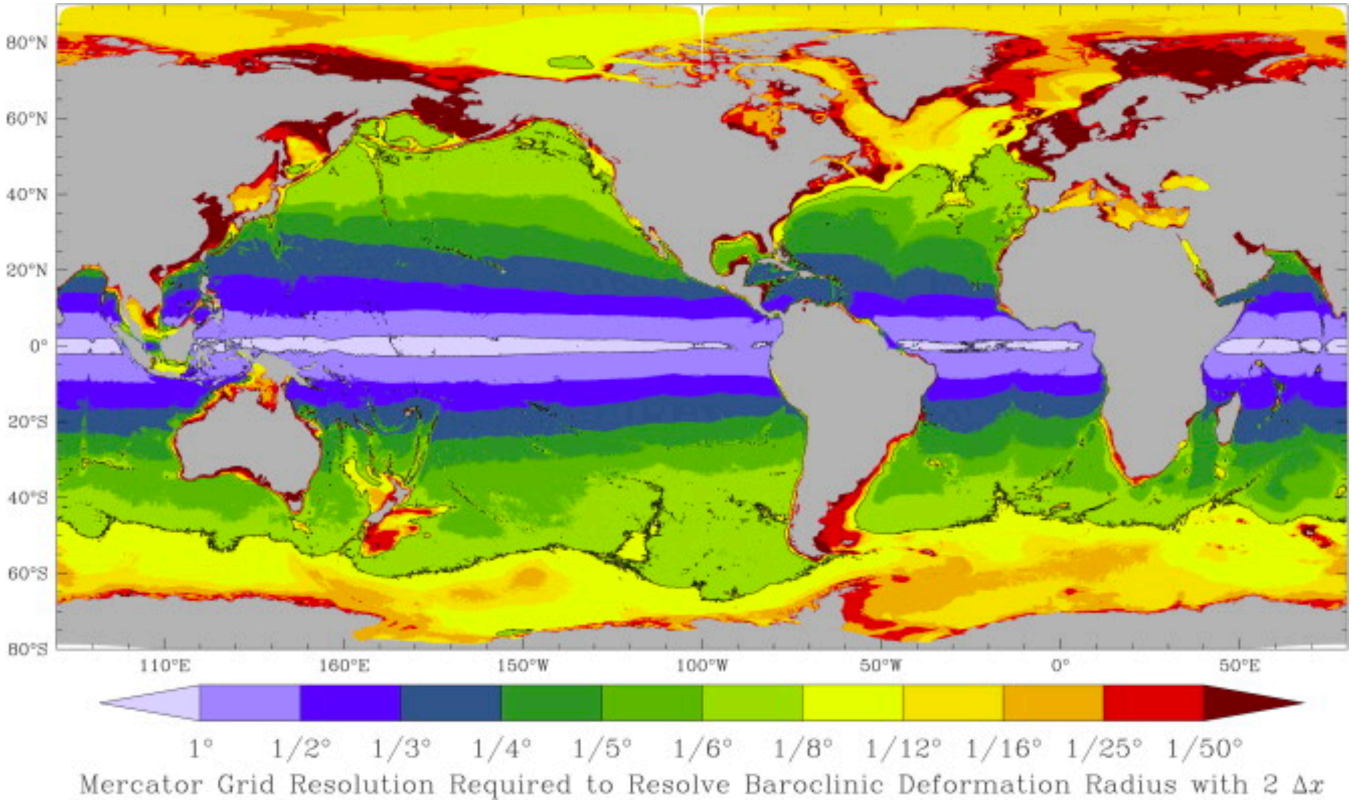


- Mixing associated with sub-gridscale turbulence must be parameterized.

Ocean Modeling Challenges: Eddy-Resolving Scales

- The density change from top to bottom is much smaller than the atmosphere. This makes the Rossby radius (R_d) much smaller – 100s to 10s km;

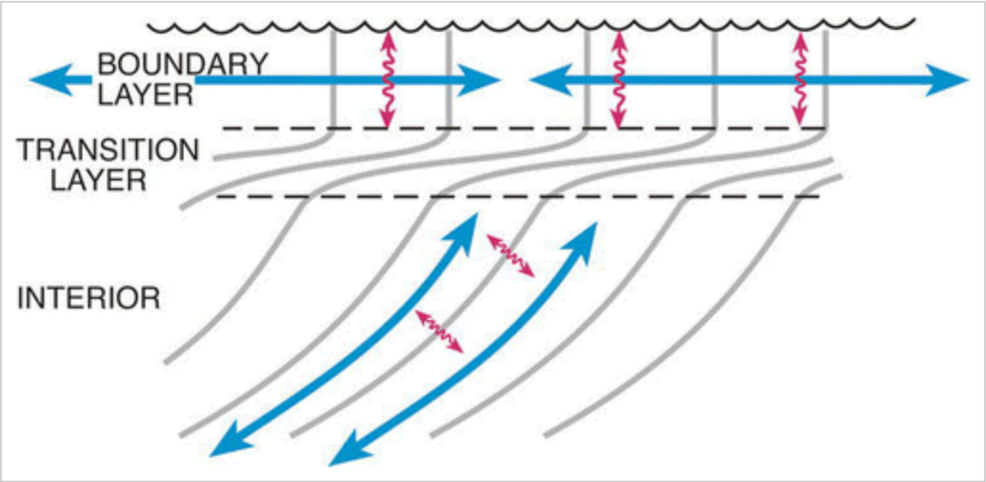
$$R_d = \frac{NH}{\pi f}$$



From Hallberg (2013)

