Ocean Modeling I

Ocean Modeling Basics and Overview of CESM Ocean Models

Gustavo Marques
(gmarques@ucar.edu)

Oceanography Section
Climate and Global Dynamics Laboratory
NSF National Center for Atmospheric Research

08 July 2026

This material is based upon work supported by the National Center for Atmospheric Research, which is a major facility sponsored by the National Science Foundation under Cooperative Agreement No. 1852977.

Outline

1) General ocean modelling considerations

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

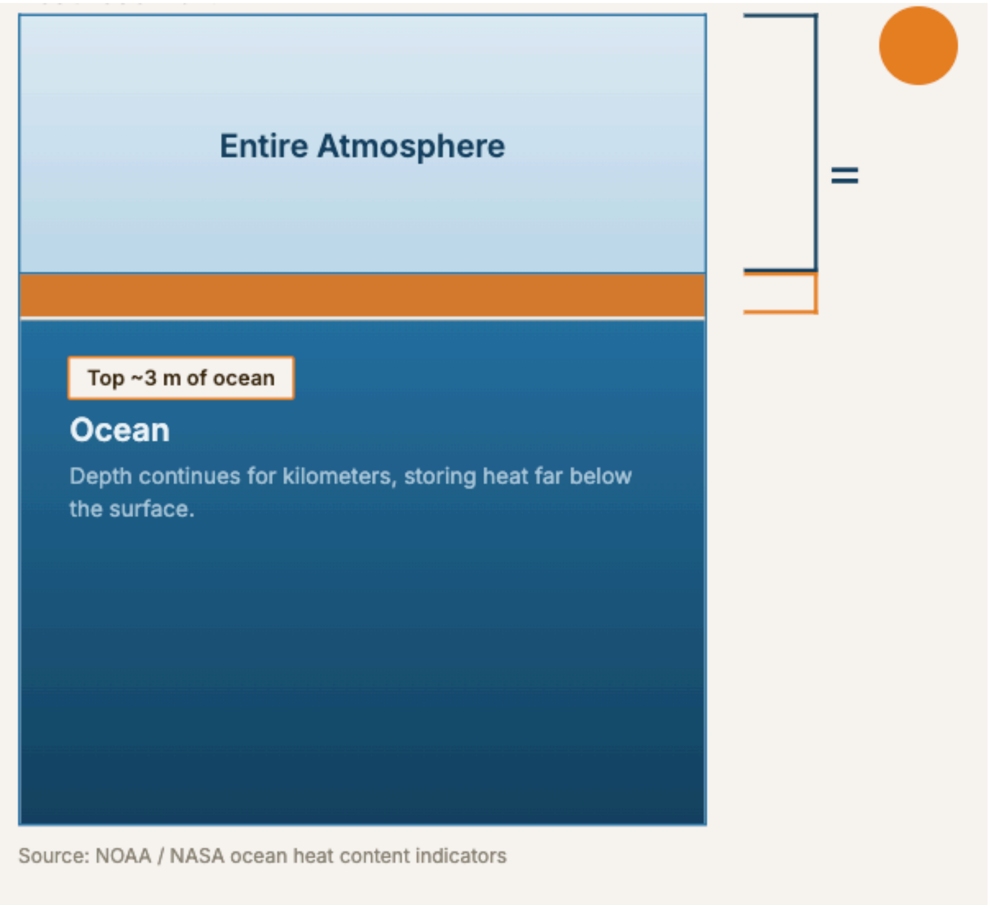
2) Modular Ocean Model version 6 (MOM6)

- Dynamical core
- Sub-grid scale parameterizations
- Alternative configurations

3) Helpful resources

Why the ocean is a major heat reservoir

Water absorbs and stores far more thermal energy than air — making the ocean Earth's dominant heat reservoir.



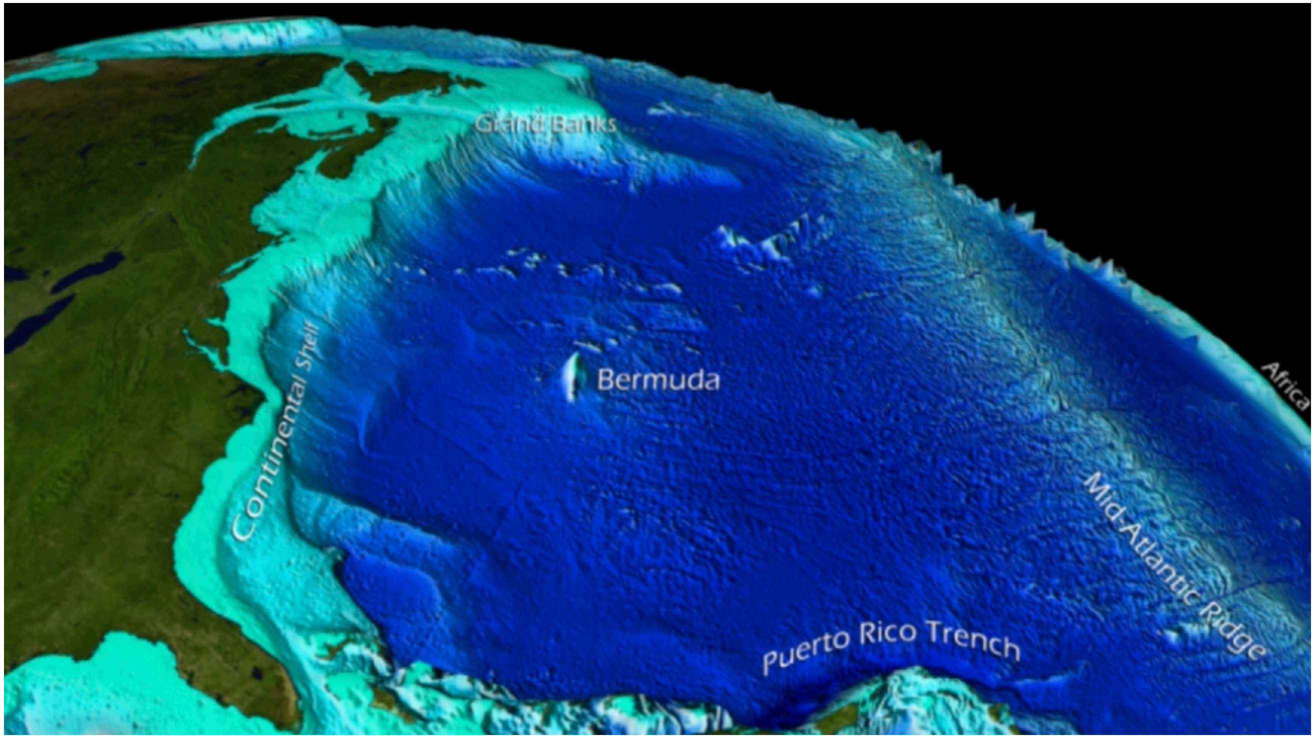
~ 3m of ocean holds as much heat as the entire atmosphere stacked above it

- Water's specific heat capacity is about **4x higher** than air's, and the ocean's mass vastly exceeds the atmosphere's.
- This is why the ocean has absorbed ~ **90% of excess heat** trapped by greenhouse gases.

