Ocean Modeling I

Ocean Modeling Basics and CESM Ocean Models

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Outline

1) General ocean modelling considerations

- Challenges for ocean modeling
- Ocean properties

2) Parallel Ocean Program version 2 (POP2)

- Governing equations
- Ocean model grid
- Advection schemes
- Boundary conditions
- Estuary Box model parameterization
- New to CESM2

3) Modular Ocean Model version 6 (MOM6)

- Brief overview
- Where we are going

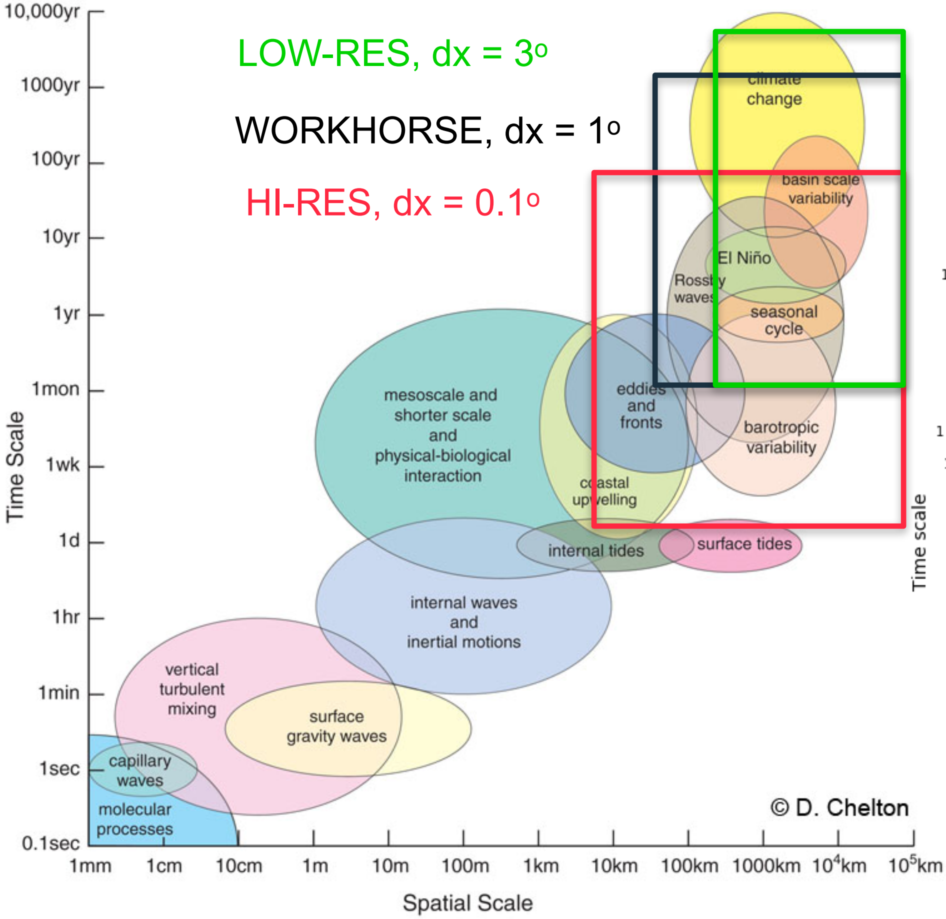
Ocean Modeling Challenges: irregular domain

1st order challenges from a numerical perspective:

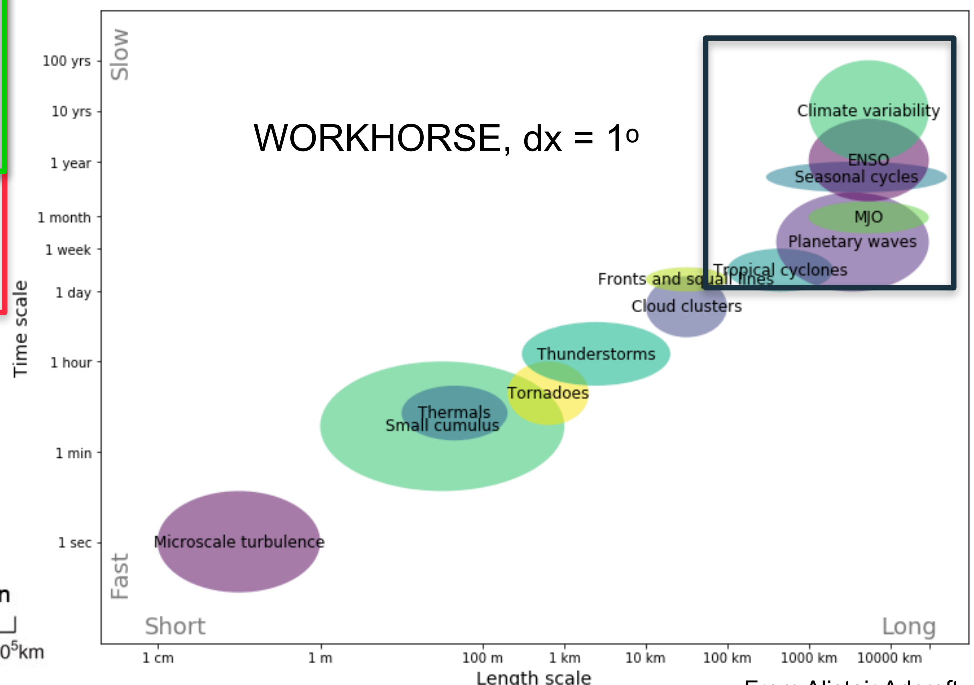
- Highly irregular domain; land boundary exerts strong control on ocean dynamics.