Ocean Modeling Challenges: diabatic versus adiabatic regimes

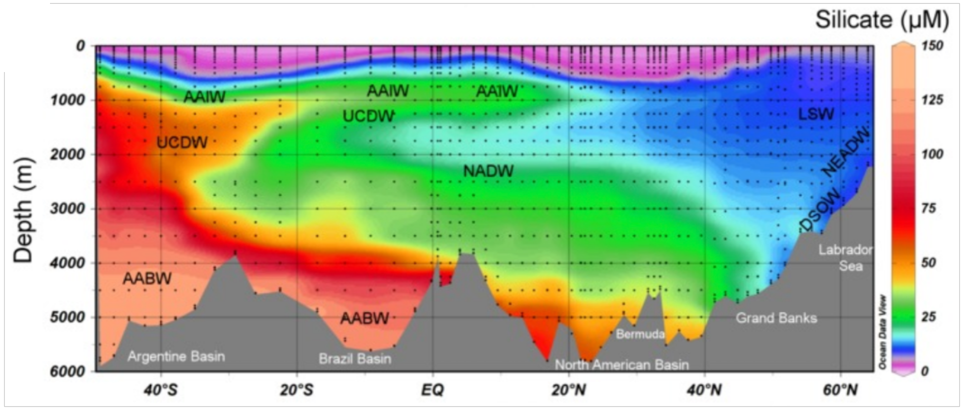
Conceptual model of eddy fluxes in the upper ocean



From: Ferrari et al. (2008)

Difficult to represent these fluxes in ocean models. Important to minimize spurious (numerical) mixing due to truncation errors in the advection schemes.

Because of weak interior mixing, water masses can be named and followed around the ocean.



From: Rijkenberg et al. (2014)

Ocean Modeling Challenges: Equilibration Timescale

- Extremely small mixing across density surfaces once water masses are buried below the mixed layer base. This is why water masses can be named and followed around the ocean;

  - **Scaling argument for deep adjustment time:**

    $H^2/K_v = (4000\text{ m})^2 / (2 \times 10^{-5}\text{ m}^2/\text{s}) = 20{,}000$ years

- **Dynamical adjustment timescale:**

Phase speed of non-dispersive long Rossby waves, $C_R = -\beta R_d^2$

Approximate time taken to cross the Pacific Ocean at mid-latitudes:

$L/C_R = (15 \times 10^3\text{ km}) / (20\text{ km/day}) = 750$ days ~ 2 years.

Bottom line for climate studies

- Performing long (climate scale) simulations at eddy-resolving/permitting resolution are not practical;
- Spurious mixing in the interior can significantly degrade the solution;
- Must live with deep ocean not being at equilibrium in most simulations;
- The heat capacity of the ocean is much larger than the atmosphere. This makes it an important heat reservoir;
- The ocean contains the memory of the climate system → important implications for decadal prediction studies.

The equations solved by the ocean models

<u>7 equations and 7 unknowns:</u>

- 3 velocity components;
- Potential temperature;
- Density;
- Pressure;
- Salinity.

Plus: 1 equation for each passive tracer, e.g. CFCs, Ideal Age.

Approximations based on scaling considerations

1) **Hydrostatic** → when ocean becomes statically unstable ($d\rho>0$) vertical overturning should occur, but cannot because vertical tendency has been excluded. This mixing is accomplished (i.e., parameterized) by a very large coefficient of vertical diffusion;

2) **Boussinesq** → $\rho = \rho_0 + \rho'$, $\rho' \ll \rho_0$; density variation is only important in the hydrostatic equation;

3) **Continuity (incompressible form)** → cannot deform seawater, so what flows into a control volume must flow out;

4) **Thin-shell** → the ocean depth is neglected compared to the earth's radius;

Together with horizontal motions >> vertical motions (traditional approximation), the thin-shell approximation of the Coriolis force results in retaining only the horizontal components due to horizontal motions.

Approximations based on scaling considerations (Cont.)

5) **Spherical Earth** → geopotential surfaces are assumed to be spheres;

6) **Turbulent closures** → subgrid scale processes can be parameterized in terms of the resolved large-scale fields / features.

Boussinesq hydrostatic eqs. in height coordinates

In Carthesian form

Horizontal momentum:

$$D_t \boldsymbol{u} + f \widehat{\boldsymbol{k}} \wedge \boldsymbol{u} + \frac{1}{\rho_o} \boldsymbol{\nabla}_z p = K_H \boldsymbol{\nabla}_z^2 \boldsymbol{u} + \partial_z (K_V \partial_z \boldsymbol{u}) \quad (1)$$

Vertical momentum (hydrostatic equation):

$$\partial_z p = -g\rho \quad (2)$$

Mass conservation / continuity equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u) + \frac{\partial}{\partial x}(\rho v) \frac{\partial}{\partial x}(\rho w) = 0 \quad (3a)$$

$$\boldsymbol{\nabla}_z \cdot \boldsymbol{u} + \partial_z w = 0, \qquad |\rho'| < < \rho_0 \quad (3b)$$

Boussinesq hydrostatic eqs. in height coordinates (cont.)

Potential temperature transport:

$$\partial_t \theta + \boldsymbol{\nabla}_z \cdot (\boldsymbol{u}\theta) + \partial_z (w\theta) = \boldsymbol{\nabla} \cdot \overline{\overline{A}} \boldsymbol{\nabla} \theta \tag{4}$$

Salinity transport:

$$\partial_t S + \boldsymbol{\nabla}_z \cdot (\boldsymbol{u}S) + \partial_z (wS) = \boldsymbol{\nabla} \cdot \overline{\overline{A}} \boldsymbol{\nabla} S \tag{5}$$

Equation of state (nonlinear):

$$\rho = \rho(S, \theta, p(z)) \tag{6}$$

Boundary conditions

Ocean surface:

- Flux exchanges at surface (momentum and tracers);
- In POP, no flux of fresh water, get equivalent of salt via virtual salt flux;

Ocean bottom:

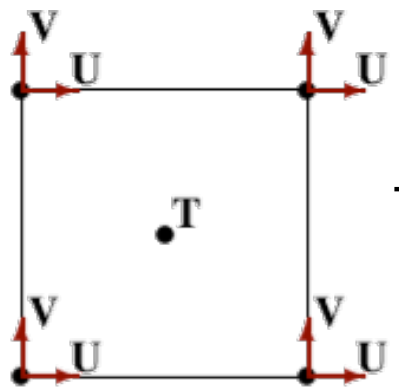
- No tracer fluxes (option to include geothermal heating in MOM6);
- Normal velocity is zero;
- Quadratic bottom drag (bottom boundary condition on viscosity term).

