Ocean Modeling I

Ocean Modeling Basics and CESM Ocean Model

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Topics

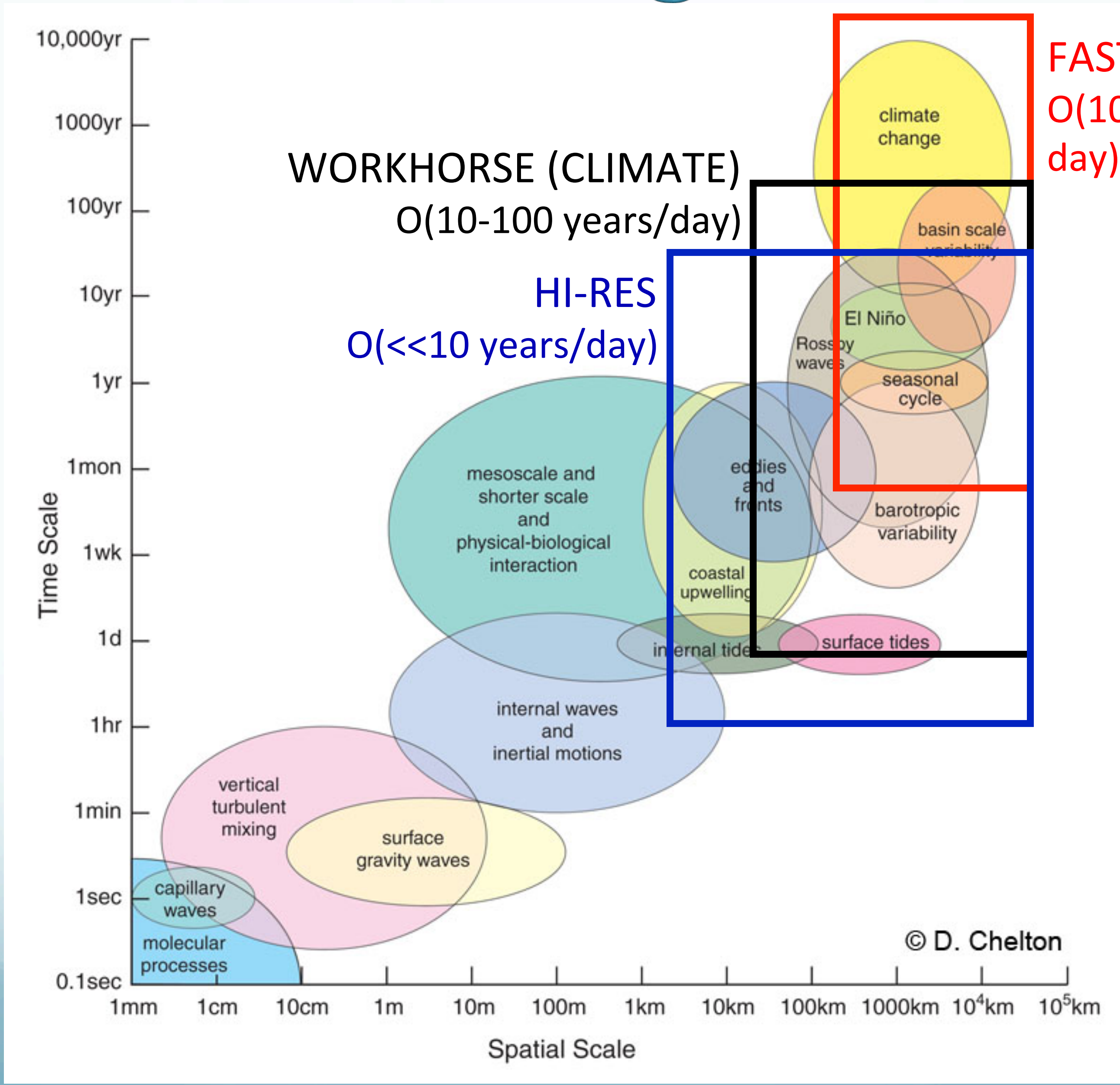
- Challenges for ocean modeling
- Ocean properties
- CESM ocean model
- Governing equations
- Ocean model grid
- Advection schemes
- Barotropic / baroclinic split
- Boundary conditions

- Parameterizations => Peter Gent's talk; but will cover the overflow parameterization