Ocean Modeling Challenges: Spatial vs. Temporal Scales

Ocean



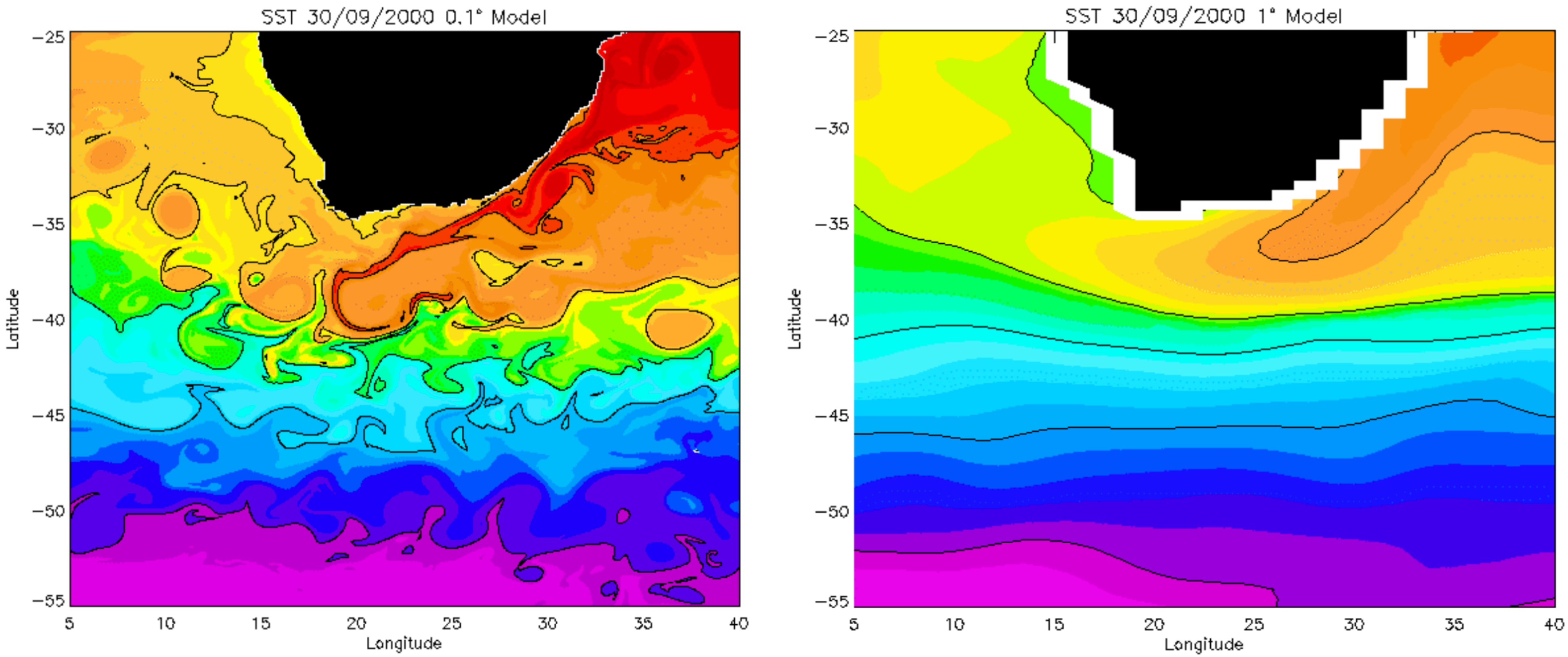
Atmosphere



From Alistair Adcroft

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

Ocean Modeling Challenges: Spatial Scales

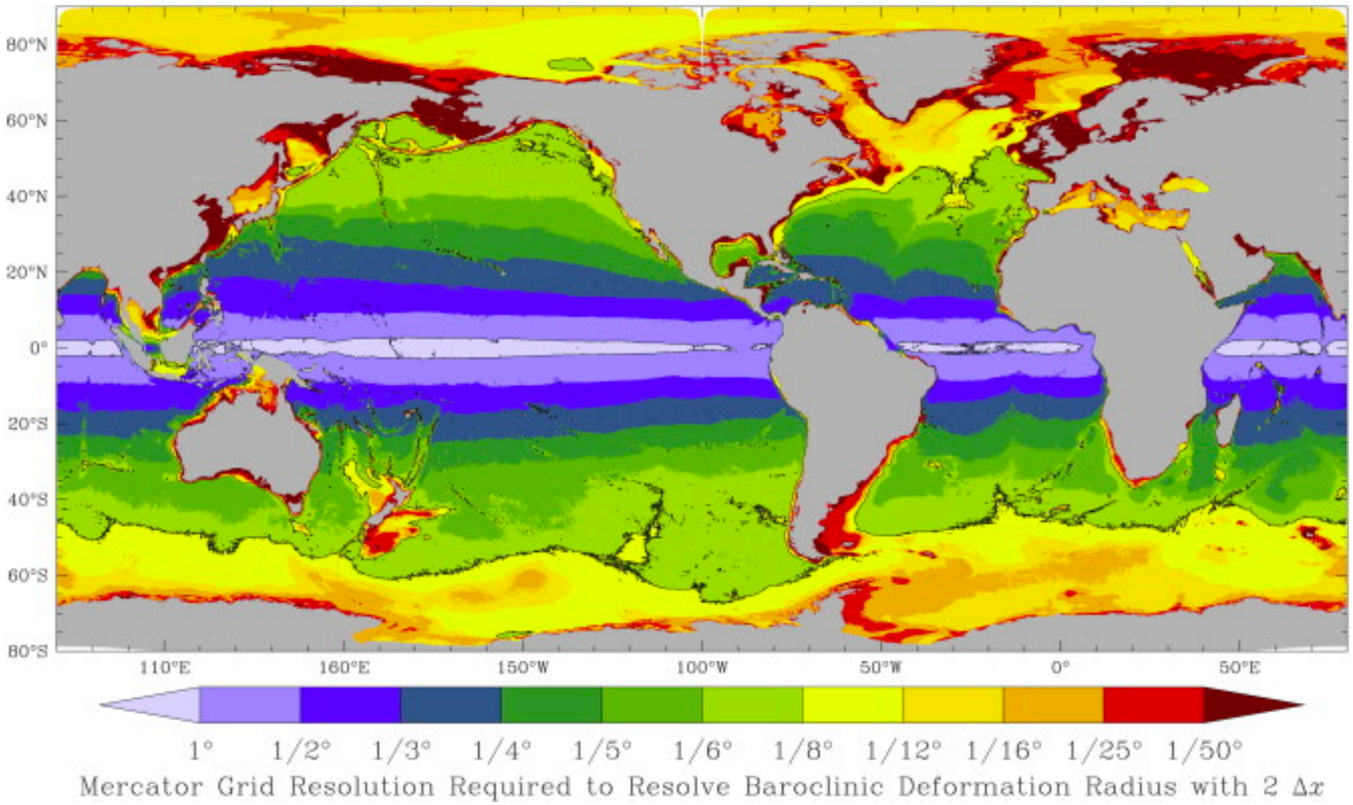


- Mixing associated with sub-gridscale turbulence must be parameterized.

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: 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 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.

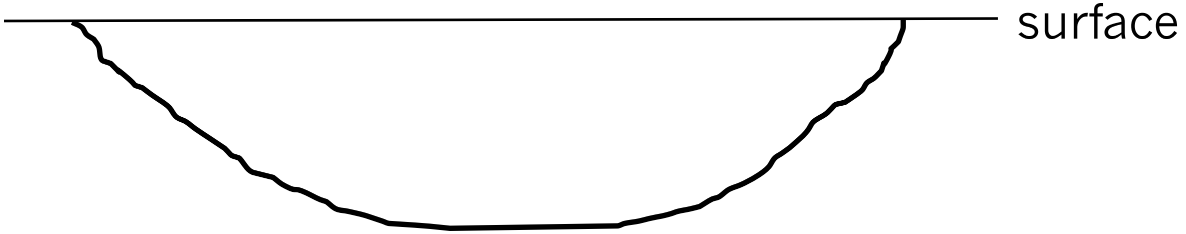
Bottom line for climate studies

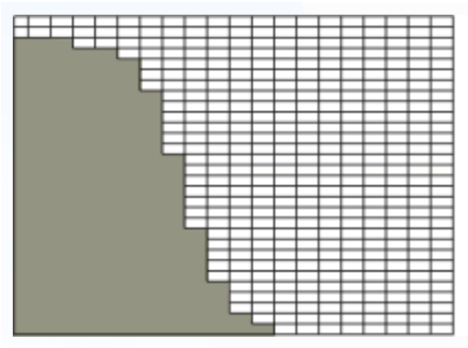
- Performing long (climate scale) simulations at eddy-resolving/permitting resolution are not practical;

- Must live with deep ocean not being at equilibrium in most simulations.