Lateral boundaries:

- No tracer fluxes;
- Flow normal to solid boundary is zero;
- No slip on lateral boundaries.

Horizontal grid staggering: Arakawa B grid

Arakawa B grid



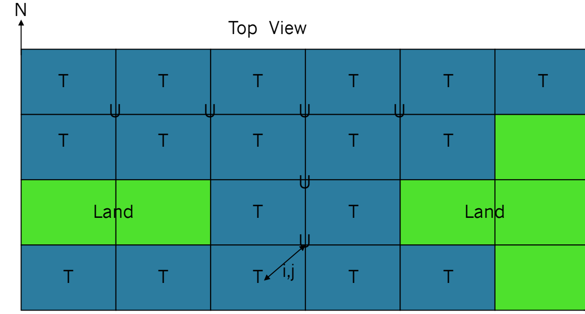
Top view

Advantages:

- Naturally fits no-slip boundary condition;
- Better dispersion for Rossby waves at very coarse resolution than C-grid;
- Smaller truncation errors in the computation of the Coriolis terms;

Disadvantages:

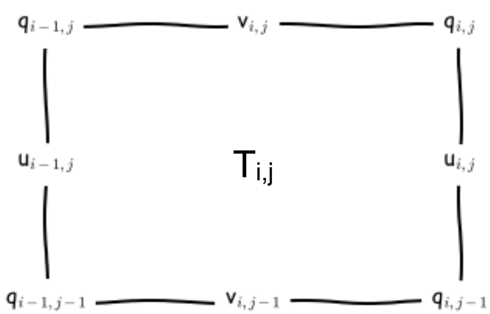
- Cannot represent single-point channels
- Larger truncation errors in the pressure gradient terms;



This is the staggering used in POP2

Horizontal grid staggering: Arakawa C grid

Arakawa C grid



Top view

Advantages:

- Allows single-point channels

Disadvantages:

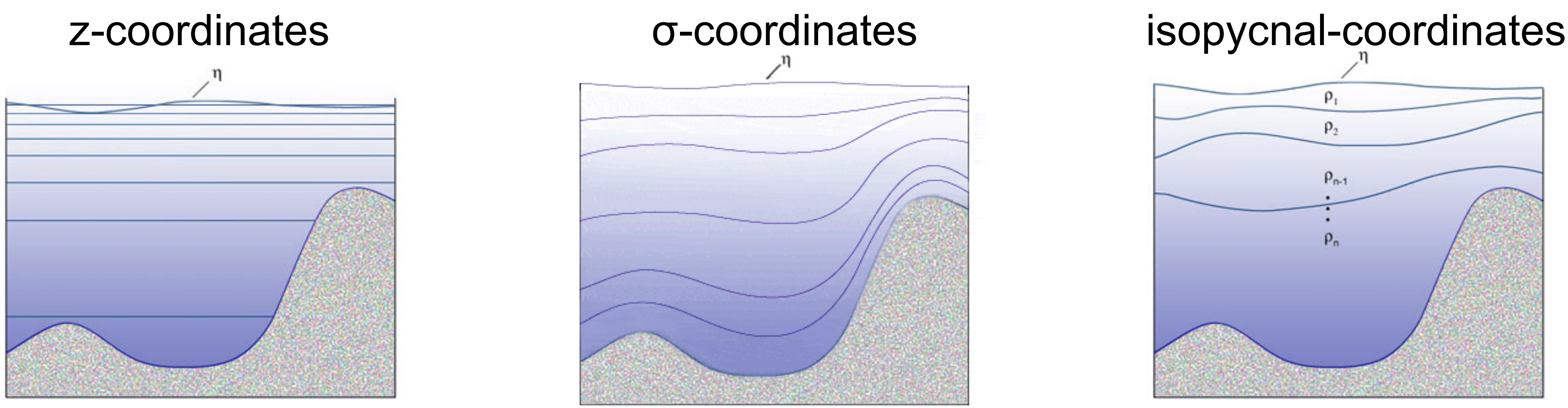
- The Coriolis acceleration terms requires horizontal averaging, making the inertia gravity waves (related with Coriolis force) less accurate;

- Poorer dispersion for Rossby waves at very coarse resolution than B-grid;

This is the staggering used in MOM6

Vertical coordinate system in ocean models

The choice of a vertical coordinate system is **one of the most important** aspects of a model's design. There are 3 main vertical coordinate systems in use:



From: https://www.oc.nps.edu/nom/modeling/vertical_grids.html

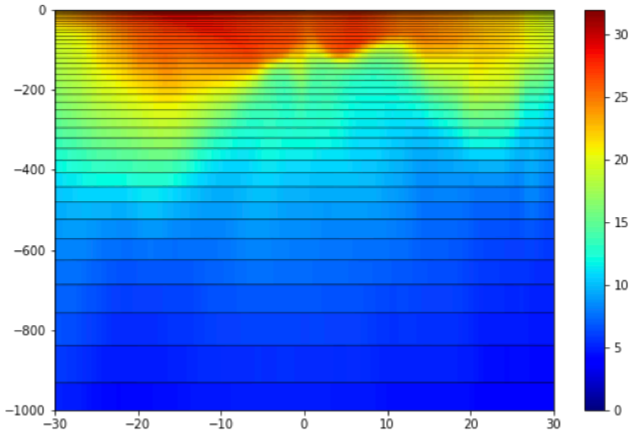
- Each one has its advantages and disadvantages, which has led to the development of **hybrid** coordinate systems;

- This is an area of very active research and development in numerical ocean models.