Ocean Modeling Challenges

Irregular Domain

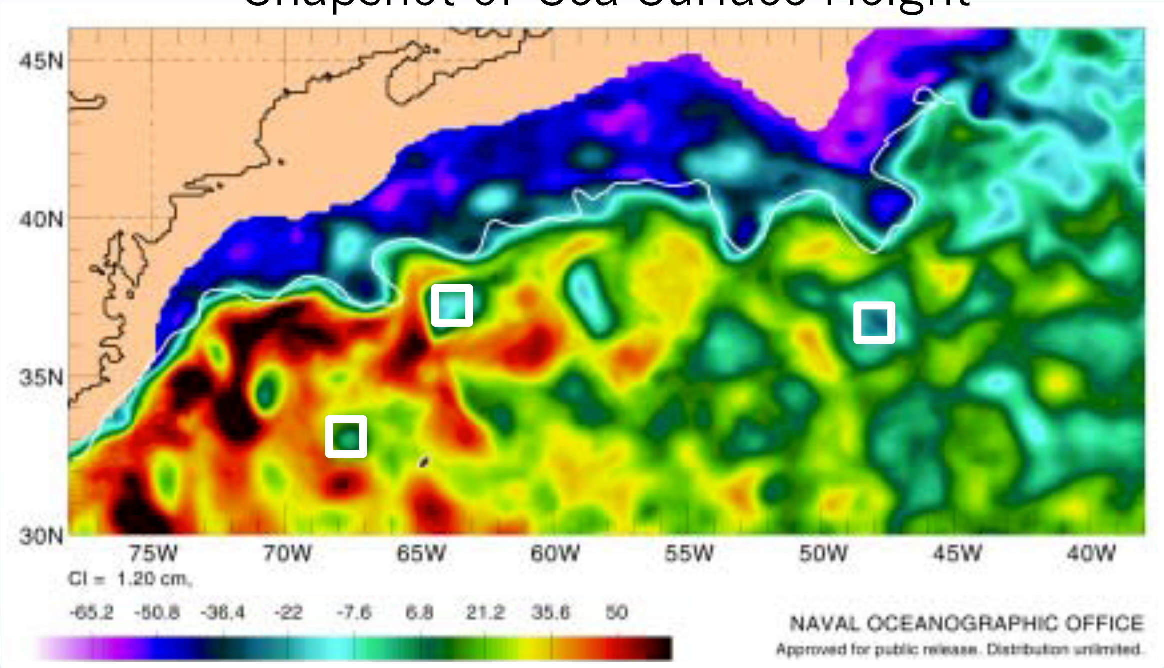
Ocean Modeling Challenges



Ocean Modeling Challenges

Spatial Scales of Flow

Snapshot of Sea Surface Height



Ocean Modeling Challenges

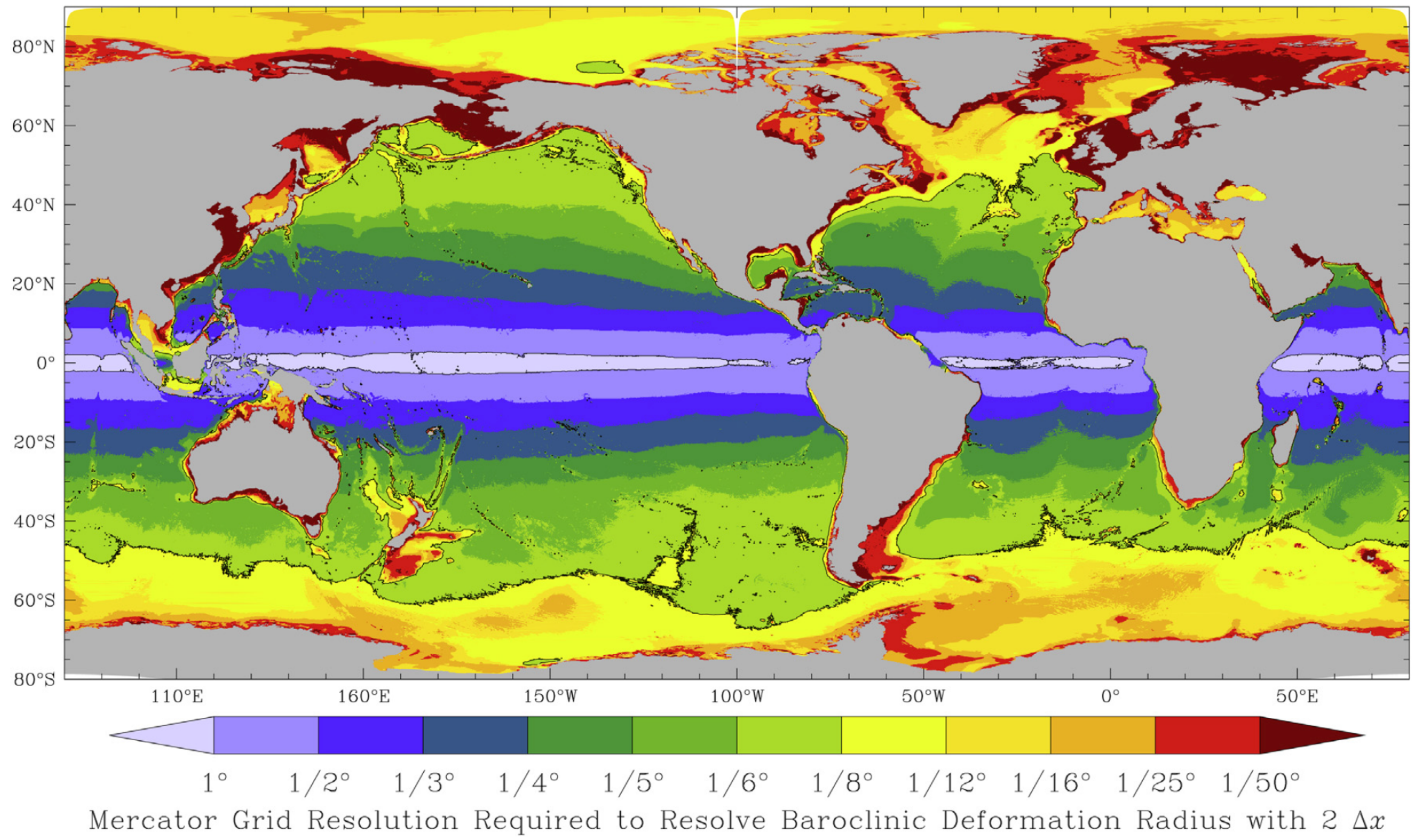


Fig. 1. The horizontal resolution needed to resolve the first baroclinic deformation radius with two grid points, based on a 1/8° model on a Mercator grid (Adcroft et al., 2010) on Jan. 1 after one year of spinup from climatology. (In the deep ocean the seasonal cycle of the deformation radius is weak, but it can be strong on continental shelves.) This model uses a bipolar Arctic cap north of 65°N. The solid line shows the contour where the deformation radius is resolved with two grid points at 1° and 1/8° resolutions.

Ocean Modeling Challenges

Equilibration Timescale

Scaling argument for deep adjustment time:

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

Bottom Line for Climate

- 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

Some Ocean Properties

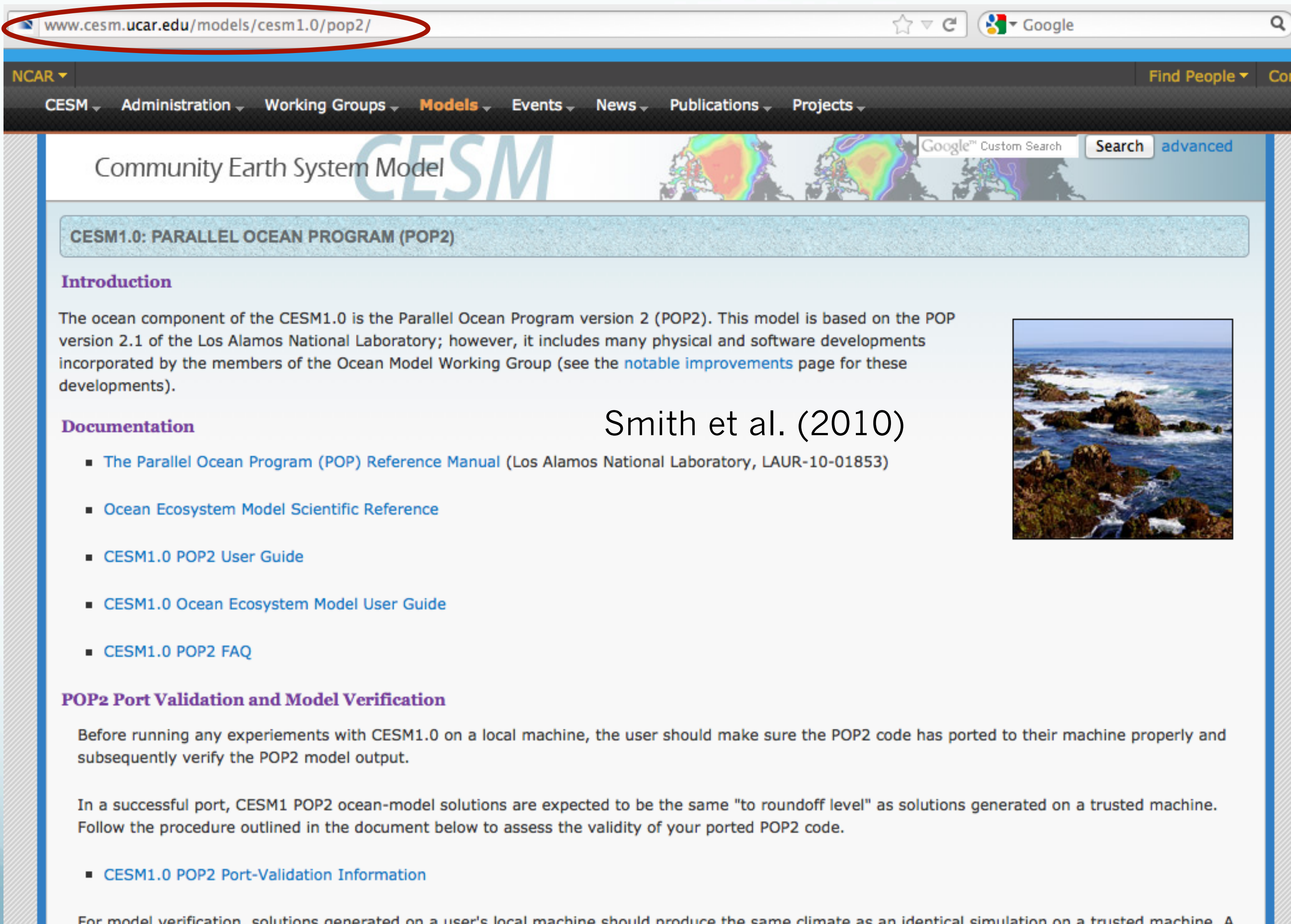
- No change of state of seawater – form ice when temperature <-1.8^{o}C
- The density change from top to bottom is much smaller than the atmosphere – 1.02 to 1.04 gr/cm^3. This makes the Rossby radius much smaller – 100s to 10s km.
- There is extremely small mixing across density surfaces once water masses are buried below the mixed layer base. This is why water masses can be named and followed around the ocean.
- The ocean is a 2 part density fluid (temperature and salinity).

Some 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... Important implications for decadal prediction studies.

CESM Ocean Model
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.



www.cesm.ucar.edu/models/cesm1.0/pop2/

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Community Earth System Model

CESM1.0: PARALLEL OCEAN PROGRAM (POP2)

Introduction

The ocean component of the CESM1.0 is the Parallel Ocean Program version 2 (POP2). This model is based on the POP version 2.1 of the Los Alamos National Laboratory; however, it includes many physical and software developments incorporated by the members of the Ocean Model Working Group (see the notable improvements page for these developments).

Documentation

- The Parallel Ocean Program (POP) Reference Manual (Los Alamos National Laboratory, LAUR-10-01853)
- Ocean Ecosystem Model Scientific Reference
- CESM1.0 POP2 User Guide
- CESM1.0 Ocean Ecosystem Model User Guide
- CESM1.0 POP2 FAQ

POP2 Port Validation and Model Verification

Before running any experiements with CESM1.0 on a local machine, the user should make sure the POP2 code has ported to their machine properly and subsequently verify the POP2 model output.

In a successful port, CESM1 POP2 ocean-model solutions are expected to be the same "to roundoff level" as solutions generated on a trusted machine. Follow the procedure outlined in the document below to assess the validity of your ported POP2 code.