Other Important Ocean Properties

- Top to bottom "lateral" boundaries;





- 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 $\longrightarrow$ important implications for decadal prediction studies.

Parallel Ocean Program version 2 (POP2)

- POP2 is a level- (z-) coordinate model developed at the Los Alamos National Laboratory (Smith et al. 2010);

- 3-D primitive equations in general orthogonal coordinates in the horizontal are 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.

Parallel Ocean Program version 2 (POP2)

- POP2 originated from Kirk Bryan's model published 50 years ago;

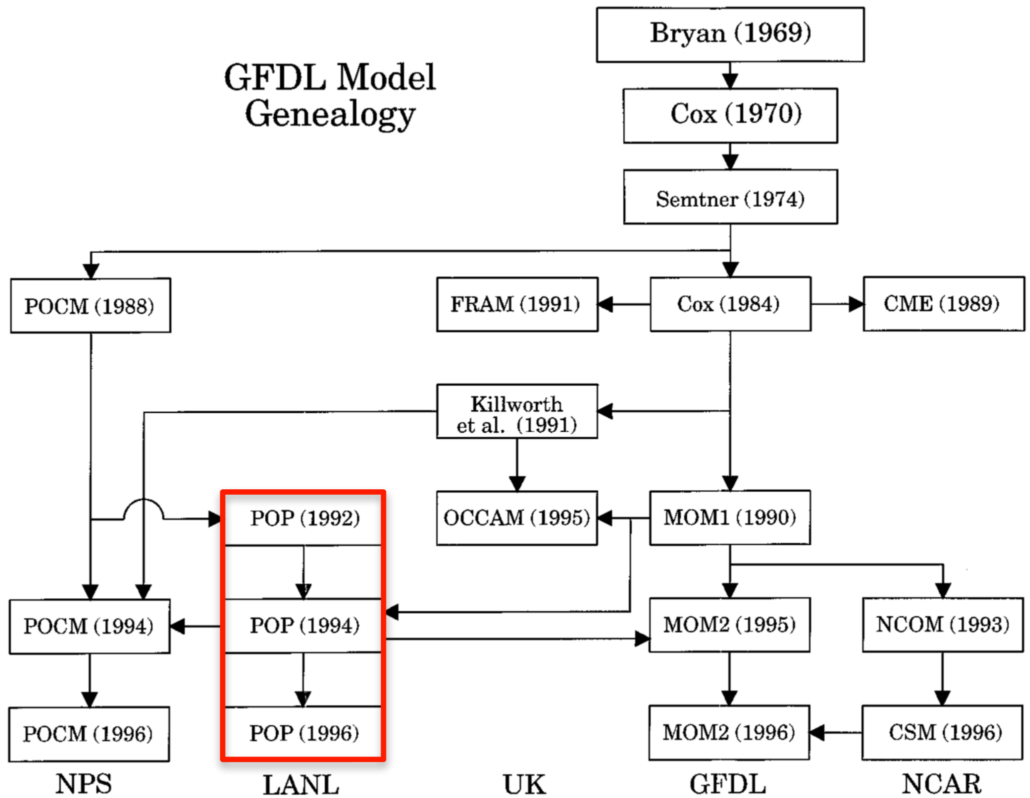


FIG. 1. Genealogy of the Bryan (1969) ocean model developed at the Geophysical Fluid Dynamics Laboratory (GFDL). Some of the boxes refer to published papers listed in the references. Other boxes refer to model versions by acronyms defined in the text and to specific years in which they reached new levels of maturity.

From Semtner (1997)

POP2: Model Equations

7 equations and 7 unknowns:

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

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

Approximations:

- **Boussinesq** ⟶ $\rho = \rho_0 + \rho'$, $\rho' << \rho_0$; density variation is only important in the hydrostatic equation;
- **Continuity (incompressible form)** ⟶ can't deform seawater, so what flows into a control volume must flow out;
- **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.

POP2: model equations

Boussinesq hydrostatic eqs. in height coordinates

Horizontal momentum:

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

Vertical momentum (hydrostatic equation):

$$\partial_z p = -g\rho \tag{2}$$

Continuity equation:

$$\boldsymbol{\nabla}_z \cdot \boldsymbol{u} + \partial_z w = 0, \tag{3}$$

POP2: model equations (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:

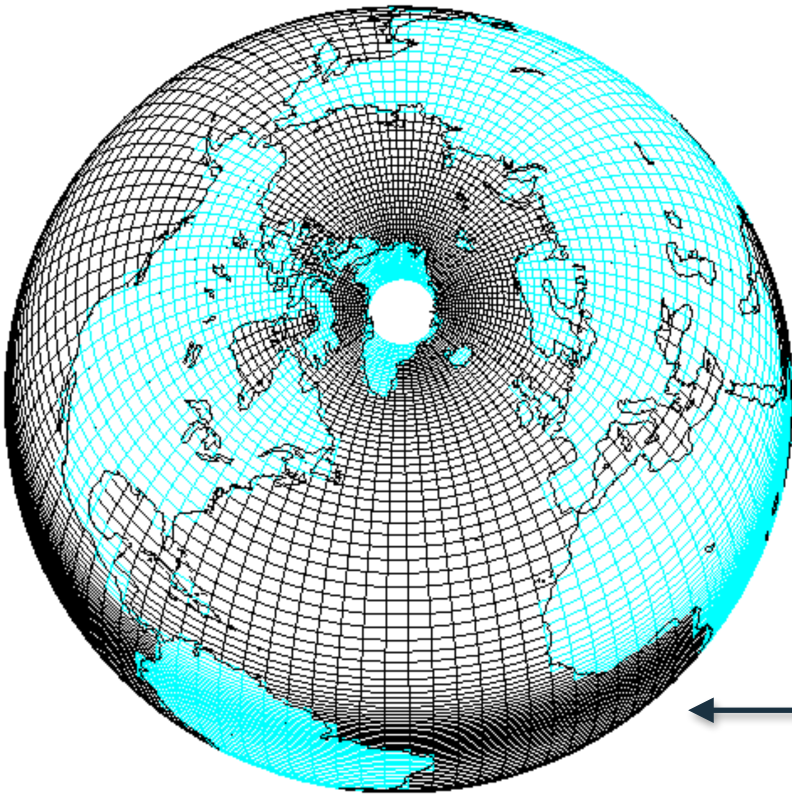
$$\partial_t S + \boldsymbol{\nabla}_z \cdot (\boldsymbol{u}S) + \partial_z (wS) = \boldsymbol{\nabla} \cdot \overline{\overline{A}} \boldsymbol{\nabla} S \tag{5}$$