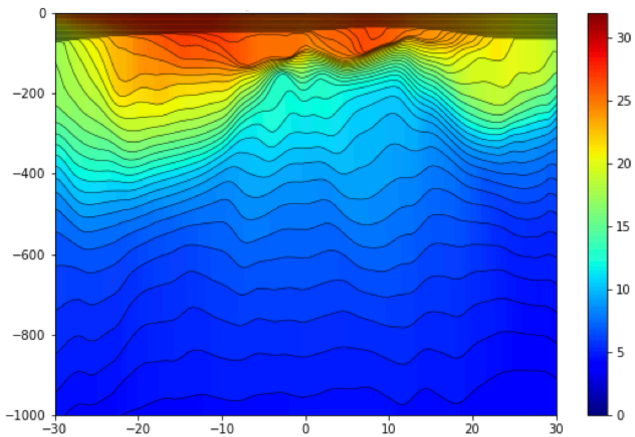
Vertical grids used in CESM

MOM6 vertical grids

z*-coordinates, 65 levels

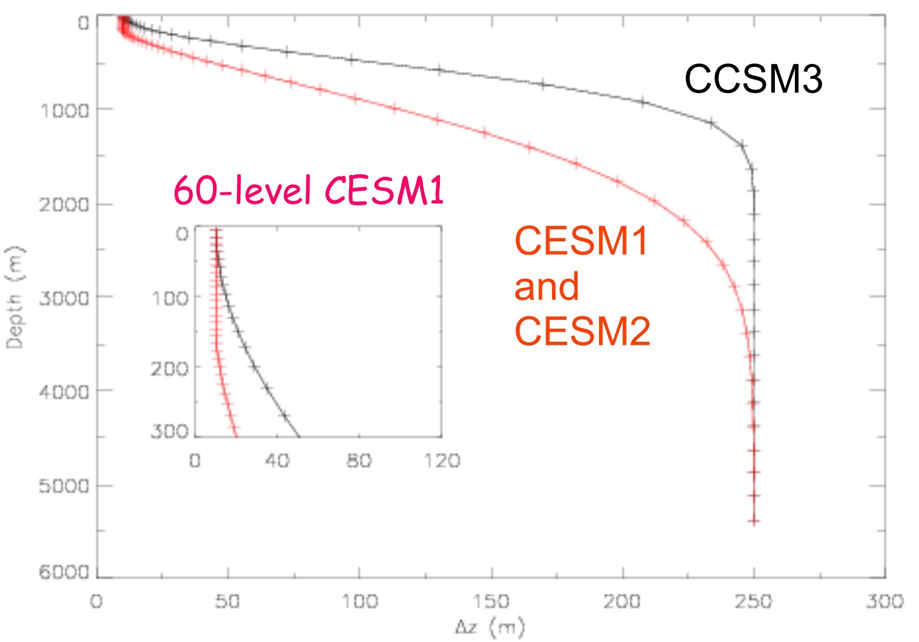


Hybrid (z*/rho), 75 levels



POP2 vertical grids

z-coordinates



Surface forcing options for ocean simulations with CESM

- Fully coupled mode (B compset);

- Forced ocean (C compset) or ocean – sea-ice coupled (G compset);

Coordinated Ocean-ice Reference Experiments (CORE)

- Inter-annual forcing (IAF; 1948-2009), http://data1.gfdl.noaa.gov/nomads/forms/mom4/CORE.html;

- Normal Year Forcing (NYF): synthetic year that repeats exactly; good for model testing and parameterization impact studies.

  Large and Yeager, NCAR Technical Note (2004)
  Large and Yeager, Climate Dynamics (2009)
  Danabasoglu et al., Ocean Modelling (2016)

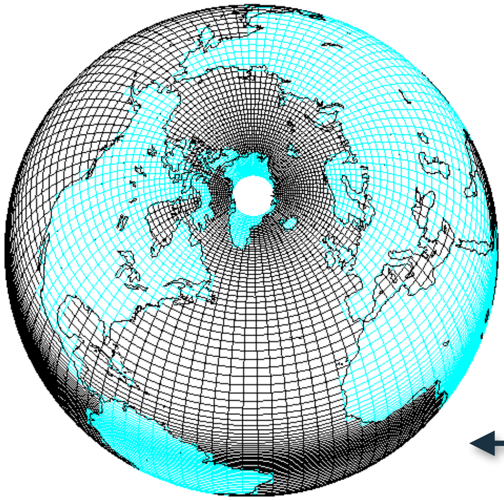
- JRA-55-DO (JRA; 1958 to 2018), https://jra.kishou.go.jp/JRA-55/index_en.html, Tsujino et al., Ocean Modelling (2018)

The Parallel Ocean Program version 2 (POP2) dynamical core

- POP2 is a level- (z-) coordinate model developed at the Los Alamos National Laboratory (Smith et al. 2010);
- 3-D primitive equations, general orthogonal coordinates in the horizontal, solved with the **hydrostatic** and **Boussinesq** approximations;
- A linearized, implicit free-surface formulation is used for the barotropic equation for surface pressure (surface height);
- The global integral of the ocean volume remains constant because the freshwater fluxes are treated as **virtual salt fluxes**, using a constant reference salinity.

POP2: horizontal grids

Displaced pole → Removes singularity from the North Pole



- gx1: climate workhorse (nominal 1°)
- gx3: testing/paleo (nominal 3°)

← Equatorial refinement (0.3° / 0.9°)

Tripole

- tx0.1 (nominal 0.1°), eddy resolving almost everywhere;
- See Murray (1996) for details on the various types of grids.