- CESM1.0 POP2 Port-Validation Information

For model verification, solutions generated on a user's local machine should produce the same climate as an identical simulation on a trusted machine. A

Smith et al. (2010)

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Community Climate System Model CCSM4
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The CCSM4 Ocean Component

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Model Equations

7 equations in 7 unknowns:

3 velocity components
potential temperature
salinity
density
pressure

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

Model Equations

Momentum equations:

$$\frac{\partial}{\partial t}u + \mathcal{L}(u) - (uv\tan\phi)/a - fv = -\frac{1}{\rho_0 a\cos\phi}\frac{\partial p}{\partial\lambda} + \mathcal{F}_{Hx}(u,v) + \mathcal{F}_V(u) \quad (2.1)$$

$$\frac{\partial}{\partial t}v + \mathcal{L}(v) + (u^2\tan\phi)/a + fu = -\frac{1}{\rho_0 a}\frac{\partial p}{\partial\phi} + \mathcal{F}_{Hy}(u,v) + \mathcal{F}_V(v) \quad (2.2)$$

$$\mathcal{L}(\alpha) = \frac{1}{a\cos\phi}\left[\frac{\partial}{\partial\lambda}(u\alpha) + \frac{\partial}{\partial\phi}(\cos\phi v\alpha)\right] + \frac{\partial}{\partial z}(w\alpha) \quad (2.3)$$

$$\mathcal{F}_{Hx}(u,v) = A_M\left\{\nabla^2 u + u(1-\tan^2\phi)/a^2 - \frac{2\sin\phi}{a^2\cos^2\phi}\frac{\partial v}{\partial\lambda}\right\} \quad (2.4)$$

$$\mathcal{F}_{Hy}(u,v) = A_M\left\{\nabla^2 v + v(1-\tan^2\phi)/a^2 + \frac{2\sin\phi}{a^2\cos^2\phi}\frac{\partial u}{\partial\lambda}\right\} \quad (2.5)$$

$$\nabla^2\alpha = \frac{1}{a^2\cos^2\phi}\frac{\partial^2\alpha}{\partial\lambda^2} + \frac{1}{a^2\cos\phi}\frac{\partial}{\partial\phi}\left(\cos\phi\frac{\partial\alpha}{\partial\phi}\right) \quad (2.6)$$

$$\mathcal{F}_V(\alpha) = \frac{\partial}{\partial z}\mu\frac{\partial}{\partial z}\alpha \quad (2.7)$$

Model Equations

Continuity equation:

$$\mathcal{L}(1) = 0 \tag{2.8}$$

Hydrostatic equation:

$$\frac{\partial p}{\partial z} = -\rho g \tag{2.9}$$

Equation of state:

$$\rho = \rho(\Theta, S, p) \rightarrow \rho(\Theta, S, z) \tag{2.10}$$

Tracer transport:

$$\frac{\partial}{\partial t}\varphi + \mathcal{L}(\varphi) = \mathcal{D}_H(\varphi) + \mathcal{D}_V(\varphi) \tag{2.11}$$

$$\mathcal{D}_H(\varphi) = A_H \nabla^2 \varphi \tag{2.12}$$

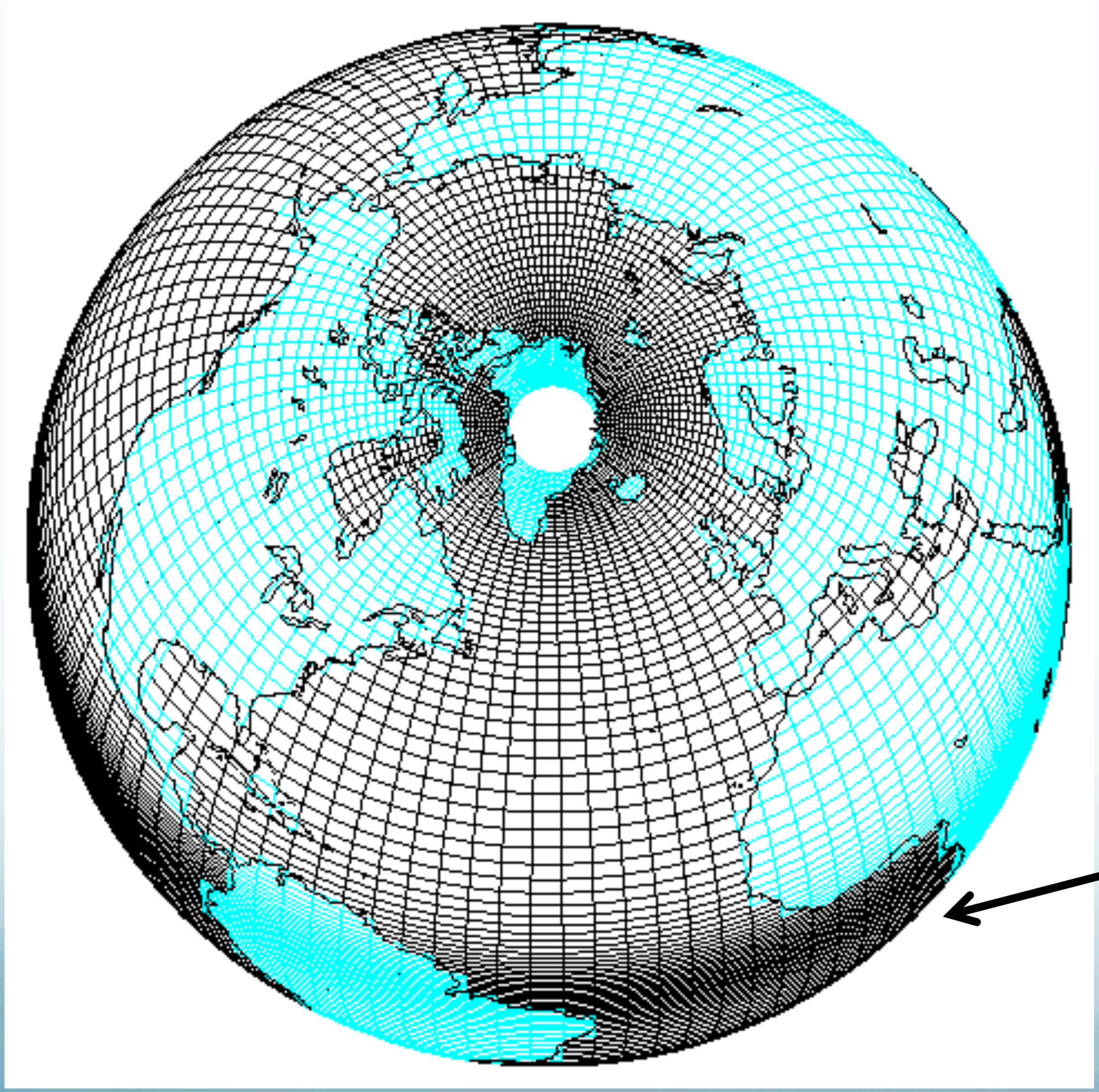
$$\mathcal{D}_V(\varphi) = \frac{\partial}{\partial z}\kappa\frac{\partial}{\partial z}\varphi, \tag{2.13}$$

Model Equations

- Continuity: can't deform seawater, so what flows into a control volume must flow out.
- Hydrostatic: when ocean becomes statically unstable ($\rho_z > 0$) => 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.

Model Grid

displaced pole



gx1: climate workhorse
nominal 1°
gx3: testing
nominal 3°

Ex. T62_gx3v7

Equatorial refinement
(0.3° / 0.9°)