Ocean Modeling Challenges: Irregular domain

1st order challenges from a numerical perspective:

- Highly irregular domain

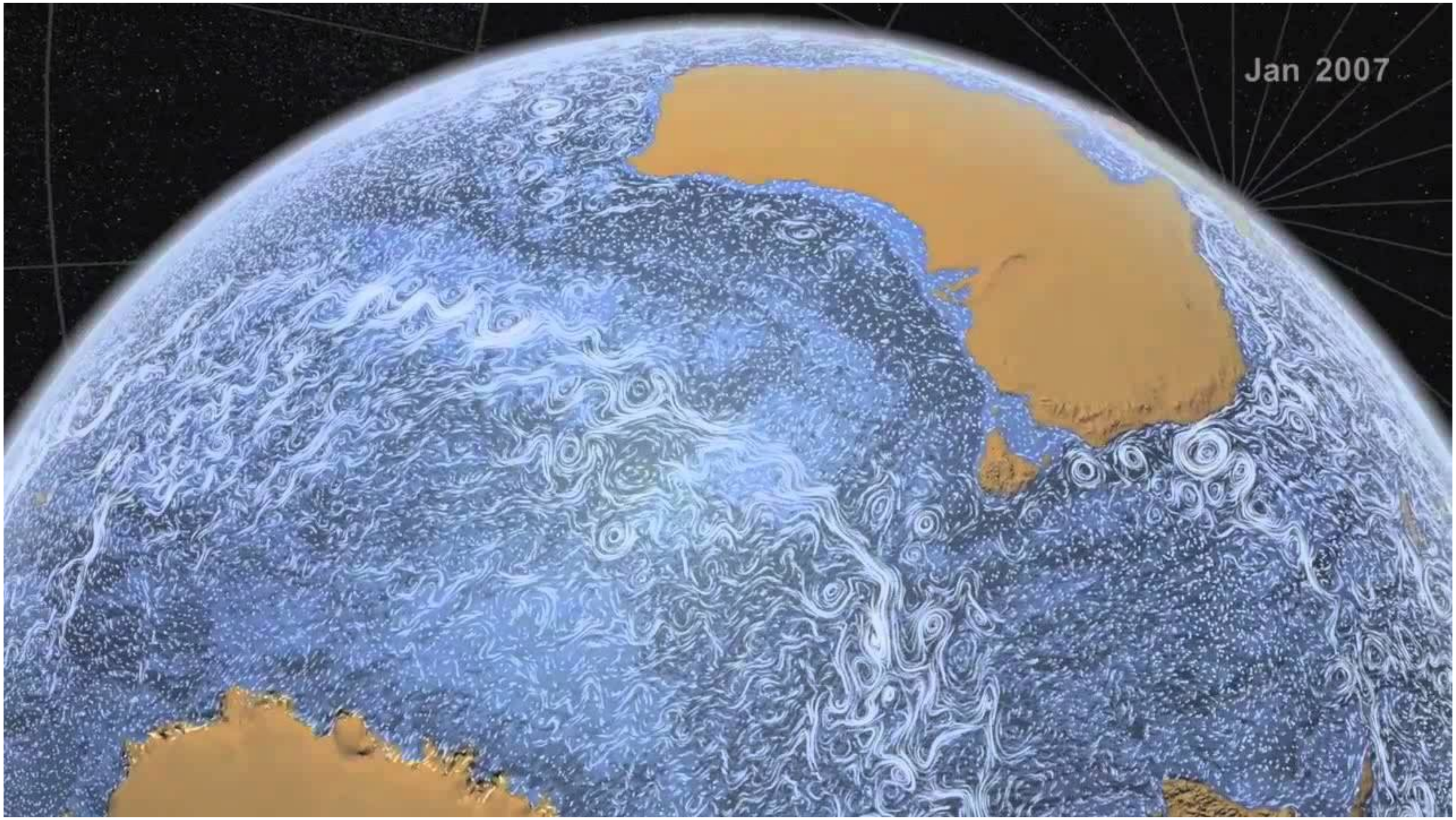


Credit: NOAA

Ocean Modeling Challenges: land boundary control dynamics

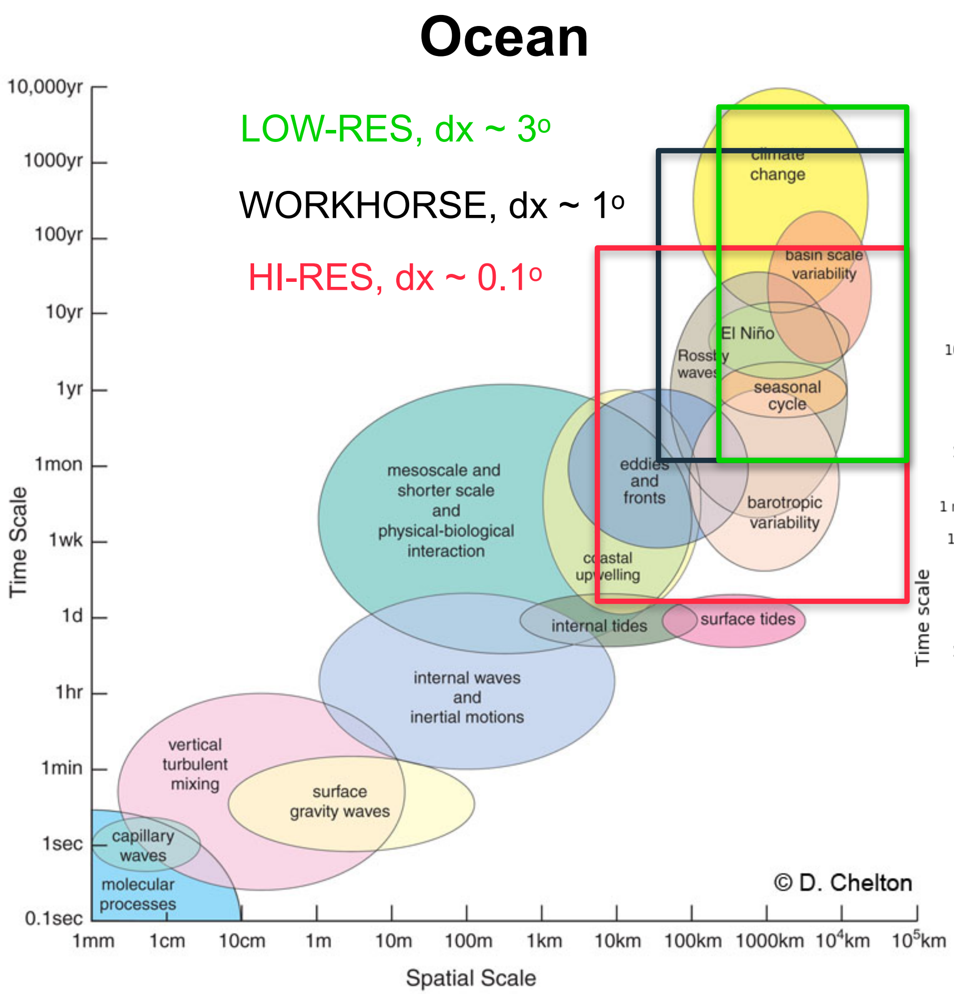
1st order challenges from a numerical perspective:

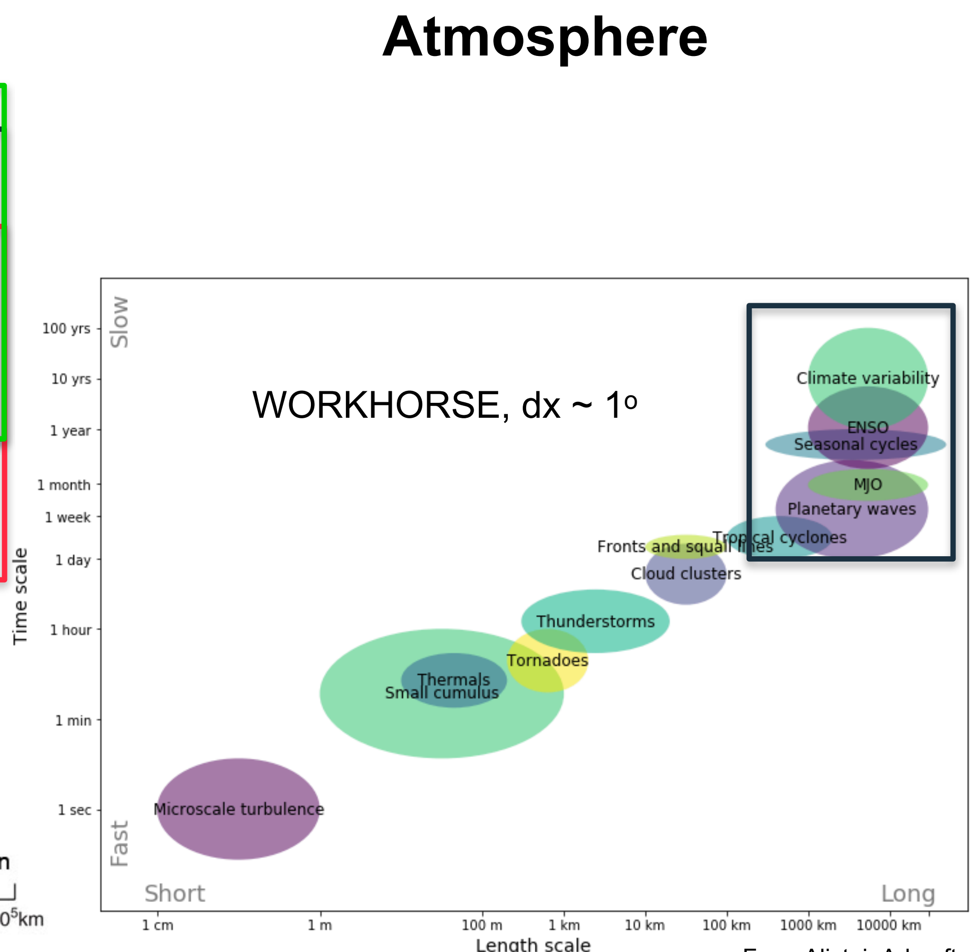
- Land boundary exerts strong control on ocean dynamics.



Perpetual Ocean; Credit: MIT/NASA-JPL ECCO2

Ocean Modeling Challenges: Spatial vs. Temporal Scales



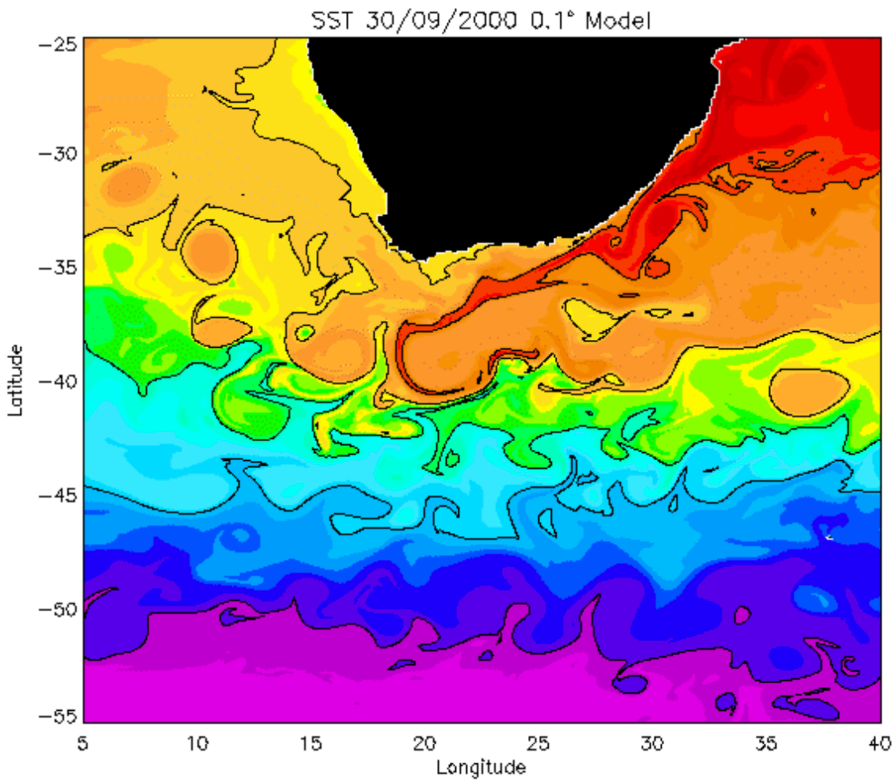


From Alistair Adcroft

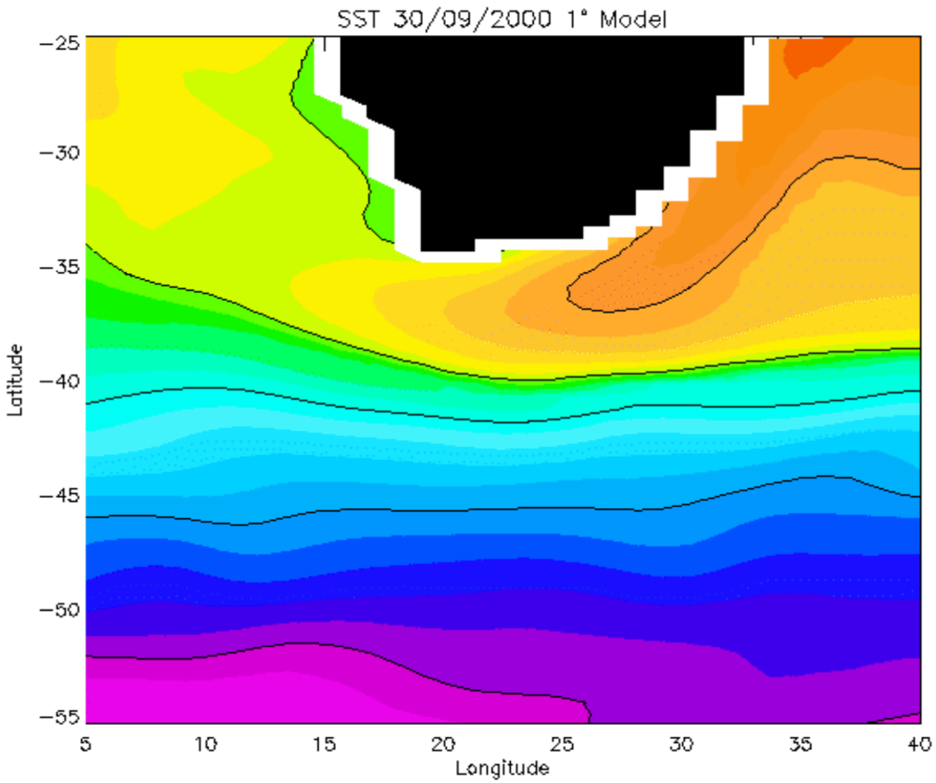
- Most global ocean models simulate the **climate**
- Most global atmospheric models simulate the **weather**