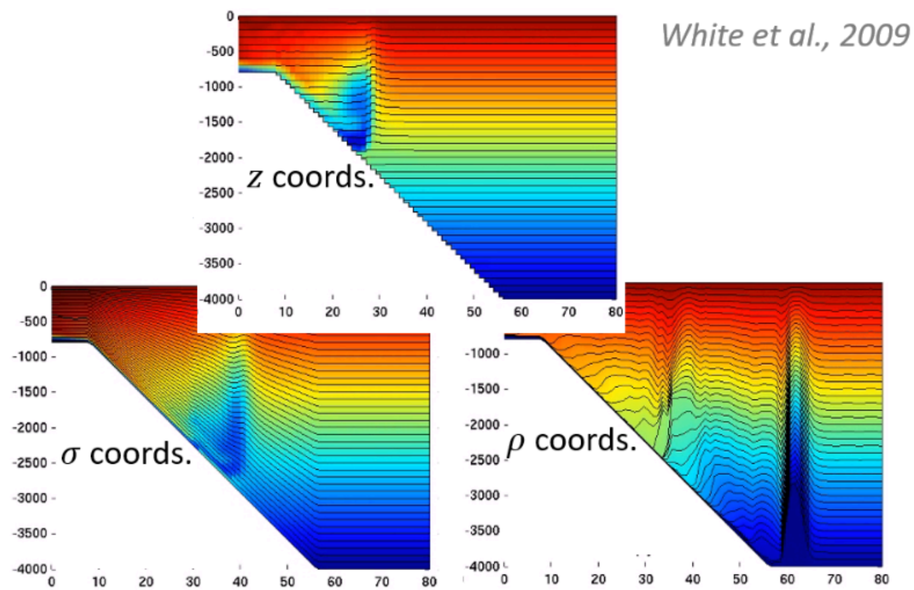
The Modular Ocean Model version 6 (MOM6) dynamical core

- **Finite volume solver**

- Hydrostatic Boussinesq or non-Boussinesq equations → Non-Boussinesq models contain all effects within the ocean acting on the sea level

- **Arbitrary-Lagrangian-Eulerian**

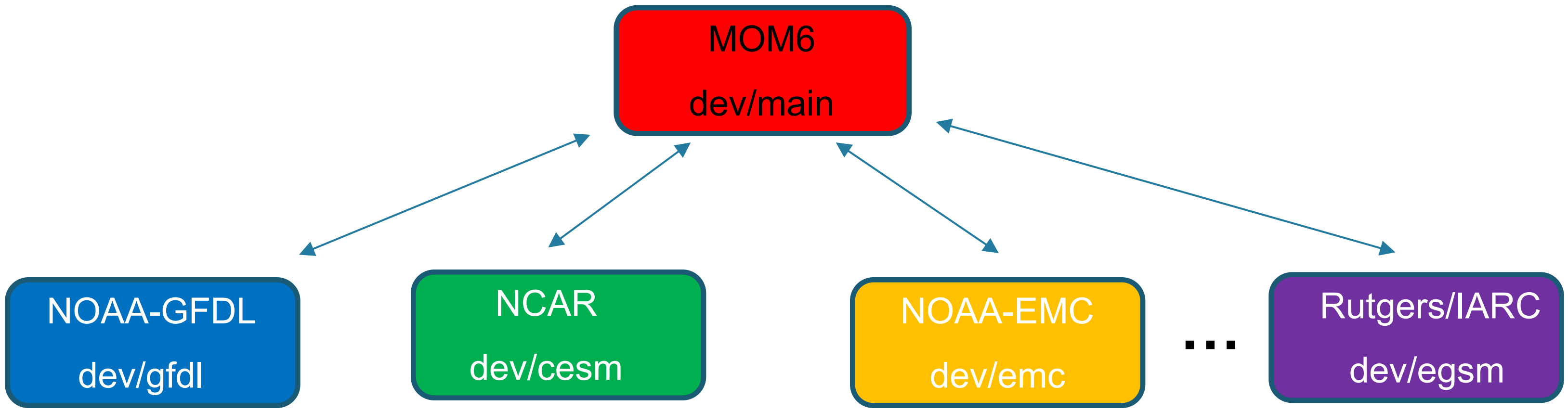
- General coordinate
- No vertical CFL limit → ultra-fine vertical resolution
- Sub-cycled gravity waves
- Built-in wetting and drying



Credit: Alistair Adcroft

MOM6 Collaborative Development Arrangement

- Tremendous support from GFDL;
- Current governance mechanism: quasi-weekly developer calls (*GFDL/NOAA, NCAR, EMC/NOAA, FSU/USN, Rutgers, IARC, GSFC/NASA, ANU*);
- Open development via GitHub;
- Growing community of users at universities and labs
- Multiple development groups working with forks from common source.