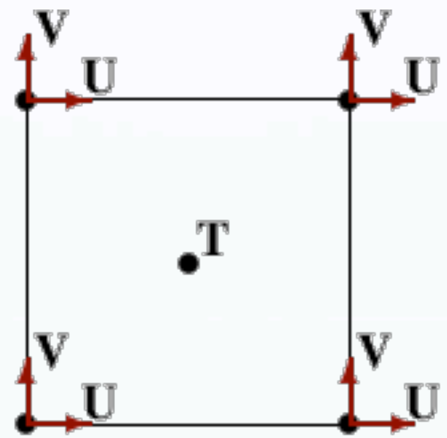
Model Grid

tripole

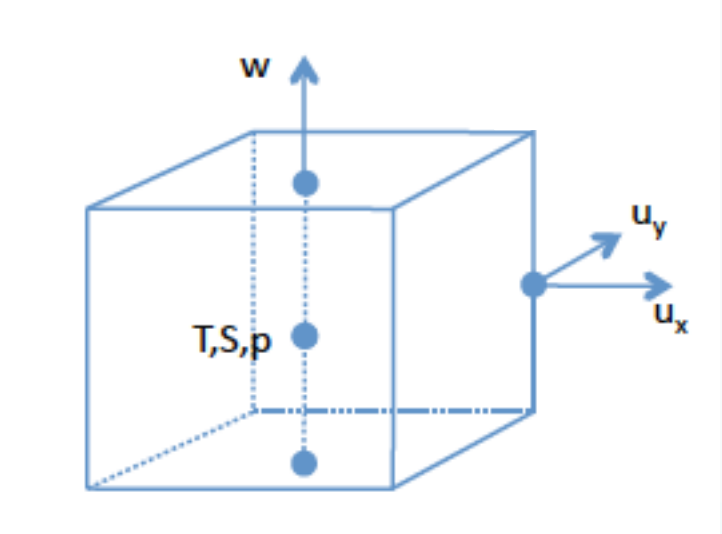
tx0.1

Finite Differencing Grid

B-grid



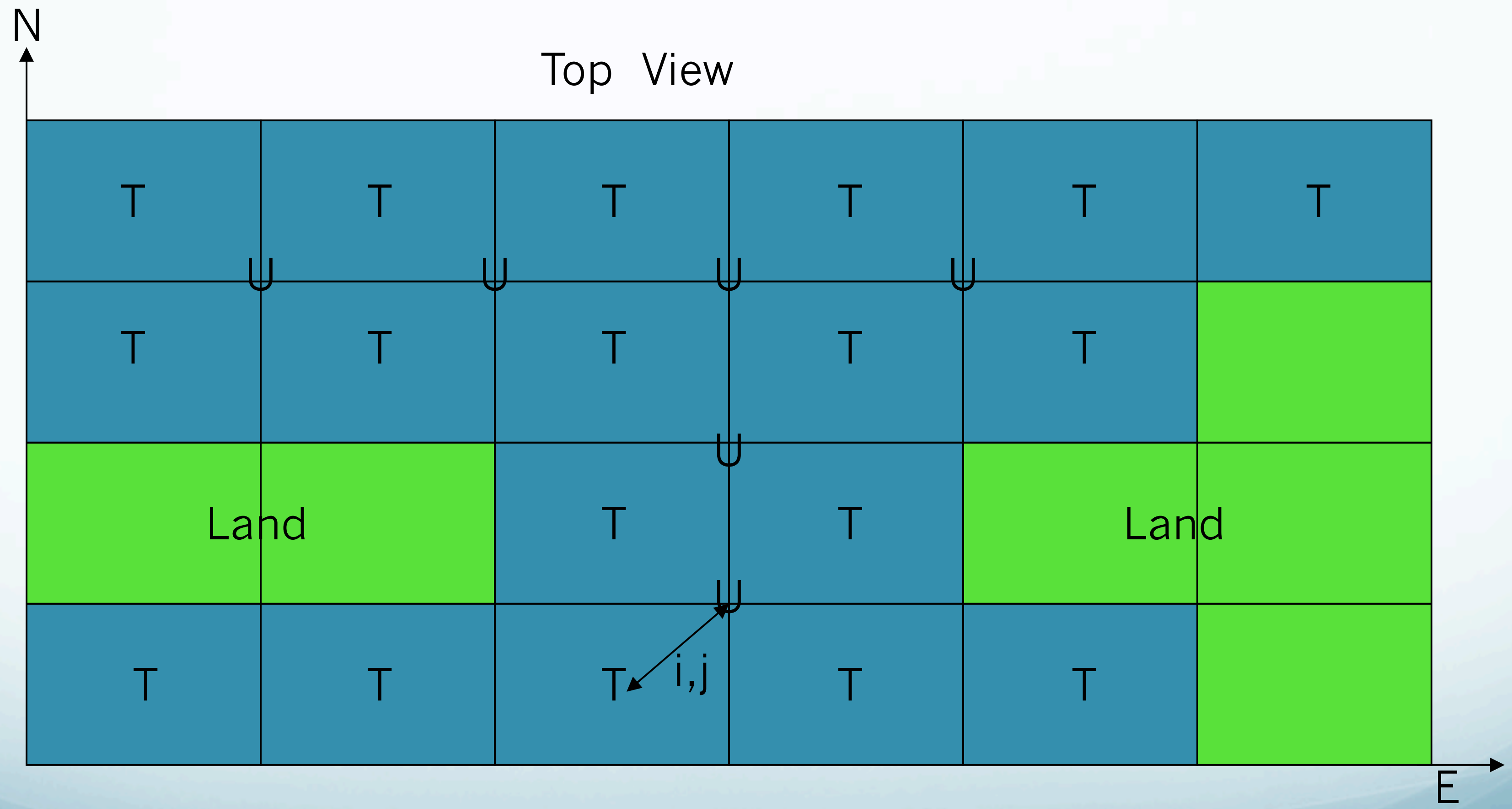
Top view



Model Grid

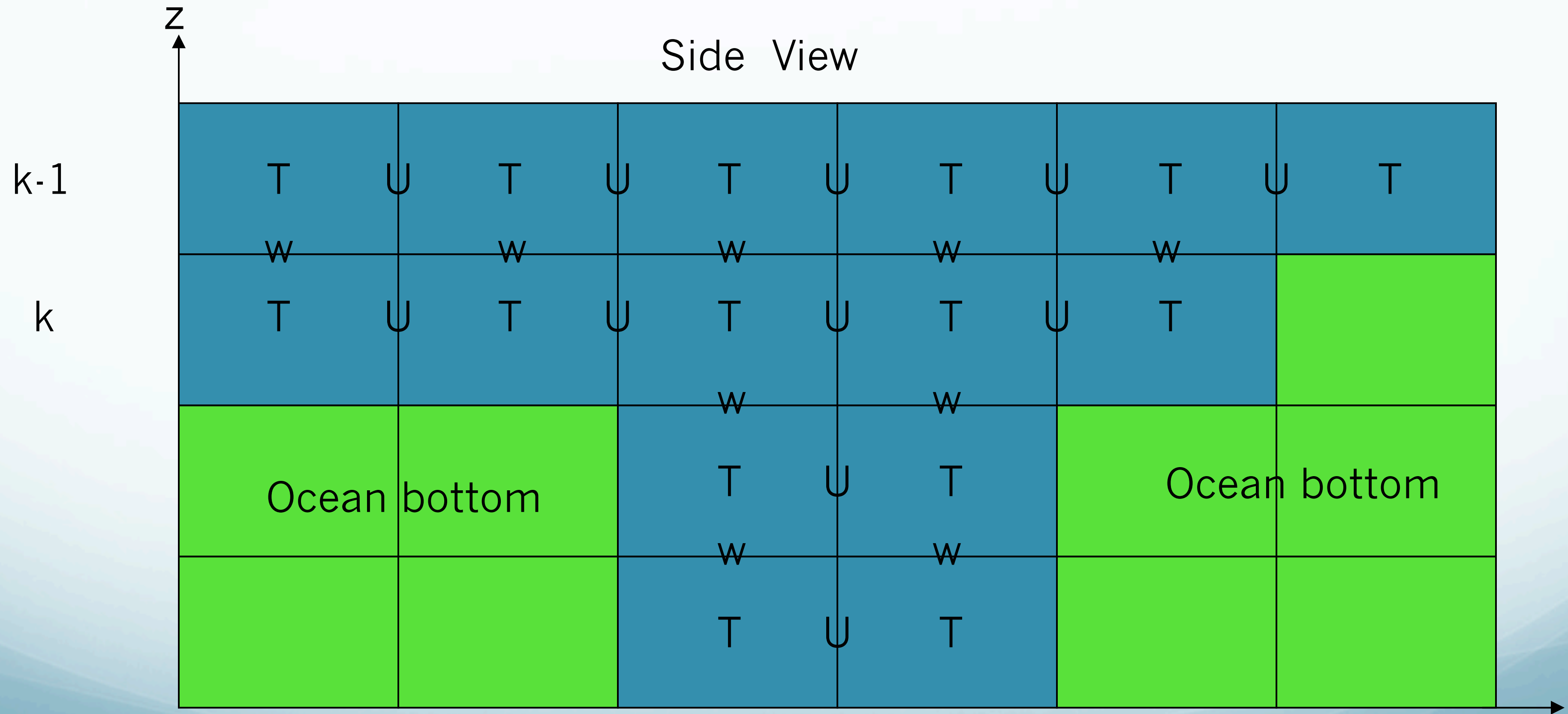
B-grid

T=tracer grid, U=velocity grid

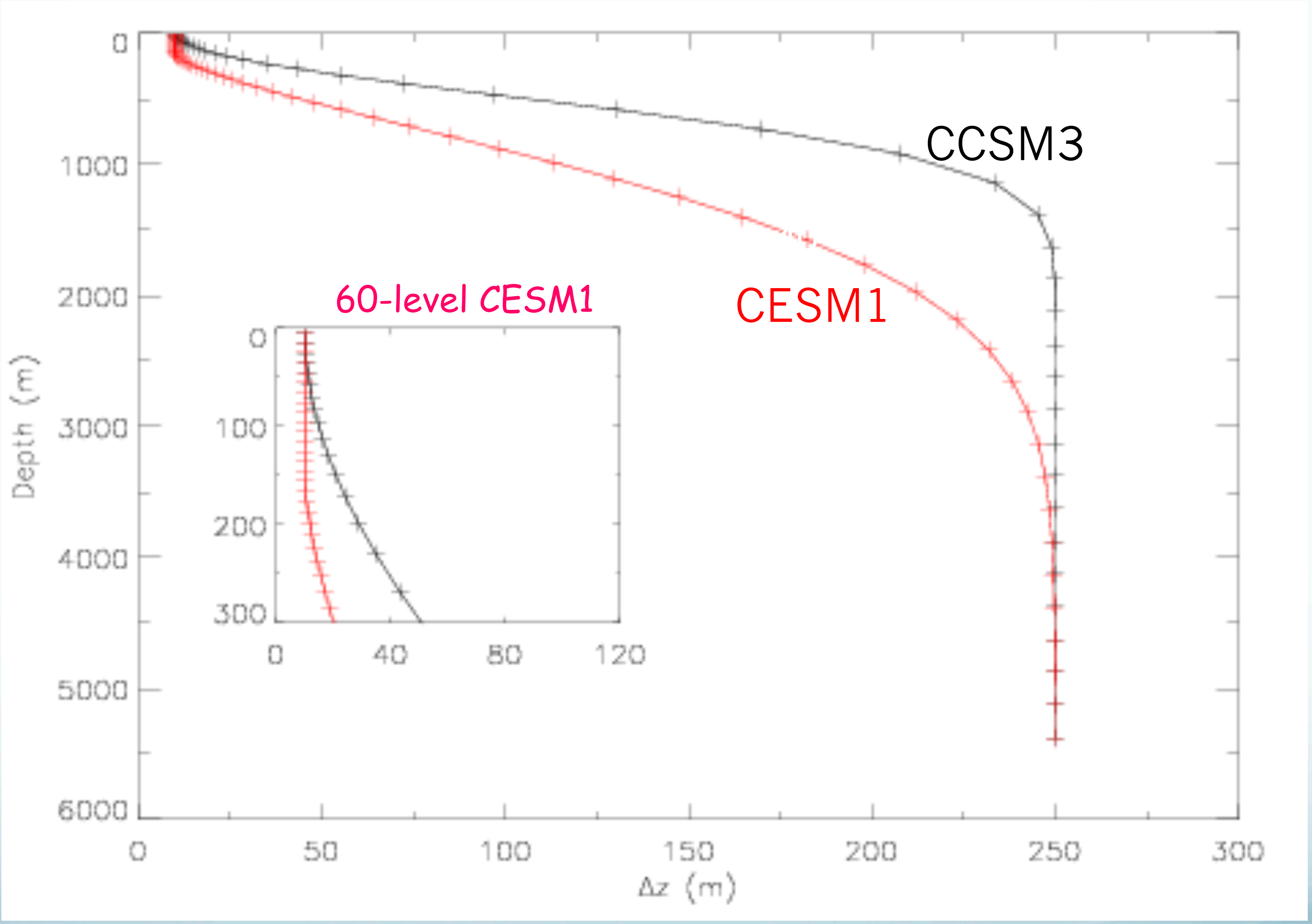


Model Grid

B-grid
T=tracer grid, U=velocity grid



Model Vertical Grid



Advection

Current practice:

- Momentum: centered differencing (2^{nd} order)
- Tracers: upwind3 scheme (3^{rd} order)
  - Concerned with keeping within physical limits

Baroclinic & Barotropic Flow

- Issue: Courant-Friedrichs-Lewy (CFL) stability condition associated with fast surface gravity waves.
  - $u(\Delta t/\Delta x) \leq 1$
  - Barotropic mode $\sqrt{gH}$ ~200 m/s
- Split flow into depth averaged barotropic (<U>) plus vertically varying baroclinic (U')
- Fast moving gravity waves are filtered out, but that's okay because they don't impact climate

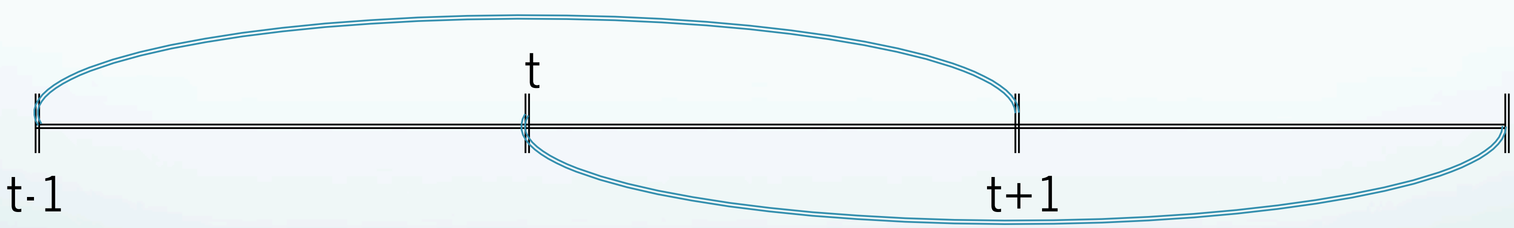