Ocean Modeling Challenges: Spatial Scales

Δx = 0.1 degree



Δx = 1.0 degree

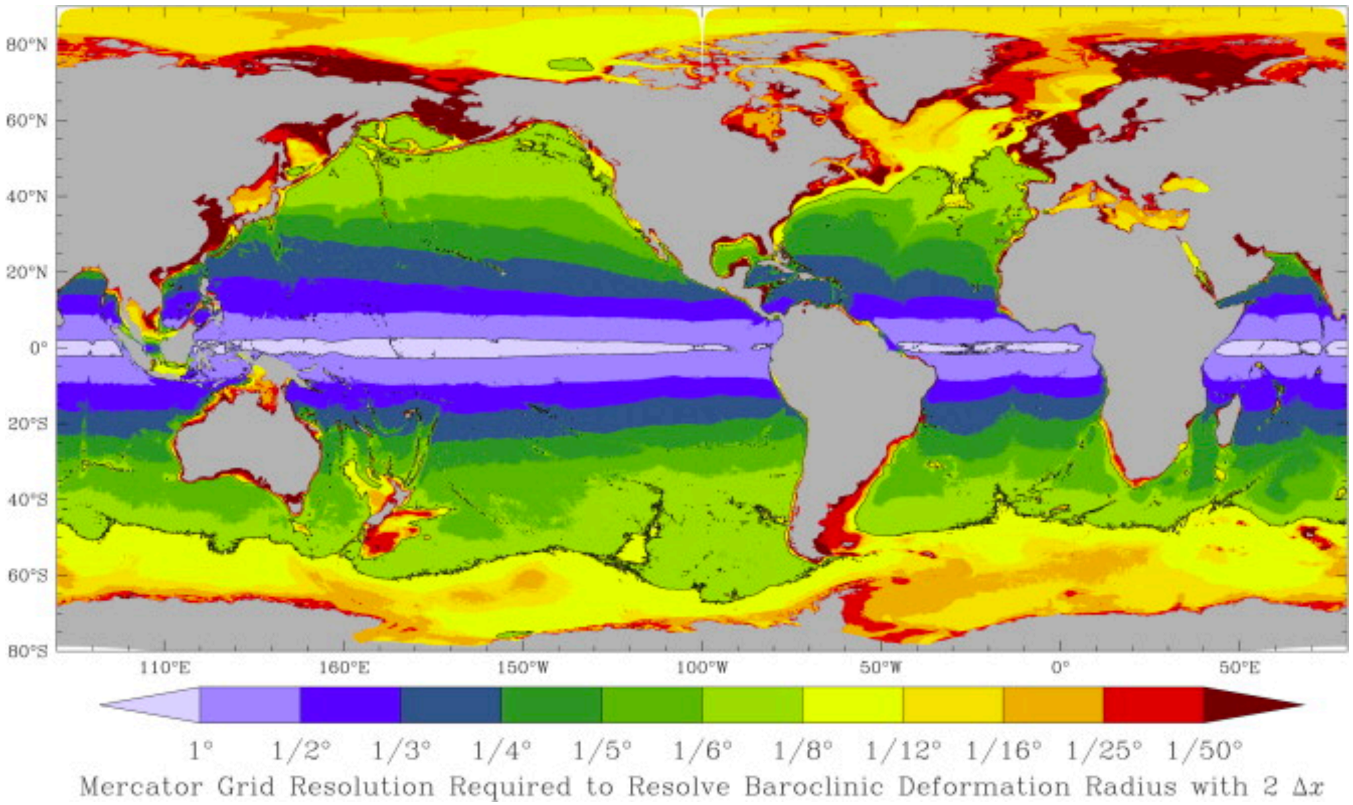


- Mixing associated with sub-gridscale turbulence must be parameterized.

Ocean Modeling Challenges: Eddy-Resolving Scales

- In the ocean, the density change from top to bottom is much smaller than in the atmosphere. This makes the **Rossby radius (R_d)** much smaller – O(10-200) km in the ocean and O(1000s) km in the Atmosphere.

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



From Hallberg (2013)

Ocean Modeling Challenges: Equilibration Timescale

- **Mixing adjustment 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 m)^2 / (2 x 10^{-5} m^2/s) = 20,000 years

- **Dynamical adjustment timescale:**

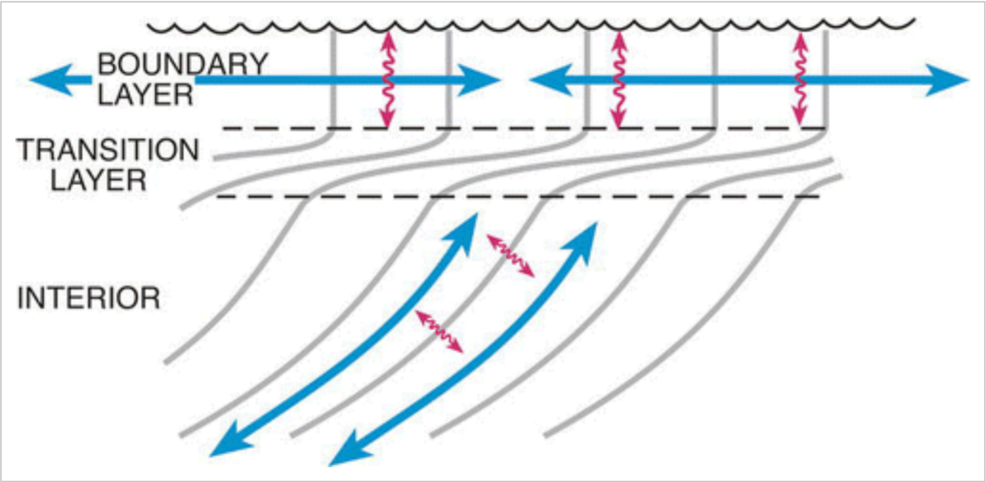
Phase speed of non-dispersive long Rossby waves, $C_R = -\beta R_d^2$

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

L/C_R = (15 x 10^3 km) / (20 km/day) = 750 days ~ 2 years.