Equation of state (nonlinear):

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

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°)

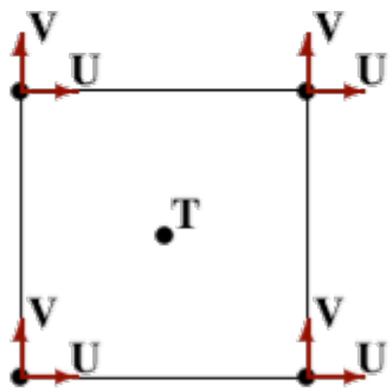
POP2: horizontal grids

Tripole

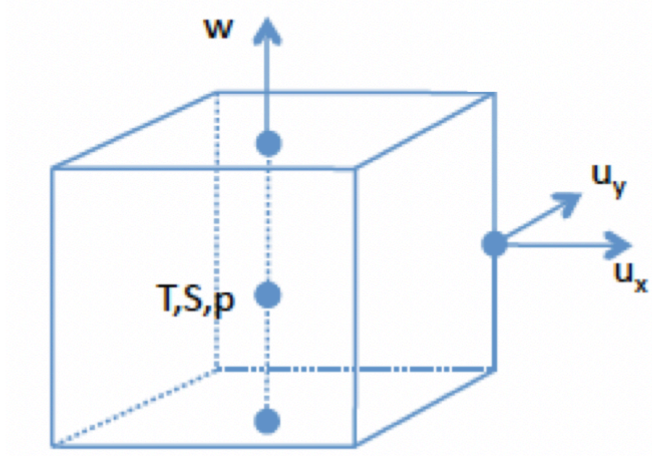
- tx0.1 (nominal 0.1°), eddy resolving almost everywhere;
- See Murray (1996) for details on the various types of grids.

POP2: finite differencing 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;

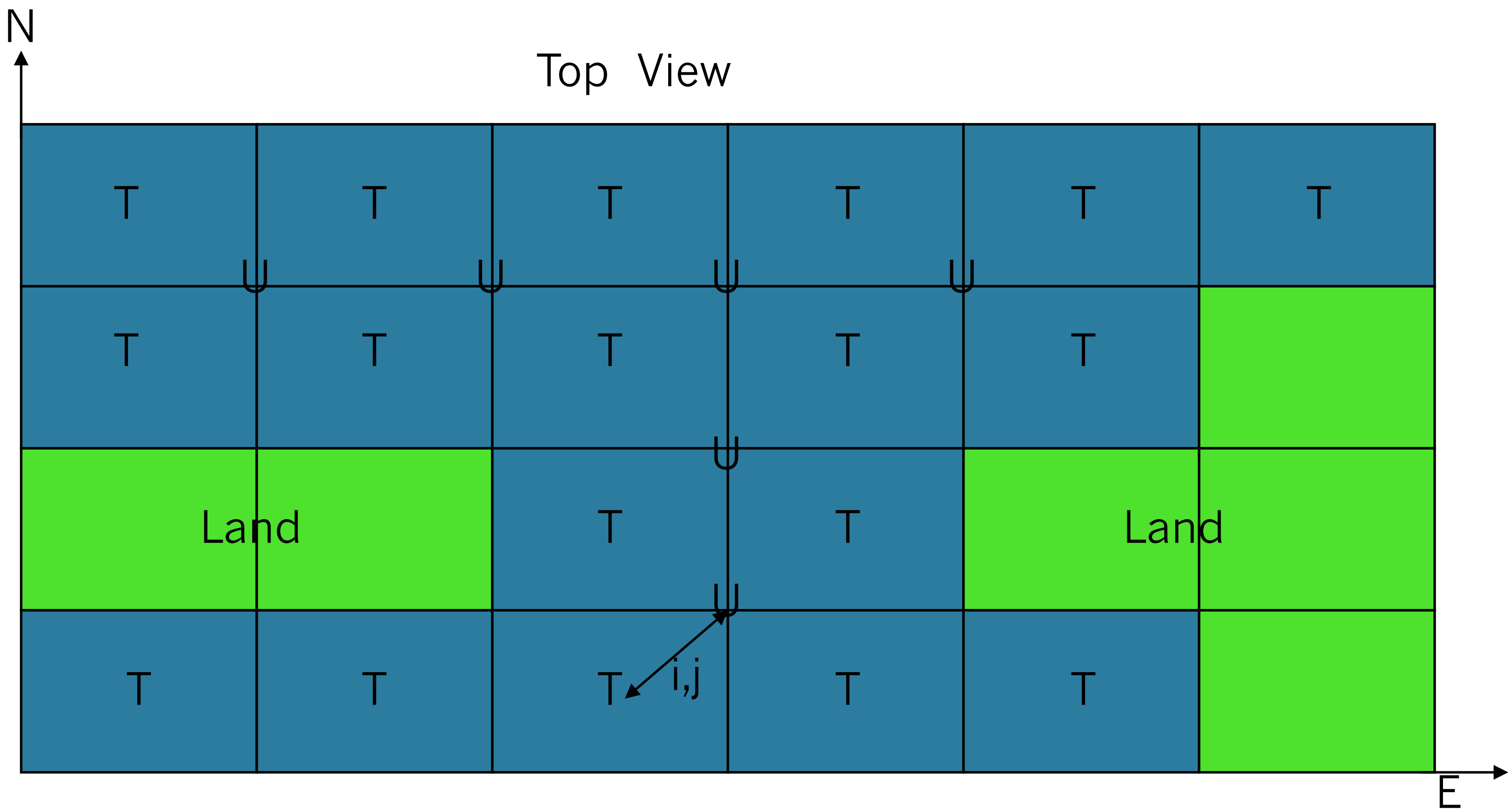
Disadvantages:

- Larger truncation errors in the pressure gradient terms;
- Poorer dispersion of gravity waves.