Barotropic and Baroclinic Flow

$$U = \langle U \rangle + U'$$

- <U>: Implicit, linearized free-surface formulation obtained by combining the vertically integrated momentum and continuity equations

- U’: use a leapfrog time stepping to solve

$$\frac{X^{t+1} - X^{t-1}}{2\Delta t} = D^{t-1} + ADV^{t} + SRC^{t,t-1}$$



- Occasional time averaging to eliminate the split mode

Boundary Conditions

- Free surface
  - Flux exchanges at surface: momentum and tracers
  - because we conserve volume, if one place comes up another must come down
- Ocean bottom
  - No tracer fluxes (but possibility of geothermal heating)
  - Normal velocity is zero
- Lateral boundaries
  - No tracer fluxes
  - Flow normal to solid boundary is zero
  - No slip

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)

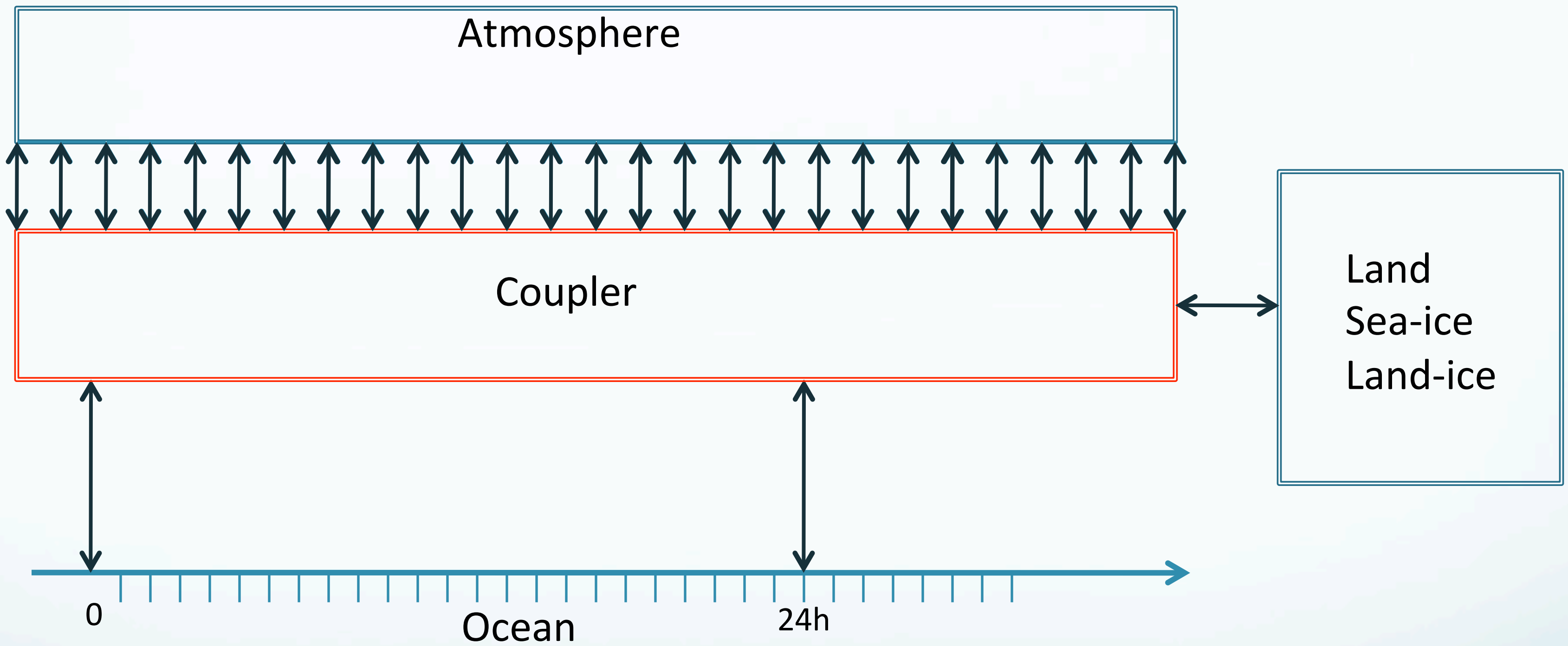
- Inter-annual forcing (IAF; 1948-2009)
  http://data1.gfdl.noaa.gov/nomads/forms/mom4/CORE.html
- Normal Year Forcing (NYF): good for model testing and parameterization impact studies