Ocean Modeling Challenges: diabatic versus adiabatic regimes

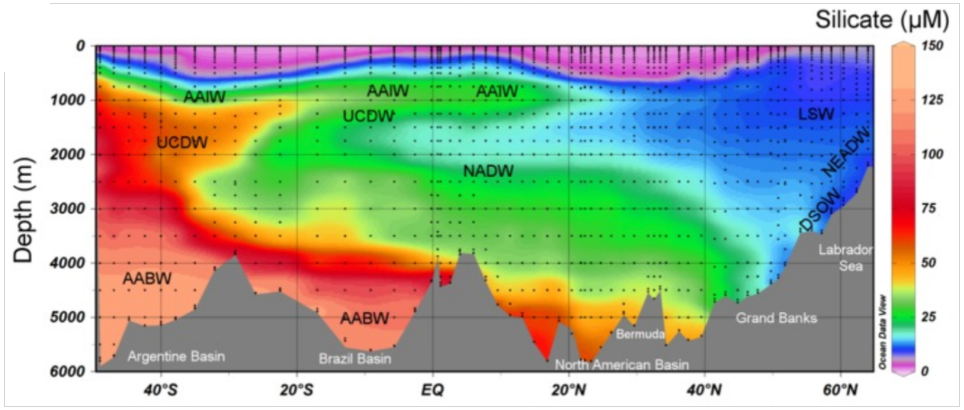
Conceptual model of mesoscale eddy fluxes in the upper ocean



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)

Bottom line for climate studies

- Performing long (climate scale) simulations at eddy-resolving/permitting resolution are not practical;
- Must live with deep ocean not being at equilibrium in most simulations;
- Spurious mixing in the interior can significantly degrade the solution;
- 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 long-term prediction studies.

The equations solved by the ocean models

7 equations and 7 unknowns:

- 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 Cartesian form

Horizontal momentum:

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

Vertical momentum (hydrostatic equation):

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

Mass conservation / continuity equation:

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

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

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);

Ocean bottom:

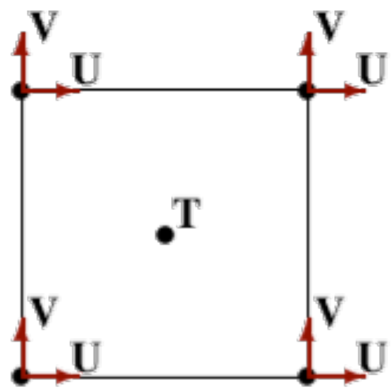
- No tracer fluxes (option to include geothermal heating in MOM6);
- Normal velocity is zero;
- Quadratic bottom drag (bottom boundary condition on viscosity term).

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



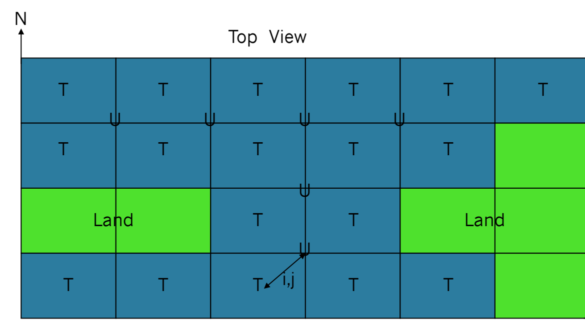
Top view

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:

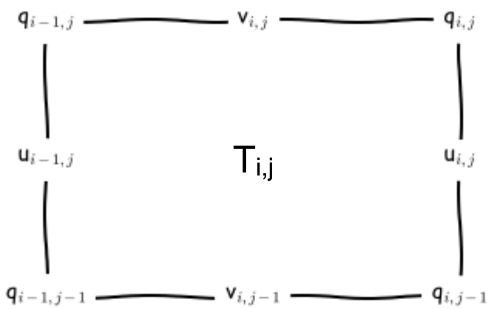
- Cannot represent single-point channels →
- Larger truncation errors in the pressure gradient terms;



This is the staggering used in POP2

Horizontal grid staggering: Arakawa C grid

Arakawa C grid



Top view

Advantages:

- Allows single-point channels

Disadvantages:

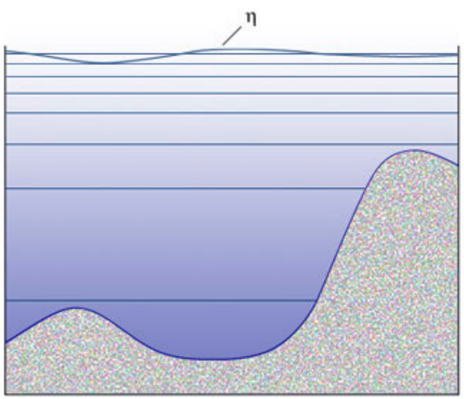
- The Coriolis acceleration terms requires horizontal averaging, making the inertia gravity waves (related with Coriolis force) less accurate;
- Poorer dispersion for Rossby waves at very coarse resolution than B-grid;

This is the staggering used in MOM6

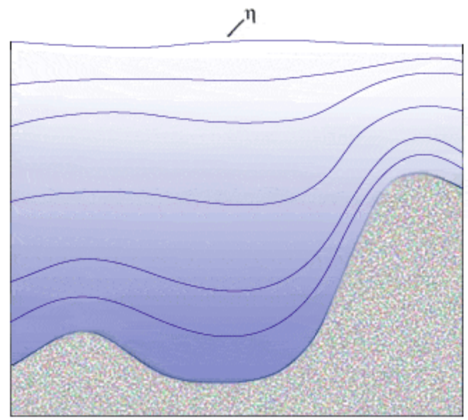
Vertical coordinate system in ocean models

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:

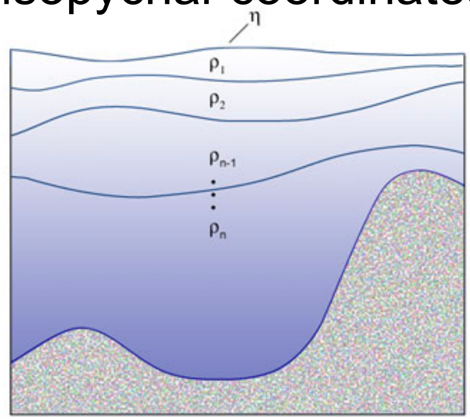
z-coordinates



σ-coordinates



isopycnal-coordinates



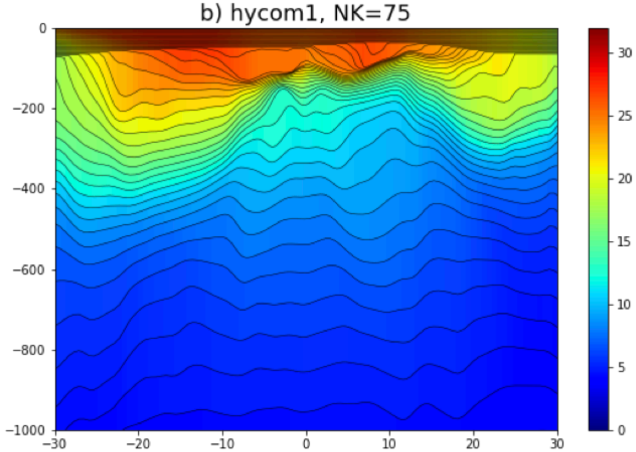
From: https://www.oc.nps.edu/nom/modeling/vertical_grids.html

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

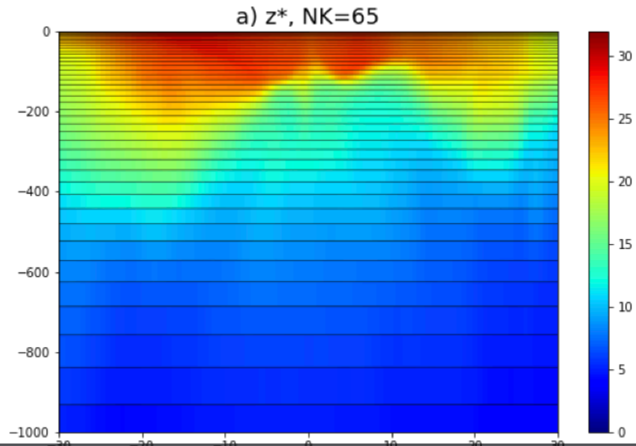
- This is an area of very active research and development in numerical ocean models.