POP2: horizontal grid staggering

Arakawa B grid

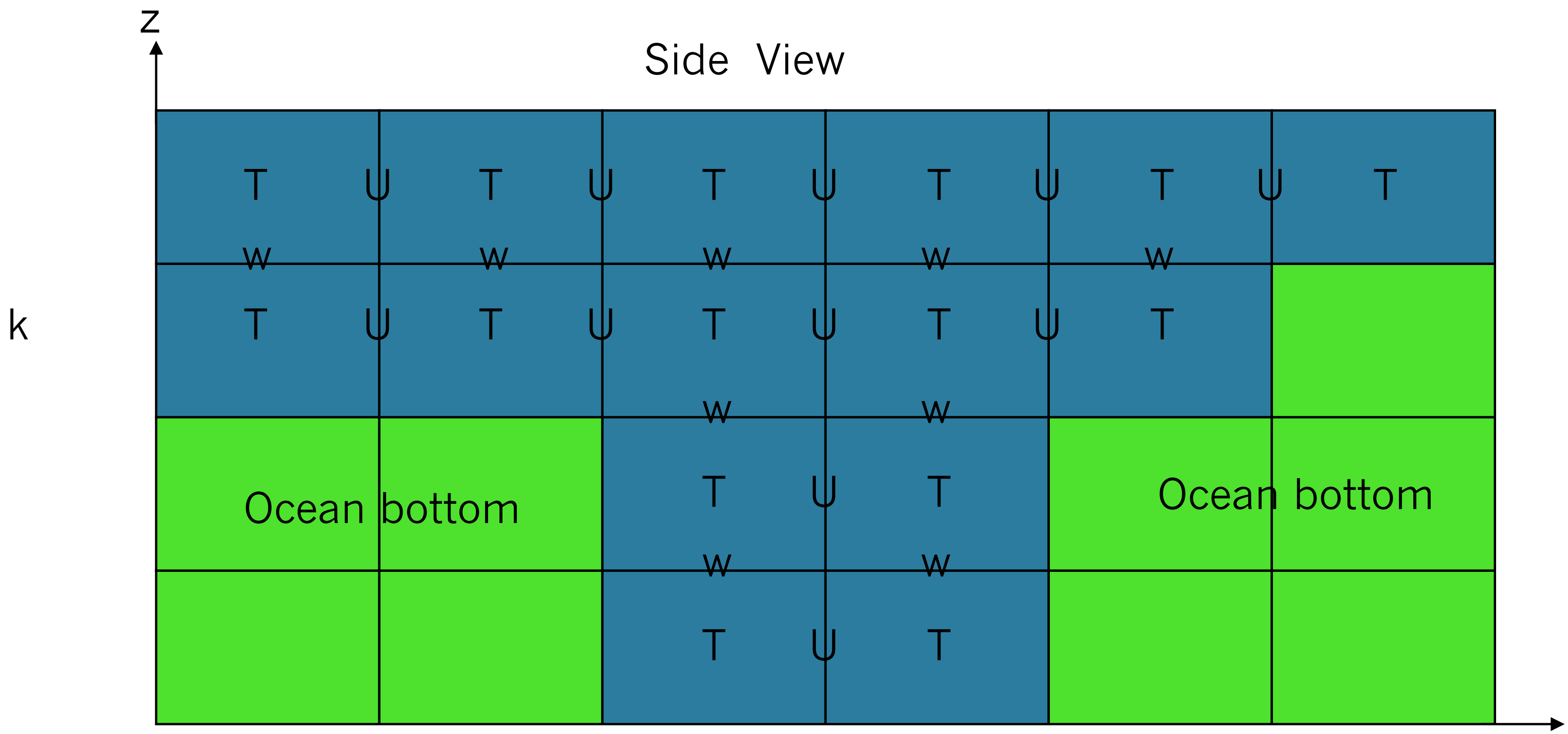
T=tracer grid, U=velocity grid



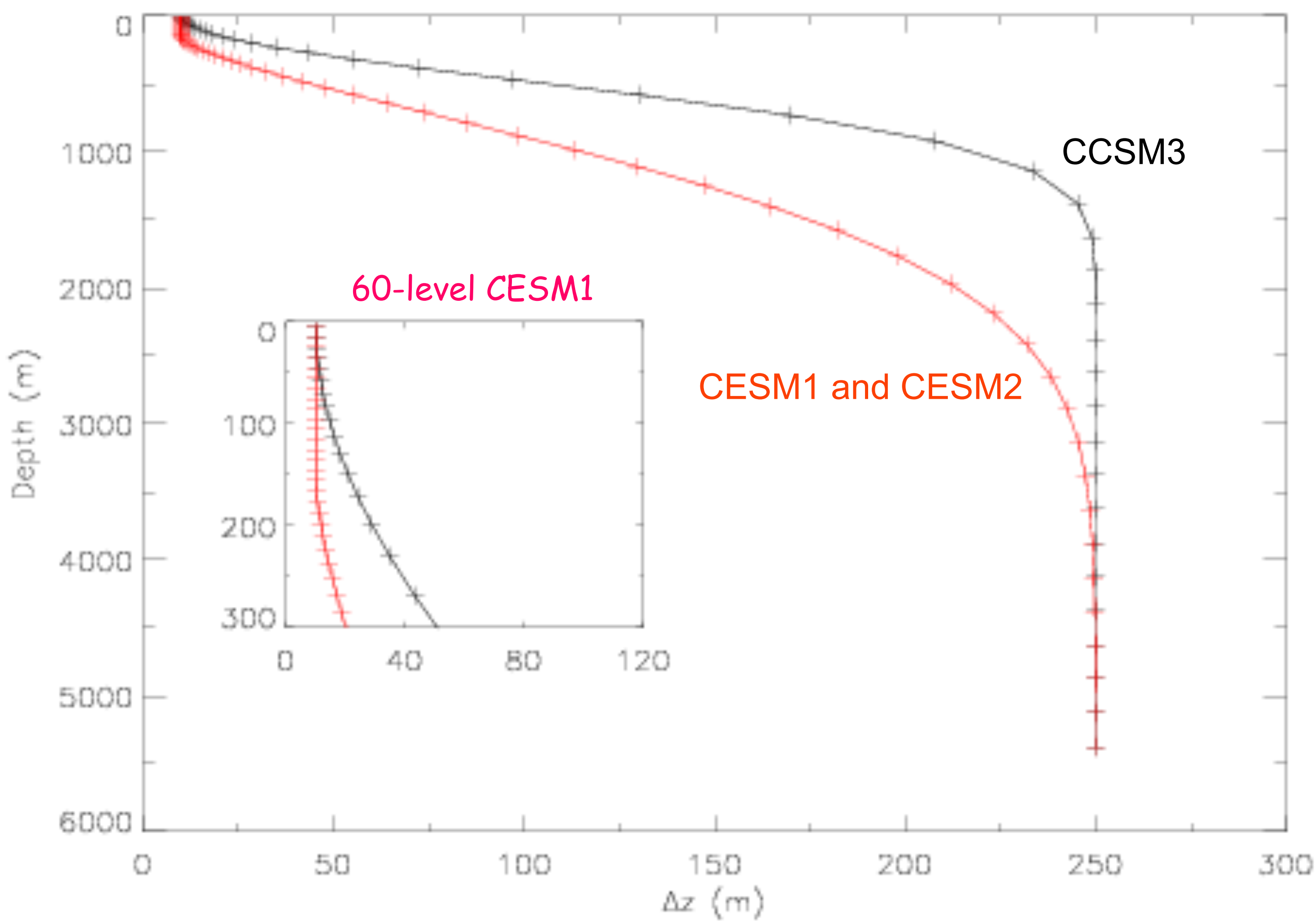
POP2: vertical grid staggering

Arakawa B grid

T=tracer grid, U=velocity grid



POP2: vertical grids



POP2: advection schemes

Because of the complexity due to topography/geometry, ocean models tend to have simpler schemes when compared to atmospheric models.