Large and Yeager, NCAR Technical Note (2004)

Large and Yeager, *Climate Dynamics* (2009)

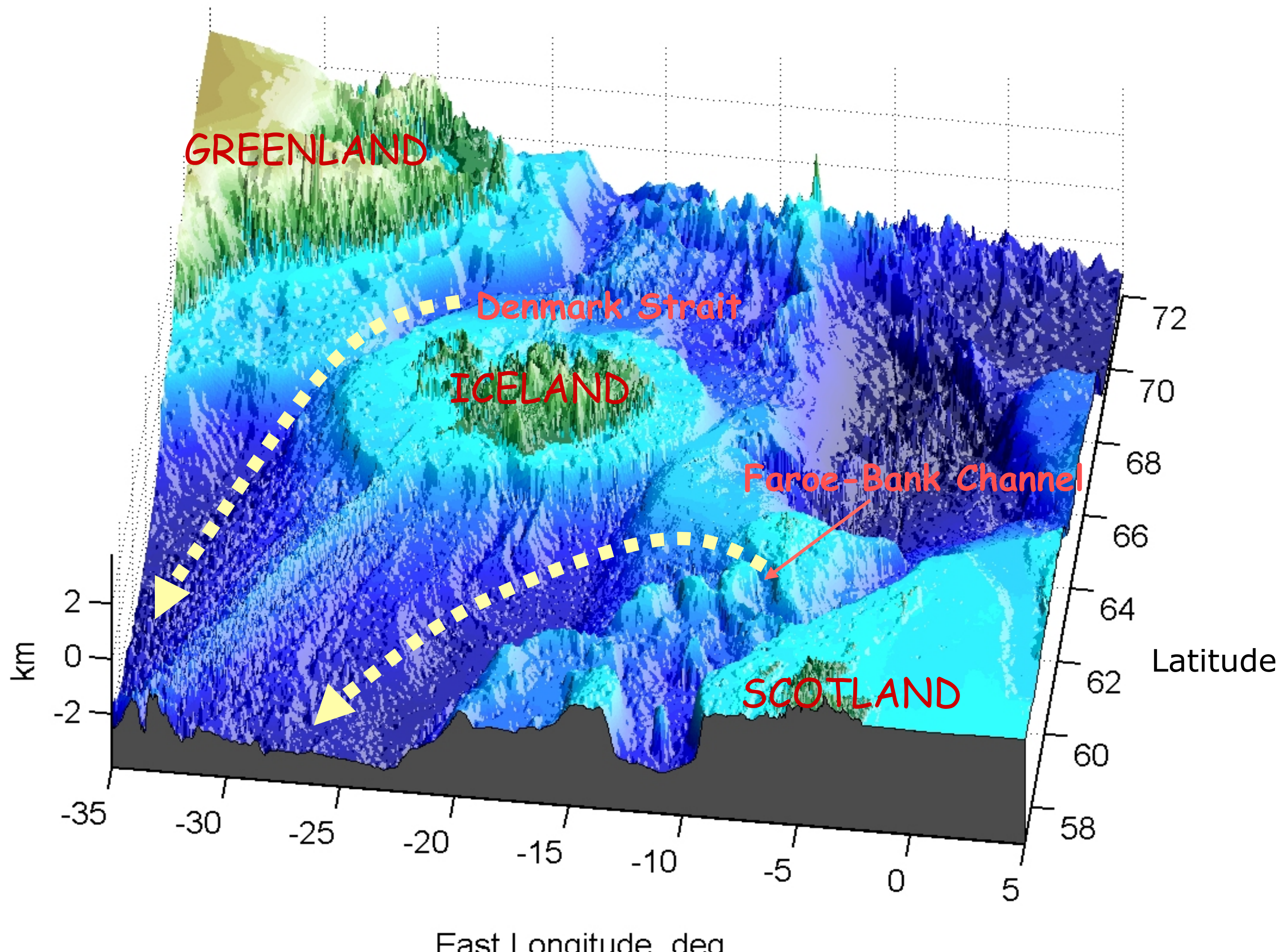
Danabasoglu et al., *Ocean Modelling* (2016)

Air-Sea Coupling



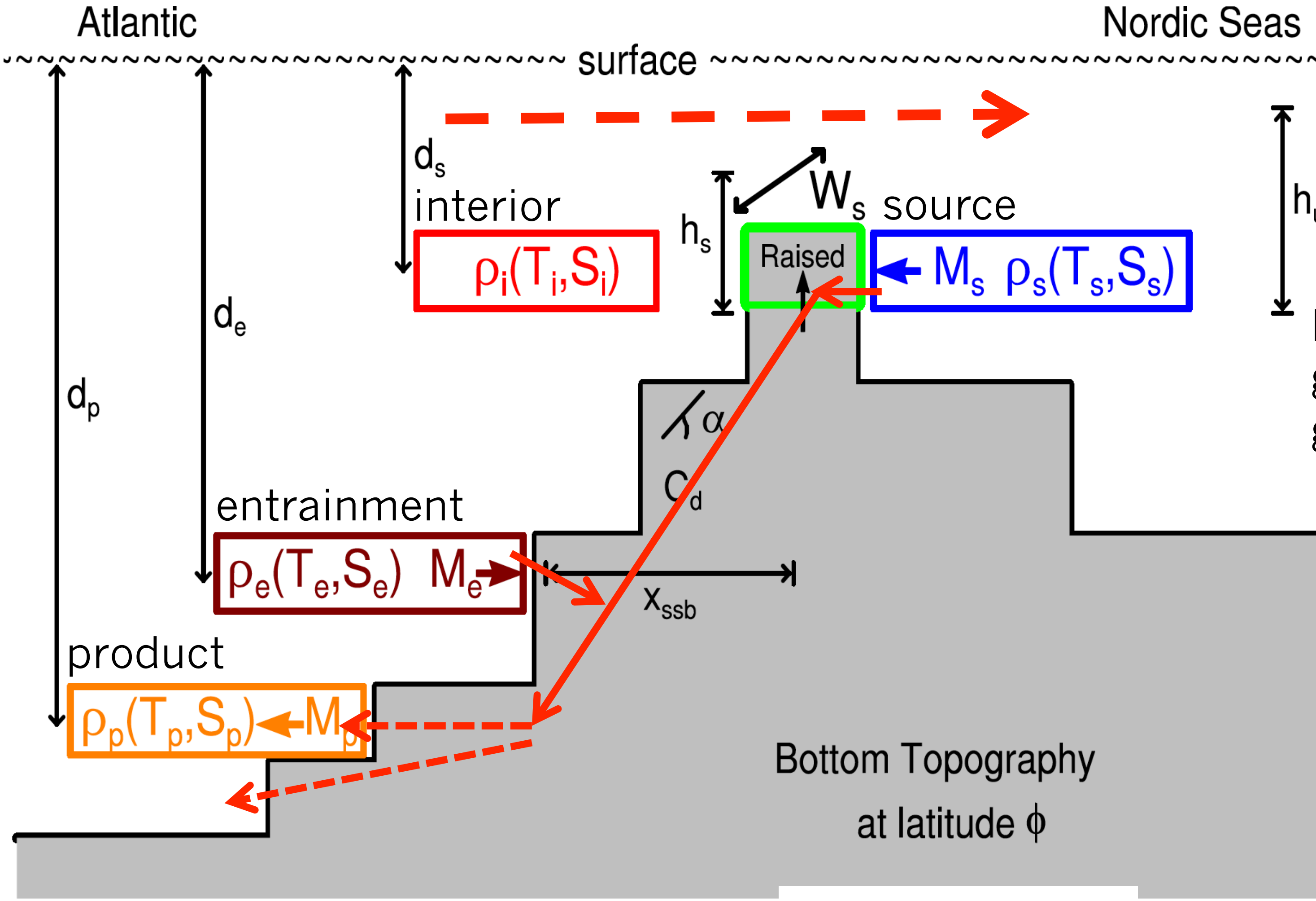
SW distributed across daylight hours (lat, long, day of year)