MOM6 vertical grids

Hybrid (z*/rho), 75 levels (default option)

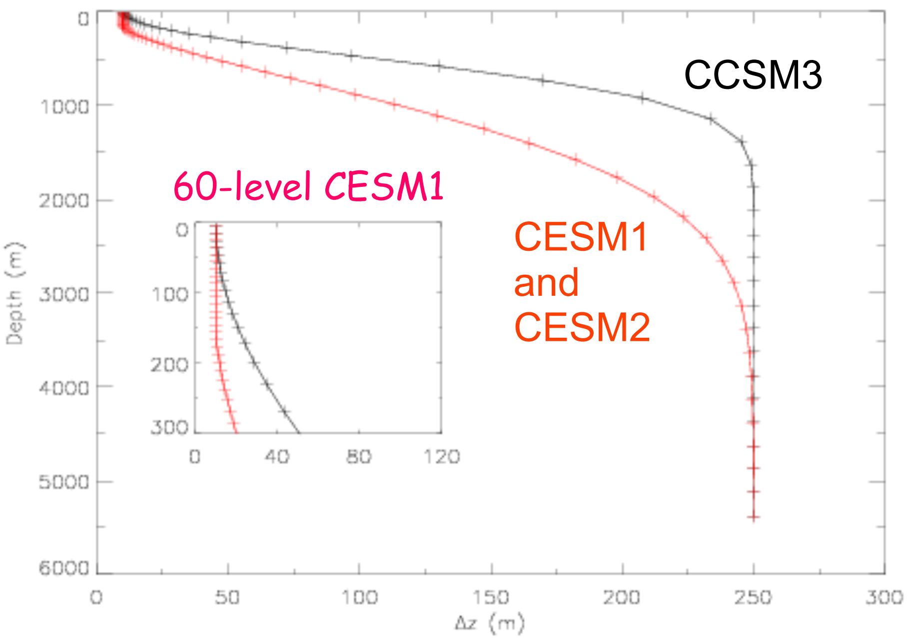


z*-coordinates, 65 levels



POP2 vertical grids

z-coordinates



Gustavo Marques (gmarques@ucar.edu)

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;

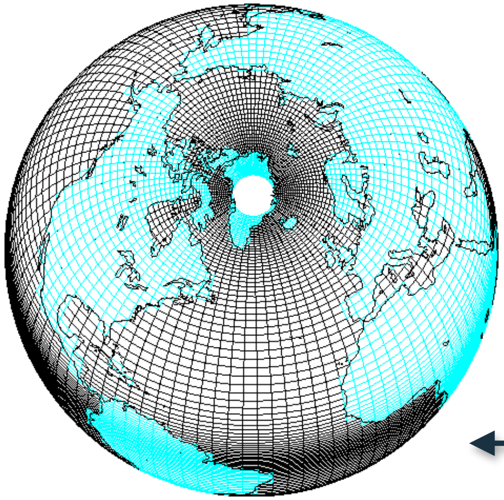
- Normal Year Forcing (NYF): synthetic year that repeats exactly; good for model testing and parameterization impact studies.

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

- JRA-55 (1958 to 2023), https://jra.kishou.go.jp/JRA-55/index_en.html, Tsujino et al., Ocean Modelling (2018)

Horizontal grids

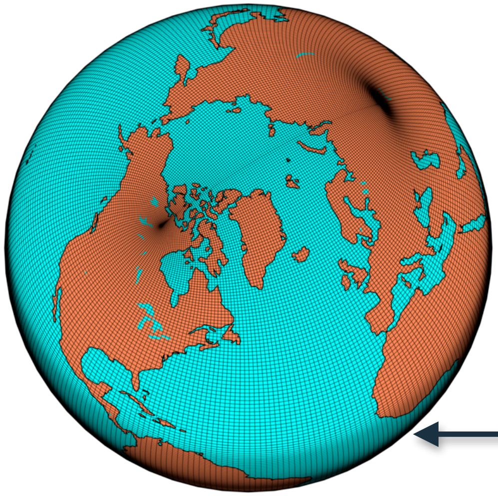
Displaced pole → Removes singularity from the North Pole



- gx1: workhorse with POP2 (nominal 1°)
- gx3: testing/paleo and wave model in CESM3 (nominal 3°)

← Equatorial refinement (0.3° / 0.9°)

Tripole → Used in CESM3/MOM6



- tx2_3: workhorse with MOM6 (nominal 2/3°);

← Equatorial refinement (0.25°)

See Murray (1996) for details on the various types of grids.

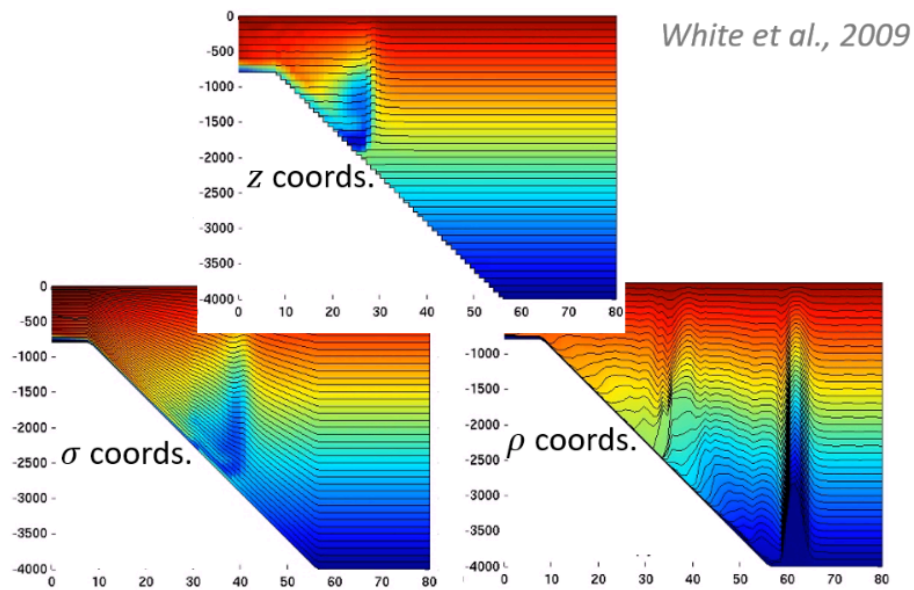
The Modular Ocean Model version 6 (MOM6) dynamical core