https://github.com/NCAR/MOM6

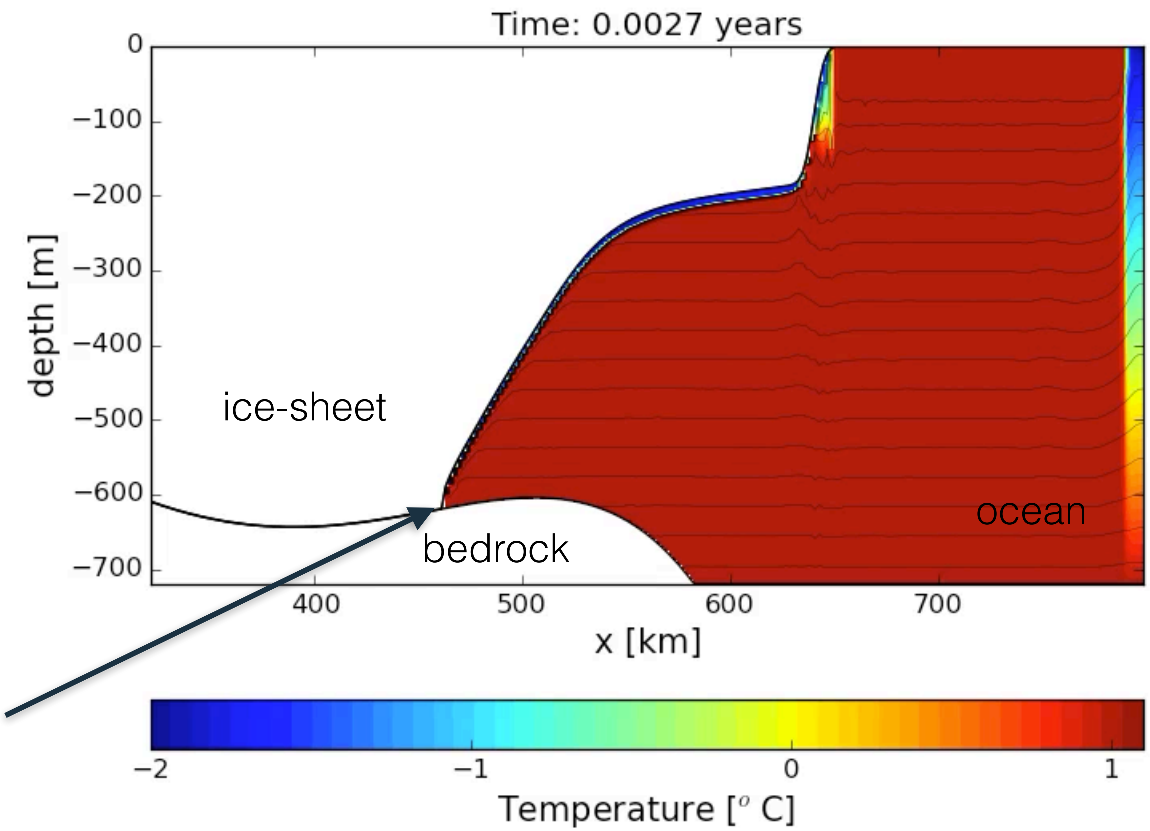
MOM6 sub-grid scale parameterizations

- **Mesoscale eddies**
  - Many ways to prescribe diffusivities
    - MEKE, Jansen et al. (2015)
    - GEOMETRIC, Marshall et al. (2012)
  - Gent & McWilliams (1990)
    - Ferrari et al., 2010
  - Neutral diffusion (aka Redi tensor)
    - Shao et al., 2020; Marques et al. (2023)
  - Backscatter
    - MEKE, Jansen et al. (2015)
    - GM+E, Bachman et al. (2019)
- **Surface boundary layer**
  - KPP via Cvmix, Large et al. (1994)
  - ePBL, Reichl and Hallberg (2018)
  - Bulk mixed layer
- **Submesoscale eddies**
  - Fox-Kemper et al. (2008)
- **Shear-mixing**
  - Jackson et al. (2008)
  - CVmix (LMD94)
- **SW penetration**
  - Manizza et al. (2005)
  - Morel (1988)
- **Bottom boundary layer**
- **Geothermal**
- **Internal tide-driven mixing**

Option to represent ice shelf cavities

Ice-shelf cavities simulated with evolving ice-shelf module coupled to ocean

ISOMIP+ (ocean-only)



Moving grounding line

Functional release of MOM6 starting in CESM 2.2

Functional release = it works but it has not being scientific validated. CESM/MOM6 is evolving very fast.

Downloading CESM+MOM6 (assuming CESM is already ported)

- Clone CESM GitHub repository: (~ 5 sec)

  $ git clone https://github.com/ESCOMP/CESM.git

- Check out the following CESM 2.3 tag, which includes MOM6 : (~ 1 sec)

  $ cd CESM

  $ git checkout cesm2_3_beta15

- Check out externals : (~ 2 min)

  $ ./manage_externals/checkout_externals -o

Detailed instructions:

https://github.com/ESCOMP/MOM_interface/wiki/Detailed-Instructions

Available configurations

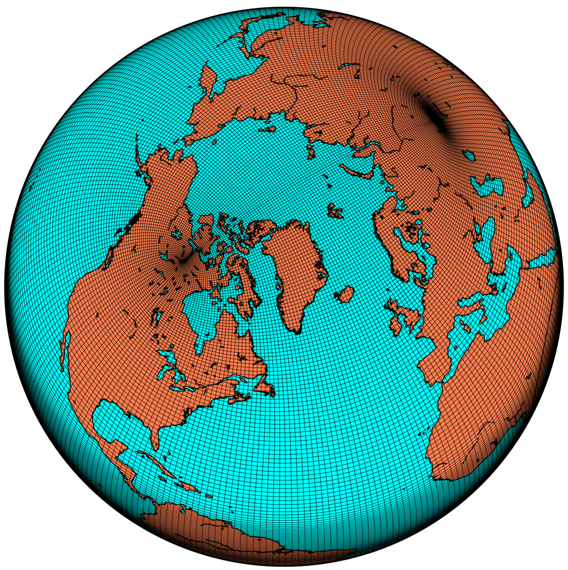
COMPSET	Compatible Resolutions	Description
CMOM	T62_t061, T62_g16, T62_t025	*MOM6 only, CORE2 NYF*
CMOM_IAF	T62_t061, T62_g16, T62_t025	*MOM6 only, CORE2 IAF*
CMOM_JRA	TL319_t061, TL319_g16	*MOM6 only, JRA55*
GMOM	T62_t061, T62_g16, T62_t025	*MOM6 and CICE only, CORE2 NYF*
GMOM_IAF	T62_t061, T62_g16, T62_t025	*MOM6 and CICE only, CORE2 IAF*
GMOM_JRA	TL319_t061, TL319_g16	*MOM6 and CICE only, JRA55*
BMOM	f09_t061	*Fully Coupled*

- t061: tx0.66v1 ↓ 2/3° "workhorse"
- t025: tx0.25v1 ↓ 1/4° research/testing
- g16: gx1v6 ↓ 1° testing

Forced simulations are often run for **one forcing cycle** (~60 years), while **fully-coupled** simulations are often run for **100 years**.