Current practice:

- Momentum: centered differencing (2nd order), energy conserving;
- Tracers: upwind3 scheme (3rd order), concerned with keeping within physical limits.

POP2: baroclinic & barotropic flow

Issue:

- Courant-Friedrichs-Lewy (CFL) stability condition associated with fast surface gravity waves, $c(\Delta t/\Delta x) \leq 1$;
- Split flow into (fast) depth averaged barotropic (<U>) plus (slow) vertically varying baroclinic (U'), $U = \langle U \rangle + U'$;
- Barotropic waves phase speed $c = \sqrt{gH} \sim 200$ m/s;

POP's Solution:

- Linearized free-surface formulation for barotropic mode, obtained by combining the vertically integrated momentum and continuity equations (changes in surface height = flow divergence);
- Solve the fast barotropic mode implicitly (unconditionally stable);
- Slow baroclinic mode and tracer equations solved with an explicit scheme.

POP2: boundary conditions

Ocean surface:

- Flux exchanges at surface (momentum and tracers);
- No flux of fresh water, get equivalent of salt via virtual salt flux;
- Because we conserve volume, if one place comes up another must come down.

Ocean bottom:

- No tracer fluxes (including geothermal heating);
- 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.

POP2: surface forcing options

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

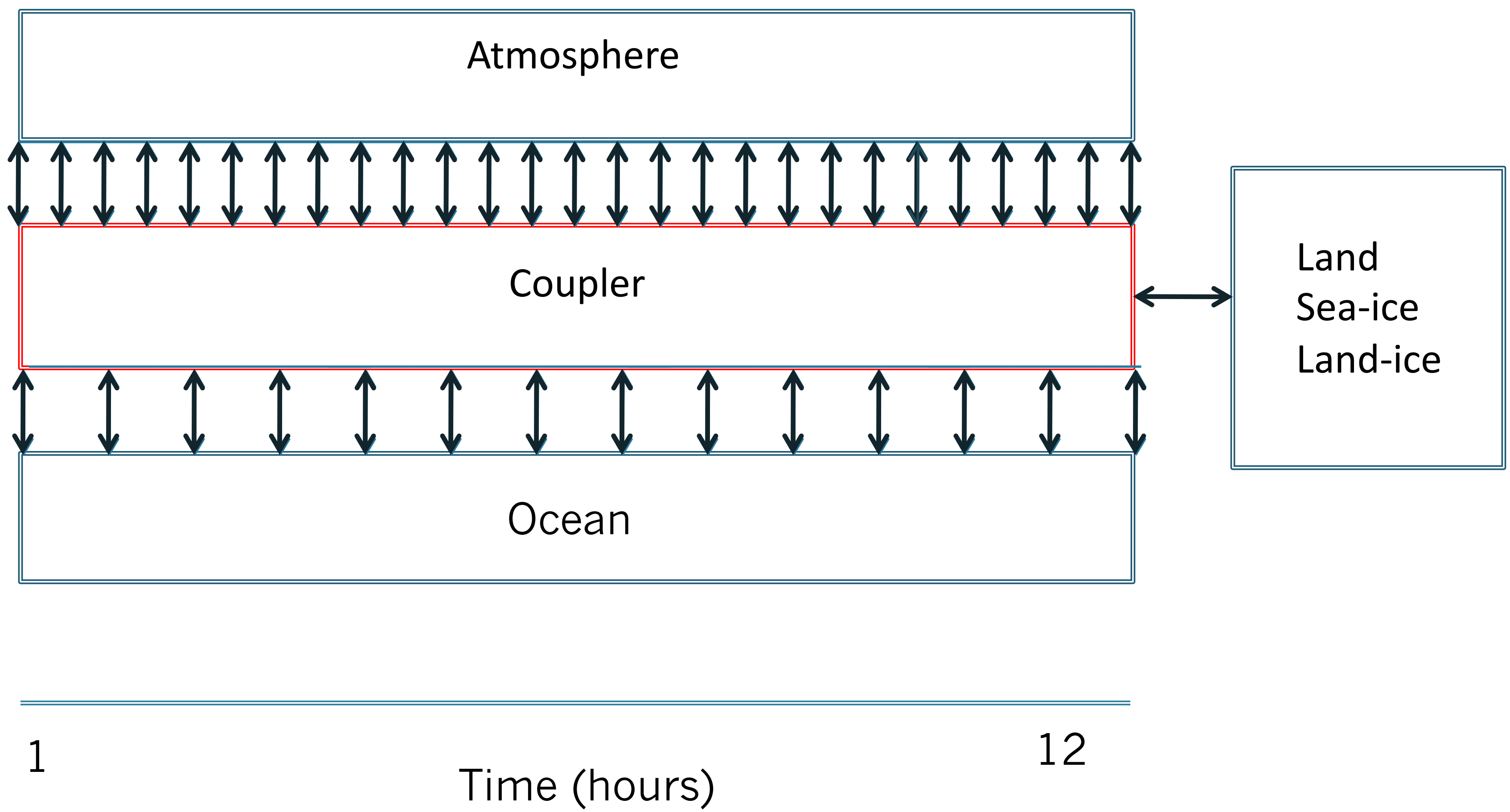
Coordinated Ocean-ice Reference Experiments (CORE)

- 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.