- **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**

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

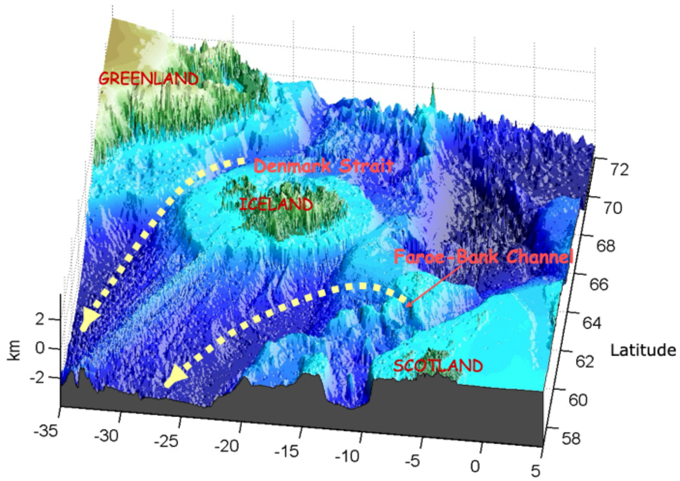


Credit: Alistair Adcroft

Some of the sub-grid scale parameterizations available

- **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)
  - Ohlmann (2003)
  - Morel (1988)
- **Bottom boundary layer**
- **Geothermal**
- **Internal tide-driven mixing**

Overflows in CESM/MOM6

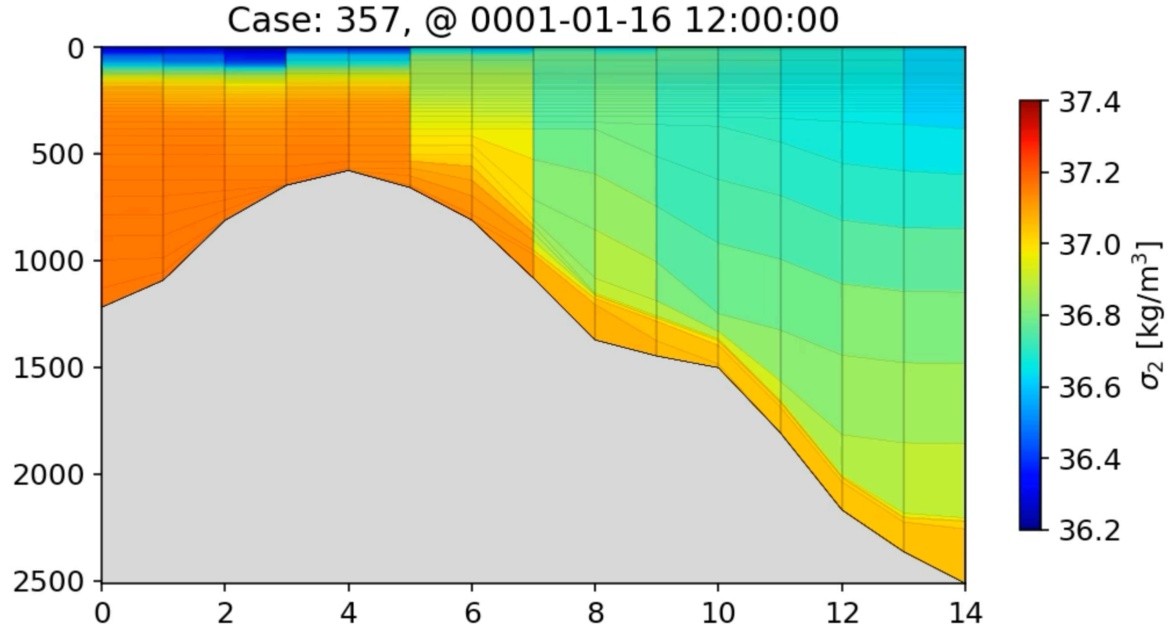


Credit: Jim Price (WHOI)

Overflows play a critical role in the formation of intermediate and bottom waters, supplying the dense water masses that drive the deep branch of the global overturning circulation.

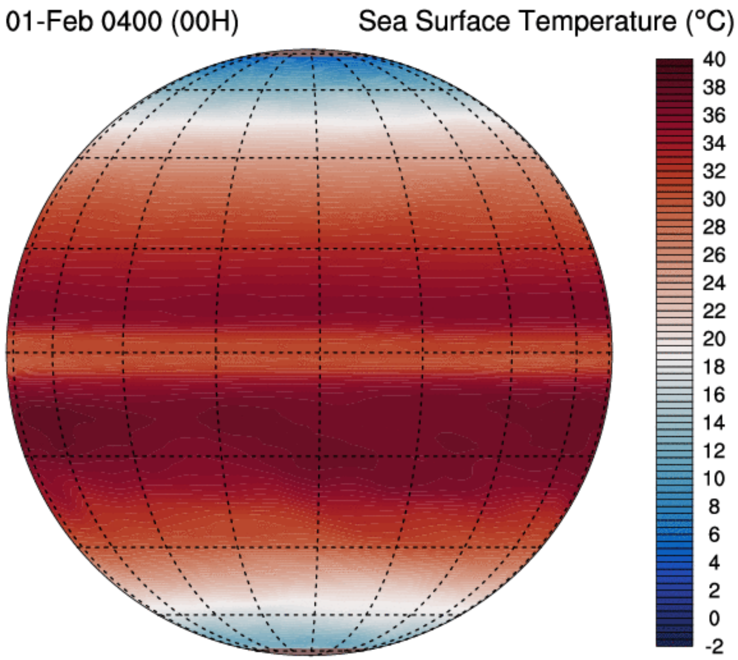
The hybrid vertical coordinate enables MOM6 to explicitly represent dense overflows.

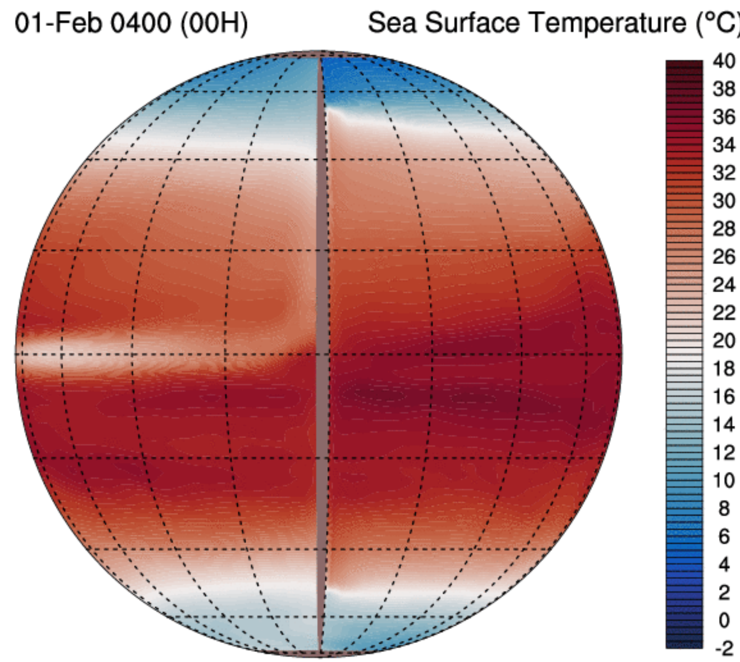
CESM3 Coupled Simulation of the Denmark Strait Overflow