GRAVITY CURRENT OVERFLOWS



from J.Price

OVERFLOW PARAMERERIZATION SCHEMATIC



Reduced Gravities:

$g_s' = (g/\rho_o)\,(\rho_s - \rho_i)$

$g_e' = (g/\rho_o)\,(\rho_s - \rho_e)$

$$M_s = \frac{g_s' h_u^2}{2f}$$

$$M_p = M_s + M_e,$$

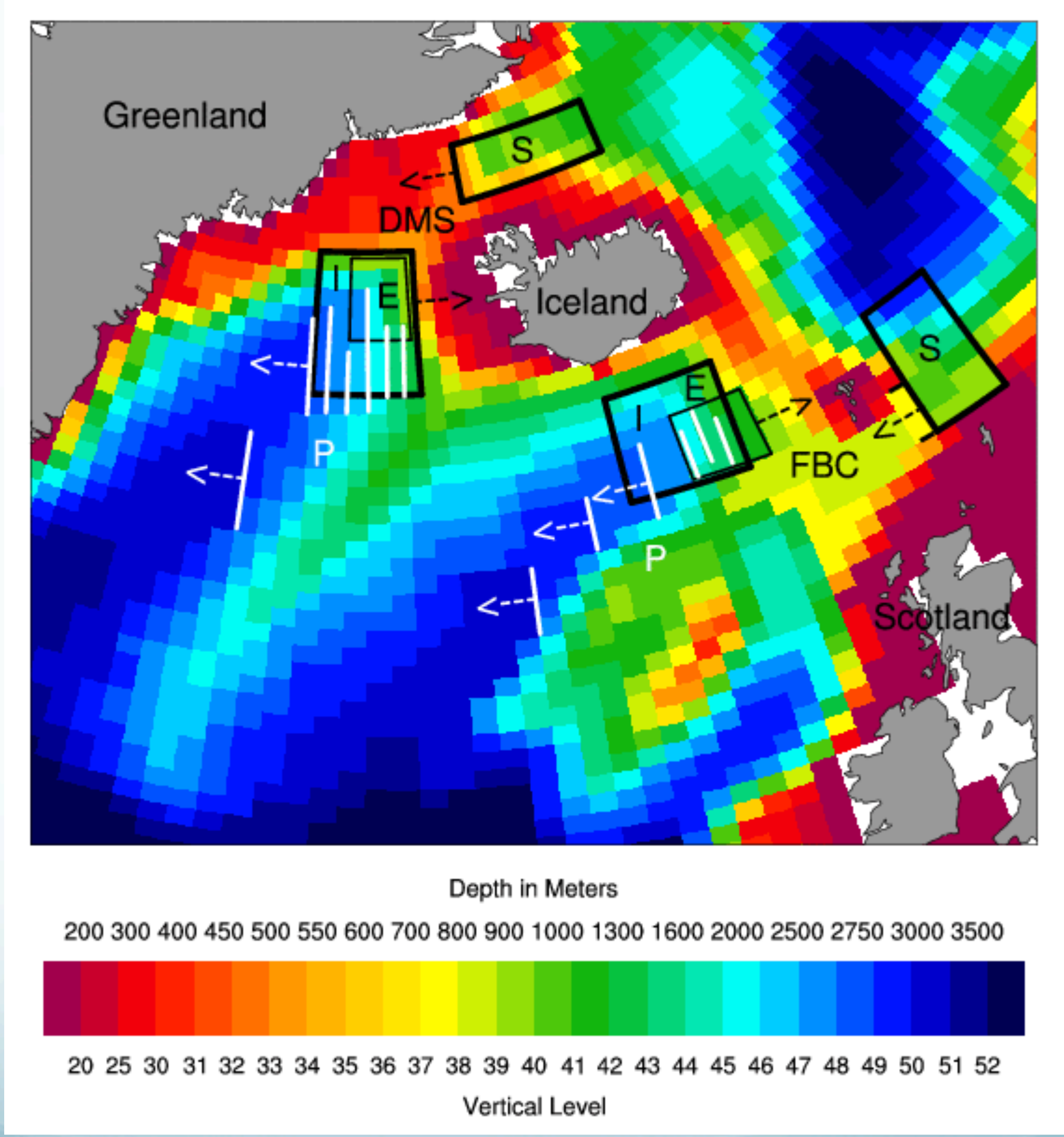
$$\vartheta = \frac{M_e}{M_s + M_e} = \frac{M_e}{M_p}.$$

$$T_p = T_s(1-\vartheta) + T_e\vartheta,$$

$$S_p = S_s(1-\vartheta) + S_e\vartheta$$

$$M_e = M_s\left(\{g_e'\mathcal{F}(\alpha, f, C_d, M_s, W_{ssb})\}^{2/3} - 1\right)$$

BOTTOM TOPOGRAPHY OF THE x1 RESOLUTION OCEAN MODEL

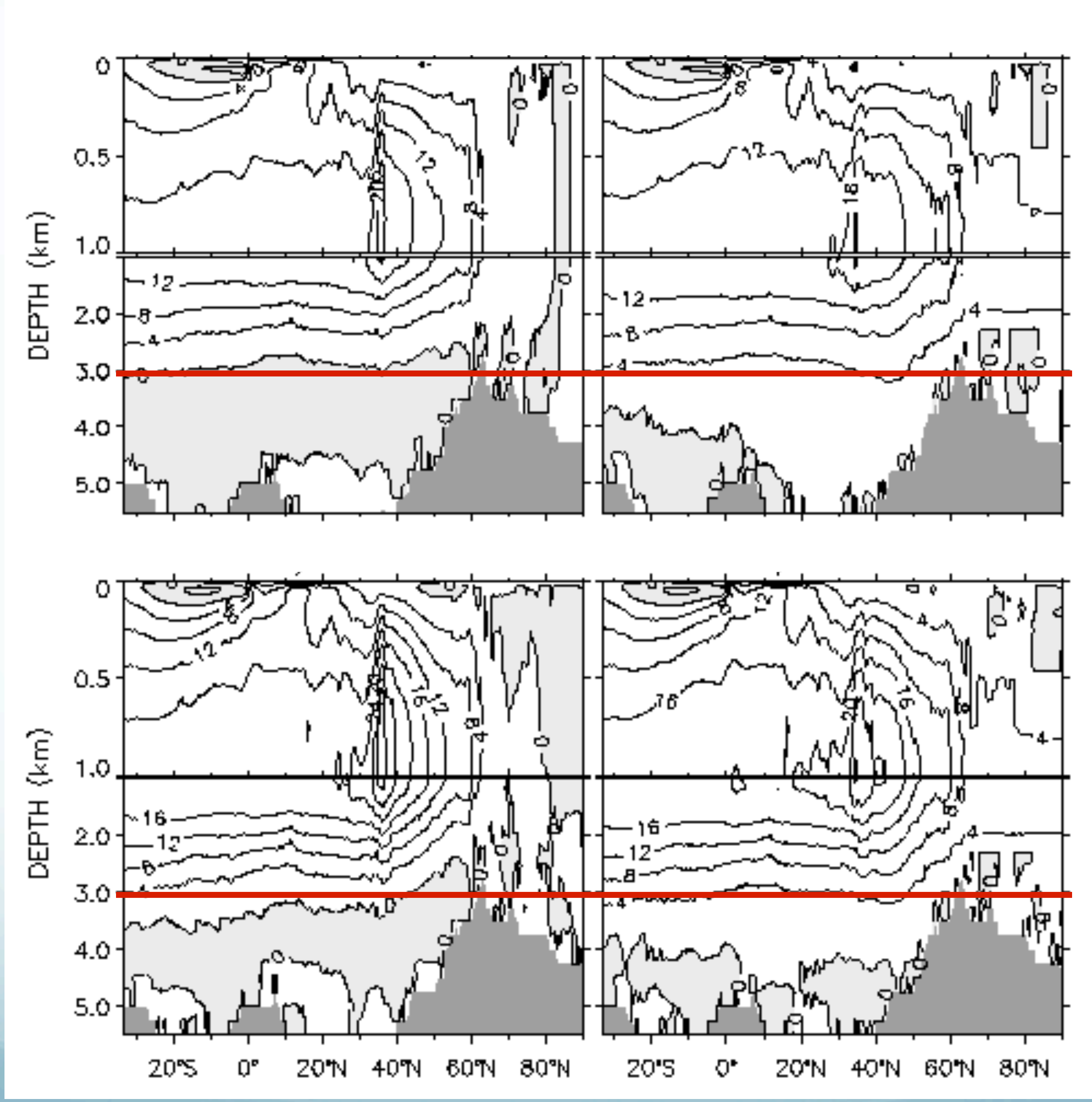


Based on Price & Yang (1998); described in Briegleb et al. (2010, NCAR Tech. Note) and Danabasoglu et al. (2010, JGR)