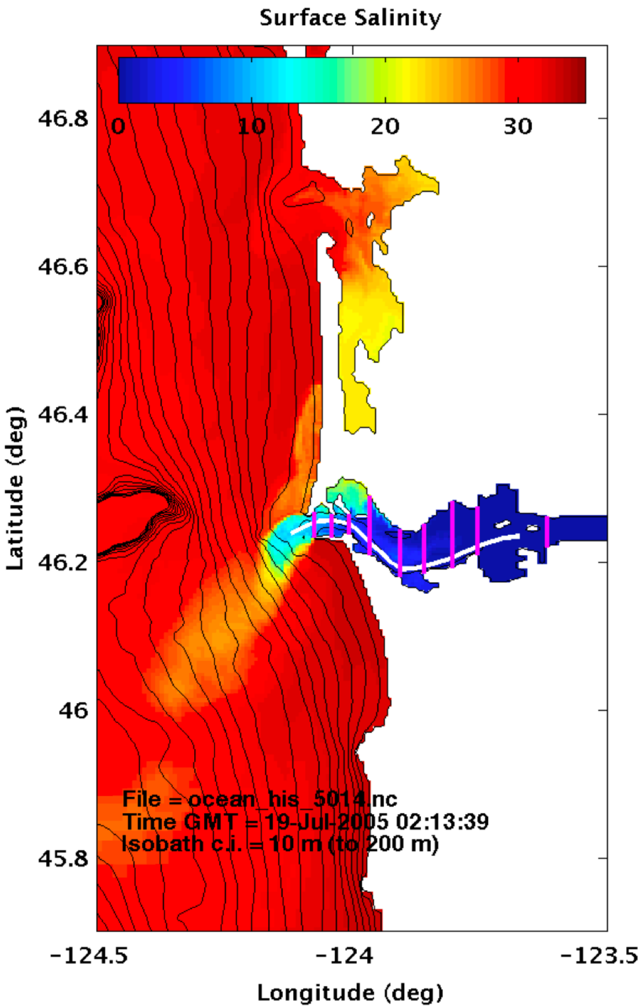
Large and Yeager, NCAR Technical Note (2004)
Large and Yeager, Climate Dynamics (2009)
Danabasoglu et al., Ocean Modelling (2016)

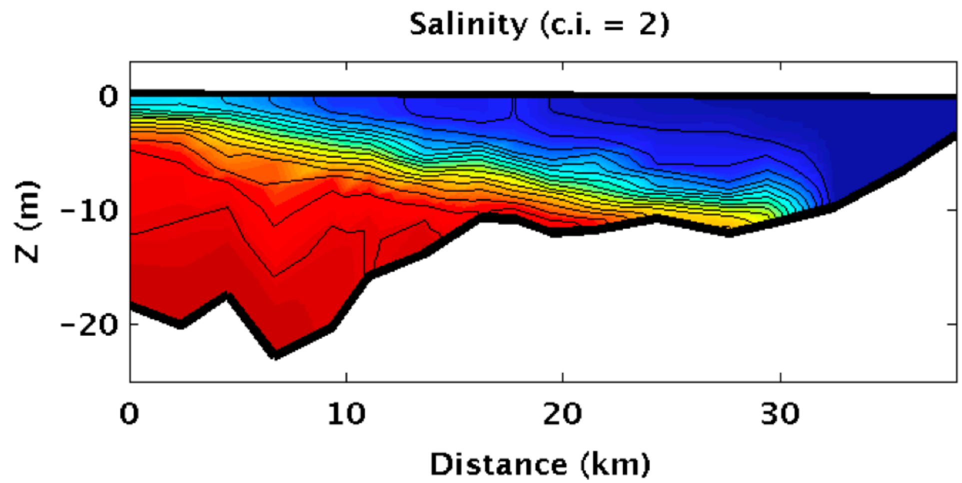
- JRA-55-DO (JRA; 1958 to 2013), https://jra.kishou.go.jp/JRA-55/index_en.html, Tsujino et al., Ocean Modelling (2018)

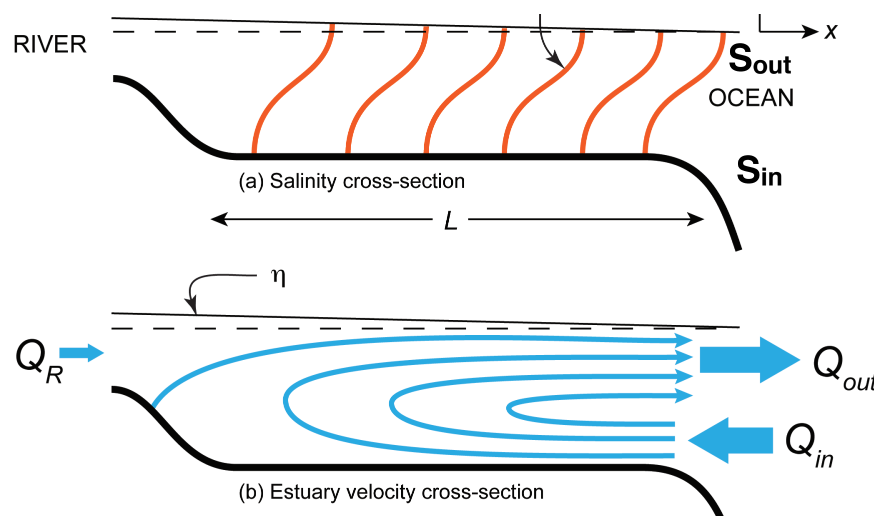
POP2: air-sea coupling



POP2: river runoff, Estuary Box Model (EBM)







See Sun et al, Ocean Modelling, 2017 for additional details on the EBM.

$Q_{out} > Q_R$ $\quad$ $S_{out} > 0$

POP2: CESM2 physics improvements

- **Estuary Box Model (EBM)**: a new parameterization for mixing effects in estuaries to improve the representation of runoff reducing significant salinity and other tracers biases in river mouth regions;

- **Enhanced mesoscale eddy diffusivities at depth** - aimed at improving ocean heat and carbon uptake, trying to reduce mixed layer depth biases, as well as improving the general temperature, salinity, and BGC tracer biases;

- **Langmuir mixing parameterization & NOAA WaveWatch III model**: improve surface mixing;

- **Prognostic chlorophyll** for short-wave absorption (couples physics to biology);

- **Salinity-dependent freezing point** – used to create sea ice when temperature reached -1.8C (coordinated with CICE).

POP2: CESM2 numerical improvements

- **Barotropic solver**: new iterative solver for the barotropic mode to reduce communication costs, particularly advantageous for high-resolution simulations on large processor counts;

- **Robert time filter** - enables sub-daily (1 to 2 hours) coupling of the ocean model much more efficiently than the default time stepping scheme, letting us resolve the diurnal cycle explicitly leading to enhanced near-inertial mixing;