Fully-coupled simplified configurations

CESM Aqua and Ridge: seasonal cycle of SST (yr 400)

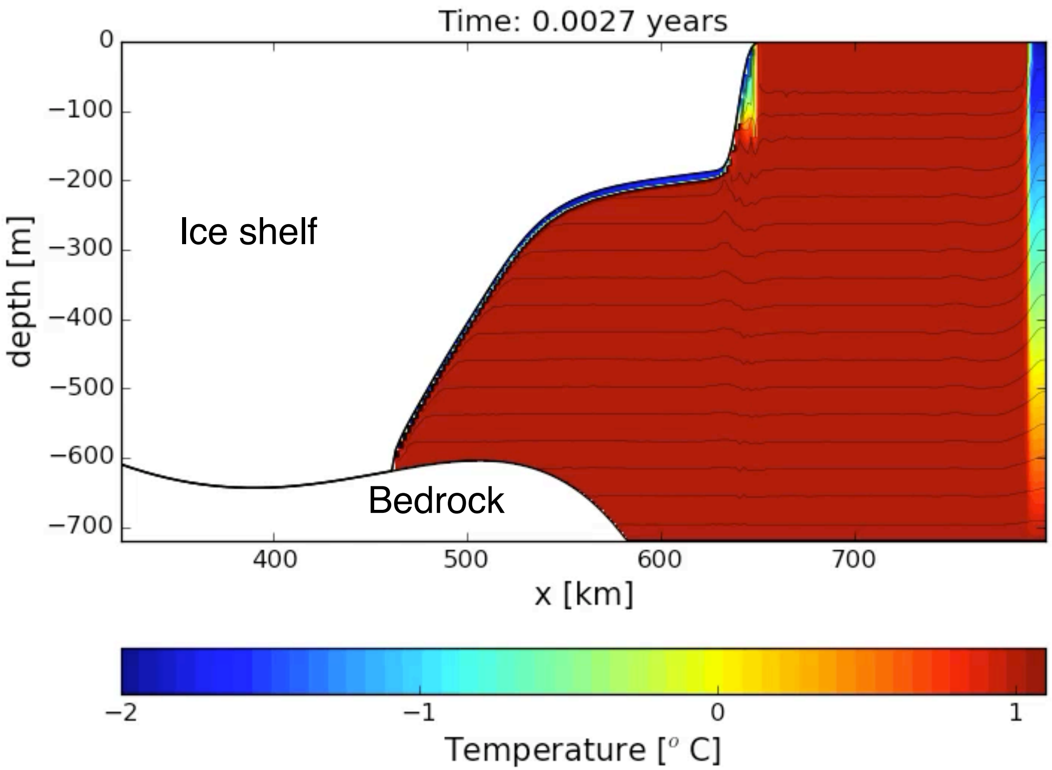




Models: MOM6 (@2°), CAM4 (@1°), CLM wetland , CICE5

- Wu et al., (2021): Coupled aqua and ridge planets in the community earth system model. *JAMES*
- Wu et al., (2021): The dependence of tropical modes of variability on zonal asymmetry. *GRL*

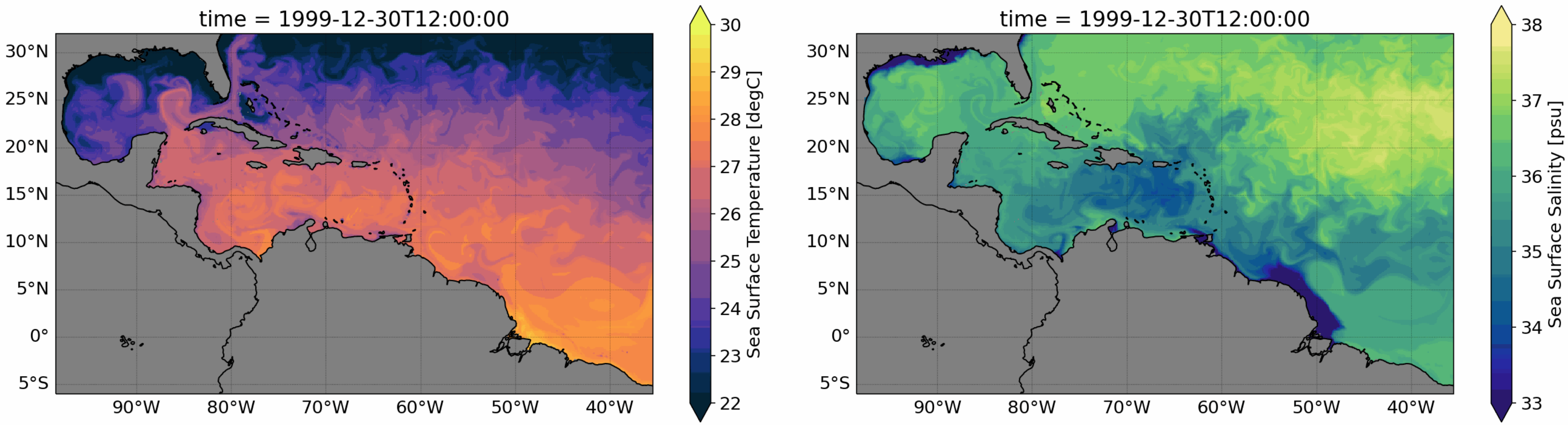
Ice shelf - ocean interactions



- This MOM6 simulation is described in Yung et al, (2026) - Results of the second Ice Shelf–Ocean Model Intercomparison Project (ISOMIP+);
- Some centers are starting to explore ice-shelf/ocean interactions in regional and global models.

This is a good example of the built-in wetting-and-drying capability in MOM6.

Regional applications



CARIB12: a regional Community Earth System Model/Modular Ocean Model 6 configuration of the Caribbean Sea

Giovanni Seijo-Ellis[1], Donata Giglio[1], Gustavo Marques[2], and Frank Bryan[2]

[1]Department of Atmospheric and Oceanic Sciences, University of Colorado, Boulder, Boulder, CO, USA
[2]Climate and Global Dynamics Laboratory, U.S. National Science Foundation National Center for Atmospheric Research, Boulder, CO, USA

This capability enables actionable ocean science for coral reef conservation, sustainable fisheries, and Marine Protected Areas (MPAs).

Upcoming workshop on regional CESM/MOM6

Models and Training for the Community: CROCODILE – An NSF Cyber Infrastructure Project (CSSI)

NSF | NCAR OPERATED BY UCAR

CROCODILE: Regional Ocean and Carbon Cycle Modeling and Data Assimilation with the Community Earth System Model

- Tools to aid researchers to easily configure regional domains using MOM6 ocean model within the CESM framework
- Connects models and observations using DART/JEDI data assimilation
- Projections at regional and local scales (needed by decision makers)

Upcoming workshop (CROCODILE + MOM6)

2026 Regional Ocean Modeling with MOM6 in the Community Earth System Model Framework

Sep. 28 to Oct. 2, 2026

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/

- **Regional MOM6:**
  - https://github.com/CROCODILE-CESM/CrocoDash
  - https://github.com/NOAA-CEFI-Regional-Ocean-Modeling
  - https://github.com/COSIMA/regional-mom6

Thank you!

Gustavo Marques
gmarques@ucar.edu

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