CESM-MOM6 “Workhorse” Configuration

Tripole grid

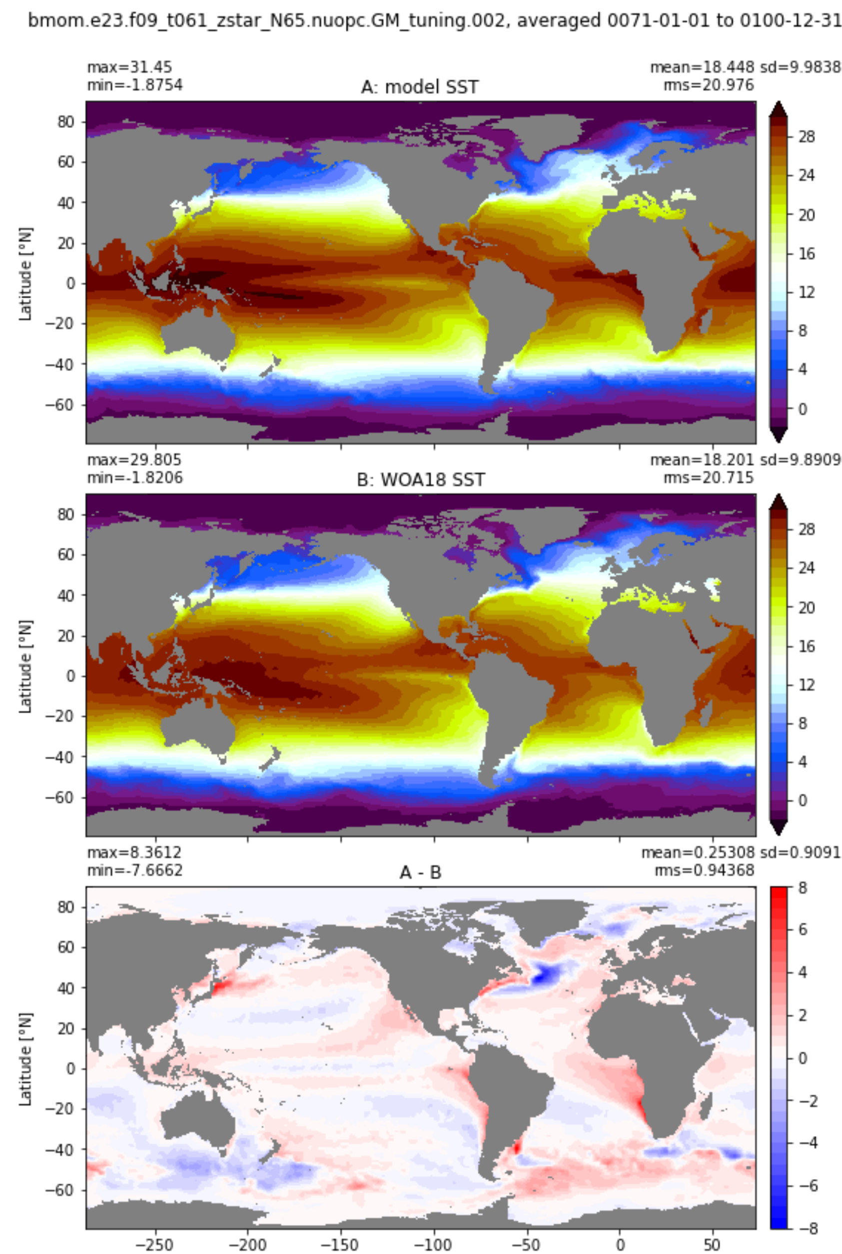


tx0.6 (nominal 2/3°)

MOM6

OBS

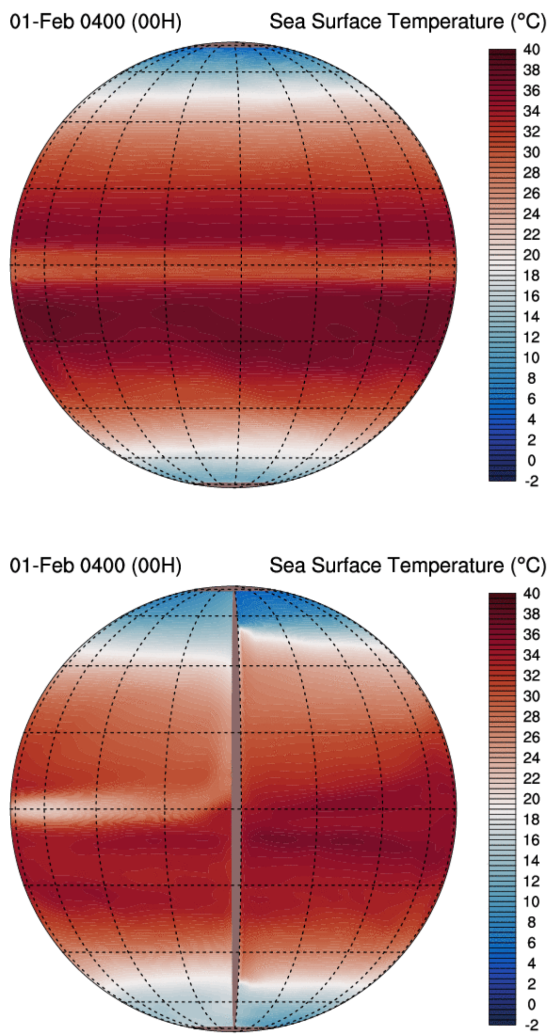
MOM6 - OBS



Century length integrations of CESM with MOM6 producing stable climate with bias and drift less than or equal to POP.

Alternative CESM ocean configrations with MOM6

Coupled Aqua- and Ridge-Planents

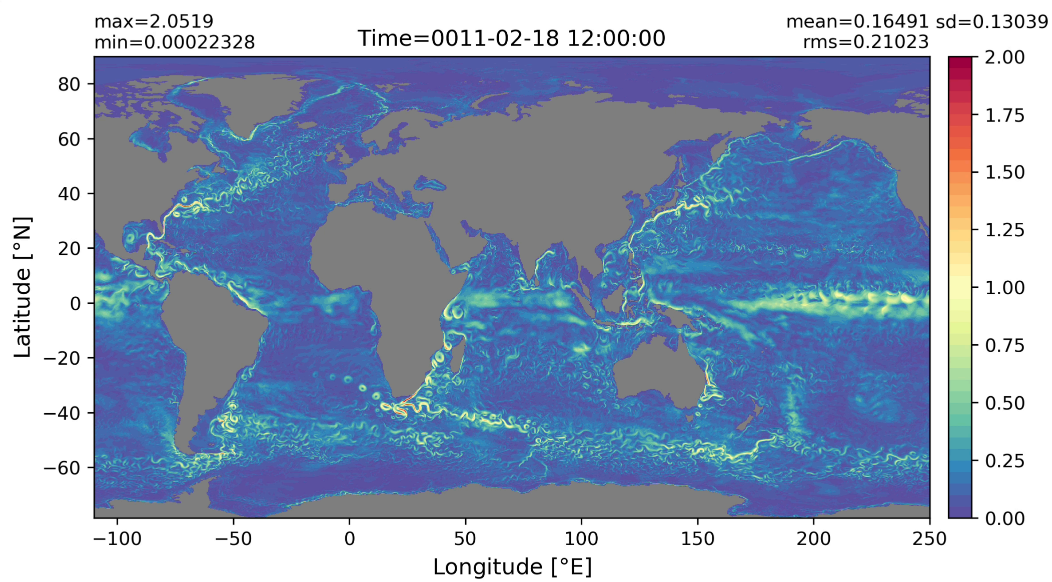


Wu et al (2021)