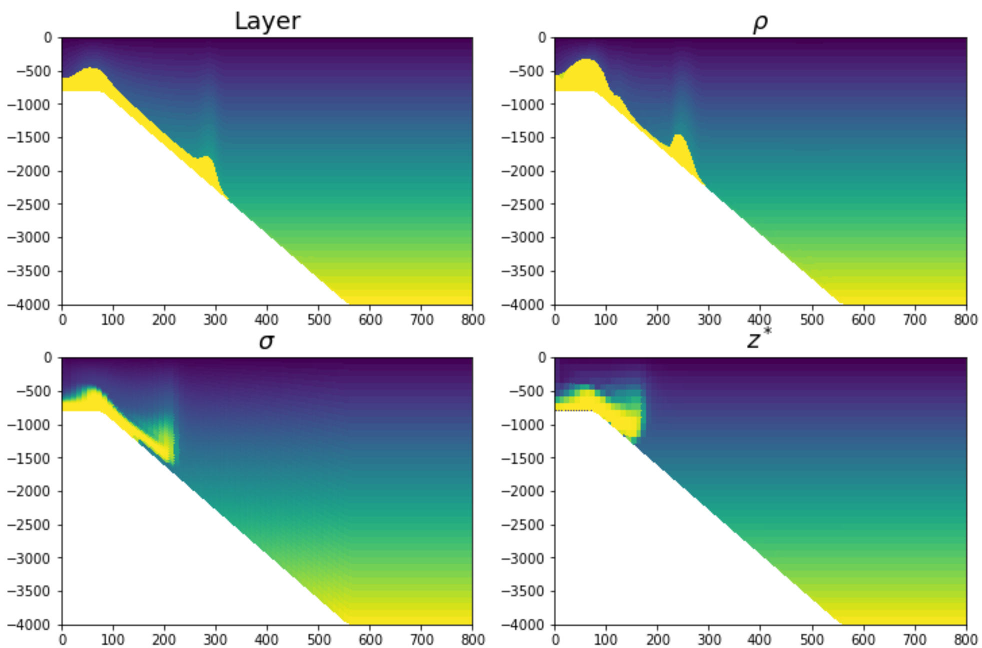
- **CVmix**: the K-Profile vertical mixing Parameterization (KPP) is incorporated via the Community ocean Vertical Mixing (CVMix) framework (all vertical mixing into common module);

- **Caspian Sea**: no longer included in the ocean model as a marginal sea, part of the land model;

- **MARBL**: ocean biogeochemisty has been modularized under the Marine Biogeochemistry Library (MARBL) to enable portability to alternative physical frameworks.

The Modular Ocean Model version 6 (MOM6)

- Recommendations for the Ocean Model Dynamical Core for CESM3
- **Arakawa C-grid** in the horizontal: allows single-point channels;
- MOM6 solves the **hydrostatic Boussinesq (or non-Boussinesq) equations** written in general vertical coordinates;
- Variable layer thickness → continuous representation of topography;
- Arbitrary-Lagrangian-Eulerian (ALE) framework.



No vertical CFL

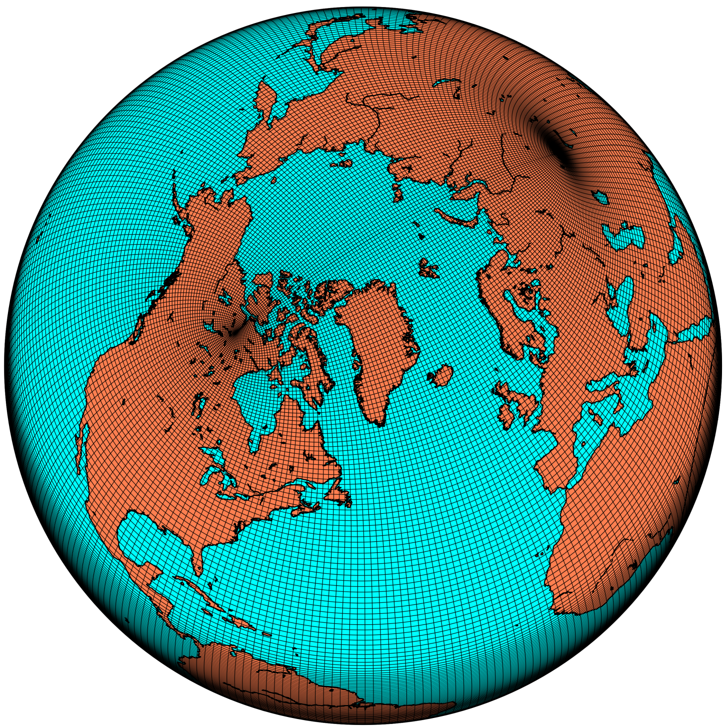
The Modular Ocean Model version 6 (MOM6)

- Resolution-aware parameterizations and transport schemes; eddy mixing CPT starting in 2020 (lot’s of development);
- Range of planetary boundary layer schemes, including KPP (implemented via CVmix);
- Freshwater flux treated as the natural boundary condition;
- Mode splitting with sub-cycling for the barotropic mode;
- Wetting and drying (inundation from sea level rise);
- Open boundary conditions (regional modeling);
- Ice-shelf cavities.

MOM6 is **open development** and, therefore, it goes beyond CESM. Many institutions are currently engaged in developing MOM6 (GFDL, NCAR, EMC, Rutgers, US NAVY).

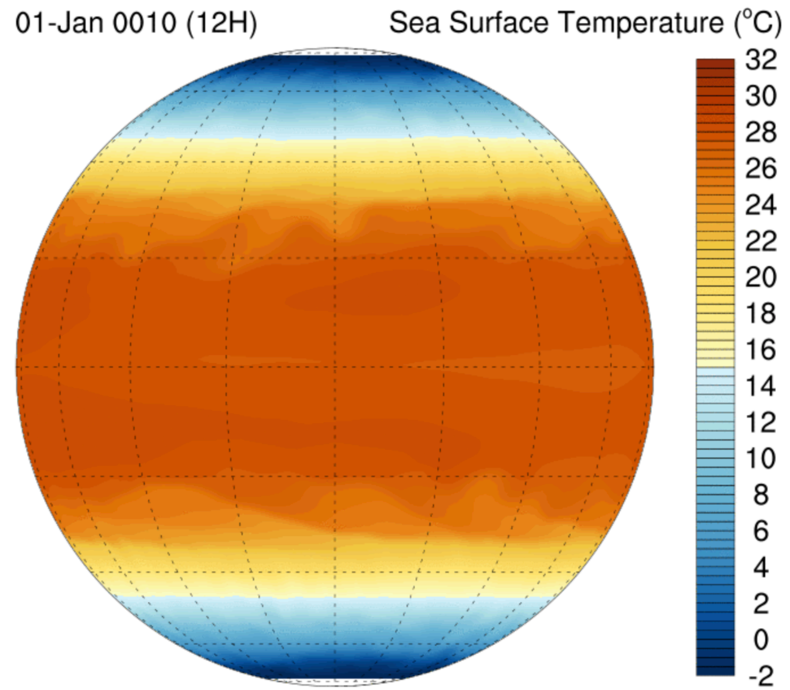
Making CESM/MOM6 available to the community

Tripole grid



tx0.6 (nominal 2/3°)

CESM MOM6 AQUA



"aqua-ish planets"

Led by Universities:

- University of Washington
- Stony Brook
- UTexas

Helpful guides

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

Webpage for CESM/MOM6: https://github.com/NCAR/MOM6/wiki

- CESM/MOM6 Quick Start
- MOM6 Overview
- MOM6 Tutorial

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

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