ATLANTIC MERIDIONAL OVERTURNING CIRCULATION (AMOC)

OCN

CCSM



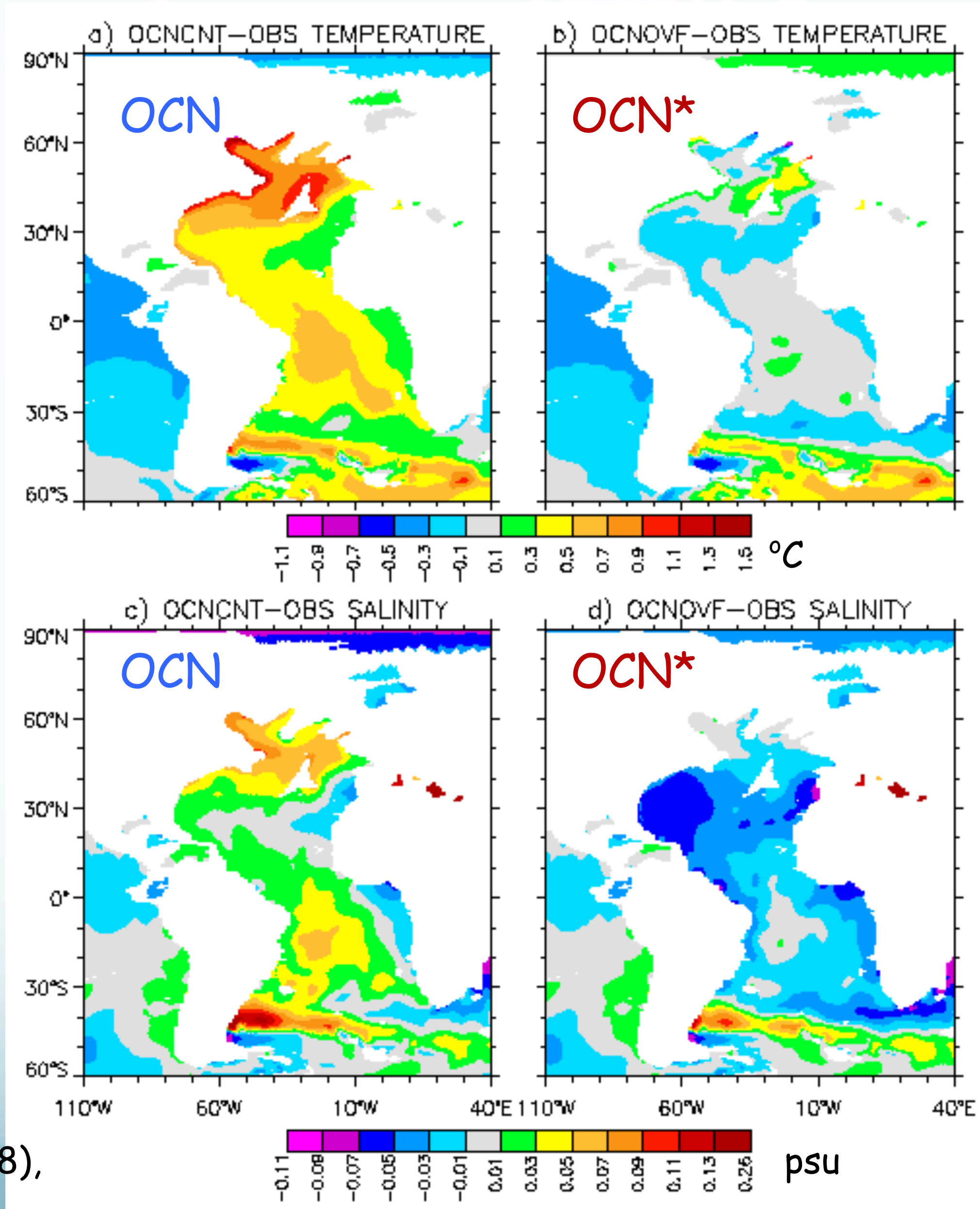
OCN*

CCSM*

in Sv

* denotes with overflows

TEMPERATURE AND SALINITY DIFFERENCES FROM OBSERVATIONS AT 2649-m DEPTH



mean= 0.45°C
rms= 0.50°C

mean= -0.04°C
rms= 0.13°C

mean= 0.02 psu
rms= 0.03 psu

mean= -0.03 psu
rms= 0.03 psu

Obs: Levitus et al. (1998), Steele et al. (2001)

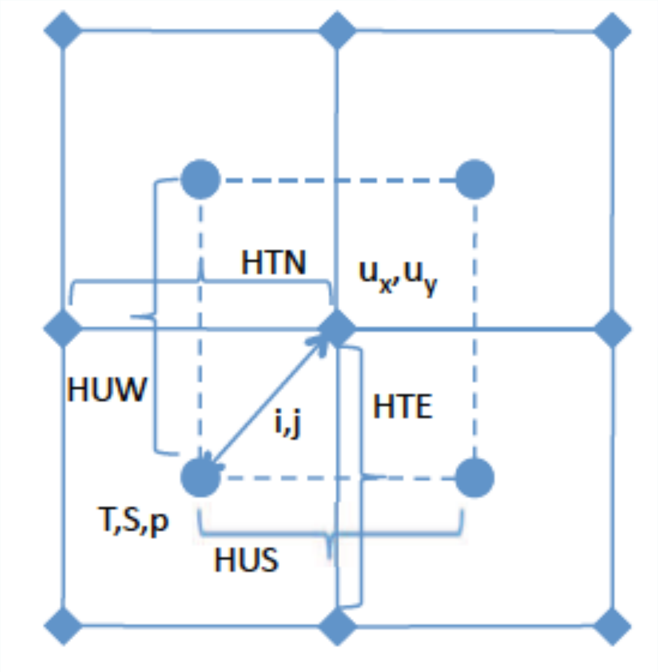
Helpful Guides

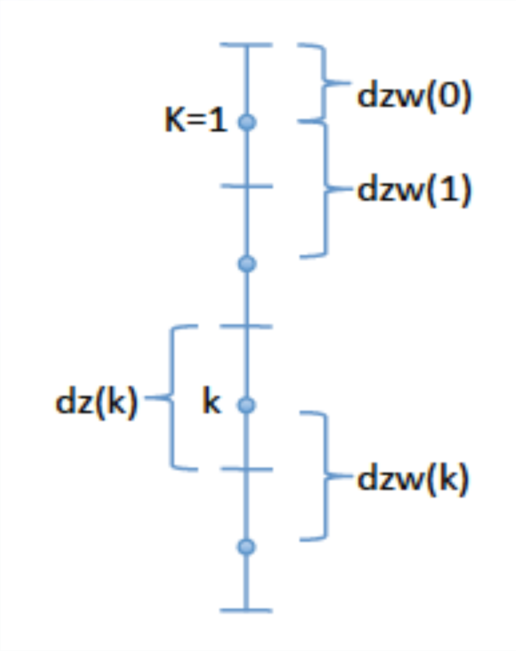
http://www.cesm.ucar.edu/models/cesm1.0/pop2/

CESM Webpage for POP

- POP2 User Guide
- Ocean Ecosystem Model User Guide
- POP Reference Manual
- Ocean Ecosystem Reference Manual

Central Advection Discretization





$$ADV_{i,j,k} = -(u_E\ T^*_E - u_W\ T^*_W)/DXT - (v_N\ T^*_N - v_S\ T^*_S)/DYT - (w_k\ T^*_T - w_{k+1}\ T^*_B)/dz$$

$$u_E(i) = (u_{i,j} DYU_{i,j} + u_{i,j-1} DYU_{i,j-1})/(2DXT_{i,j})$$
$$u_W(i) = u_E(i-1)$$
$$v_N(j) = (v_{i,j} DXU_{i,j} + v_{i-1,j} DXU_{i-1,j})/(2DXT_{i,j})$$
$$v_S(j) = (v_{i,j\text{-}1} DXU_{i,j} + v_{i-1,j-1} DXU_{i-1,j})/(2DXT)$$

$$T^*_E = ½ * (T_{i+1,j} + T_{i,j})$$