High-res global

- 1/10 degree nominal resolution (tx0.1, same grid used in POP);

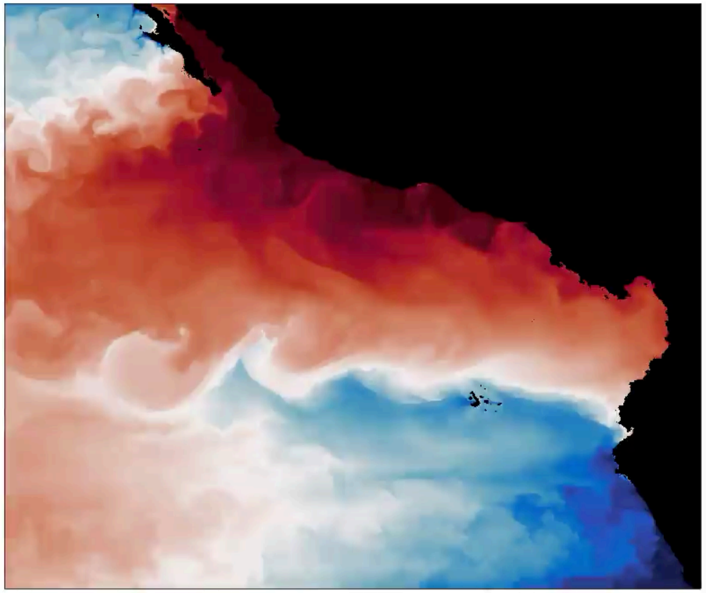
Surface velocity (m/s)



Partee et al (2022)

Eastern tropical Pacific

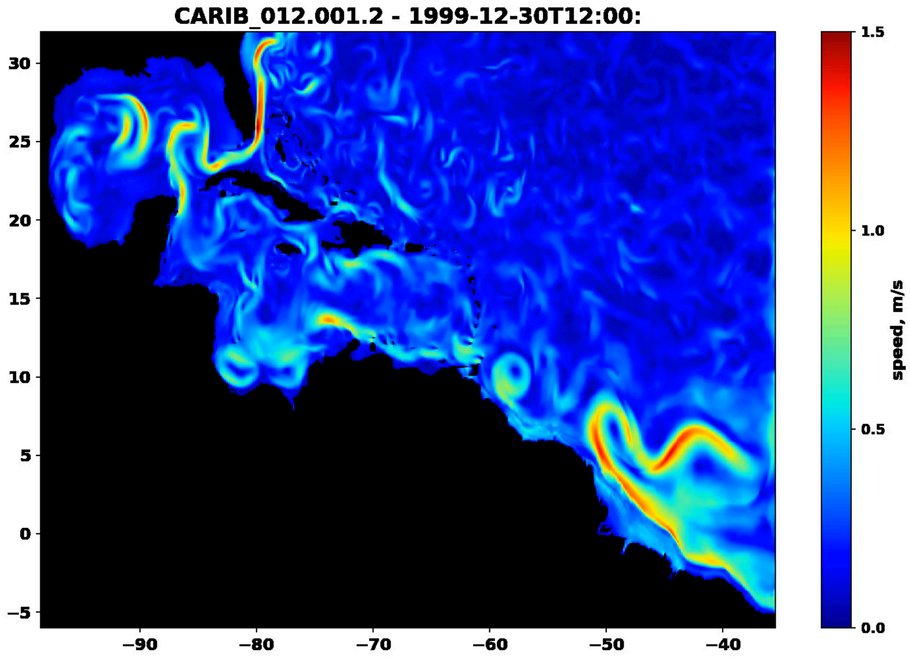
SST [°C]



Led by Scott Bachman (NCAR)

Caribbean Sea and Gulf Mexico

Surface vel. (m/s)



Led by Giovanni Seijo (grad. Student, CU Boulder/ASP)

- Actionable science applications, e.g., coral, fisheries, Marine Protected Areas, etc.

Helpful resources for the POP model

Webpage for POP: http://www.cesm.ucar.edu/models/cesm2/ocean/

- CESM2.0 POP2 User Guide
- MARBL Documentation
- Ocean Ecosystem Model User Guide
- POP Reference Manual
- Port validation
- Post-processing Utilities
- CESM1 User Guides and FAQ

CESM/POP forum:

https://bb.cgd.ucar.edu/cesm/forums/pop.136/

Helpful resources for the MOM6 model

- **Webpage for CESM/MOM6**: quick start; overview; tutorials
  https://github.com/NCAR/MOM6/wiki

- **MOM6 webinar tutorial series** spring-summer 2020: theory, how-to, use-cases
  https://www.cesm.ucar.edu/events/2020/MOM6/

- Expanding **documentation** with community contributions
  https://mom6.readthedocs.io/

- Packages for **post-processing analysis**:
  mom6_tools: https://github.com/NCAR/mom6-tools
  om4labs: https://github.com/raphaeldussin/om4labs

- **MOM6 forum** is for technical and scientific questions related to MOM6, including but not limited to its use in CESM:

  https://bb.cgd.ucar.edu/cesm/forums/mom6.148/

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Thank you!

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Ocean Model Working Group:
http://www.cesm.ucar.edu/working_groups/Ocean/