Ocean Modeling I

Ocean Modeling Basics and the CESM Ocean Model

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Outline

1. The (unique) challenges of ocean modeling associated with fluid domain/properties
2. The CESM ocean model
   a. Governing equations
   b. Grids
   c. Finite difference numerics
   d. Surface boundary conditions
3. Some model results

(Parameterization of unresolved processes will be covered in following lecture)

Ocean Modeling Challenges

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

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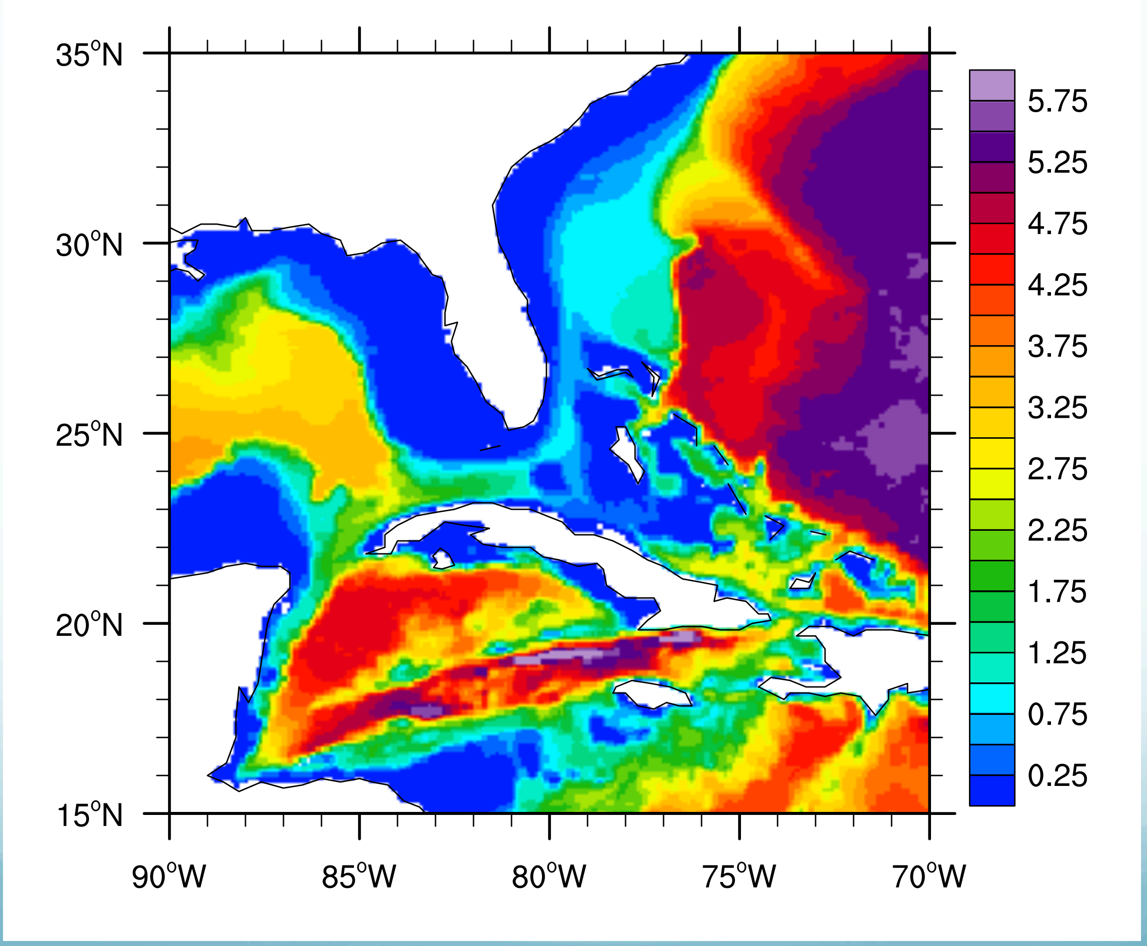
Highly irregular domain; land boundary exerts strong control on ocean dynamics

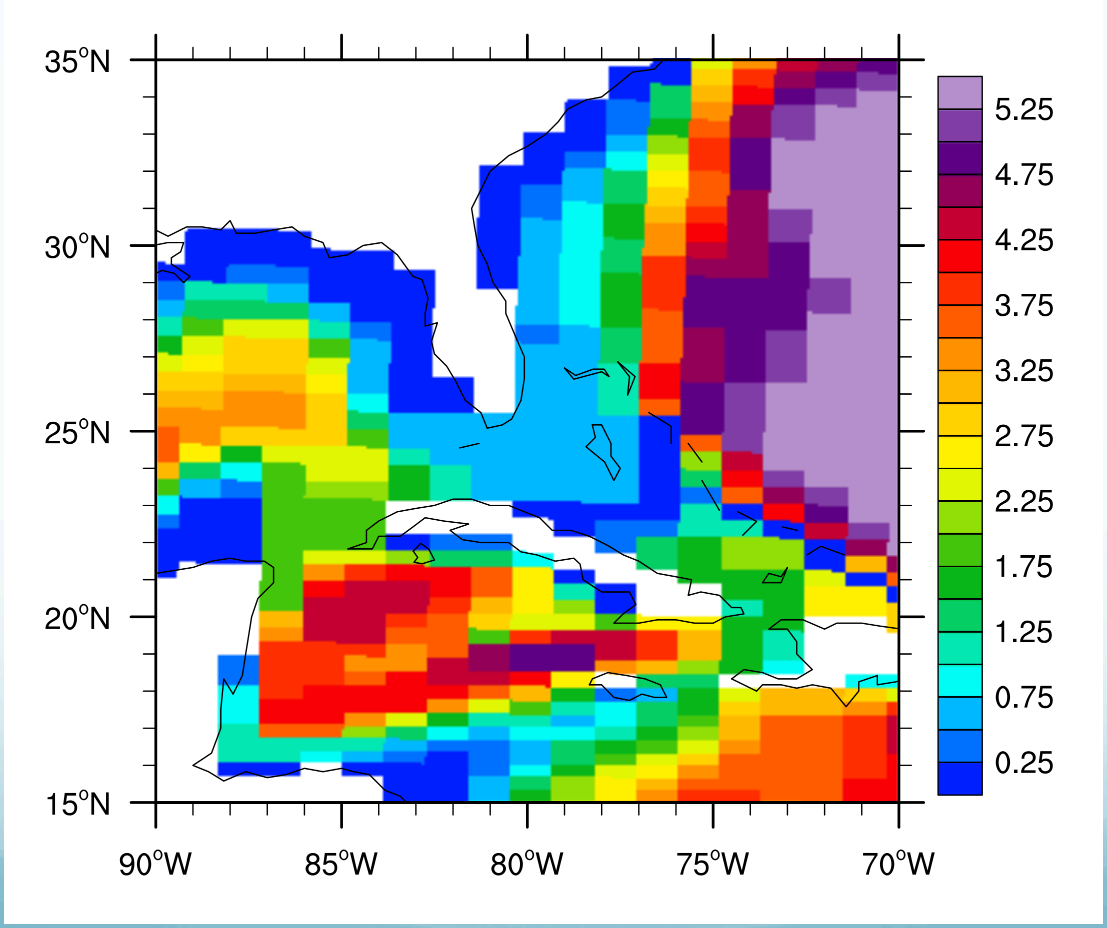
Ocean Modeling Challenges

Bathymetry (km), 0.1° model (tx0.1)



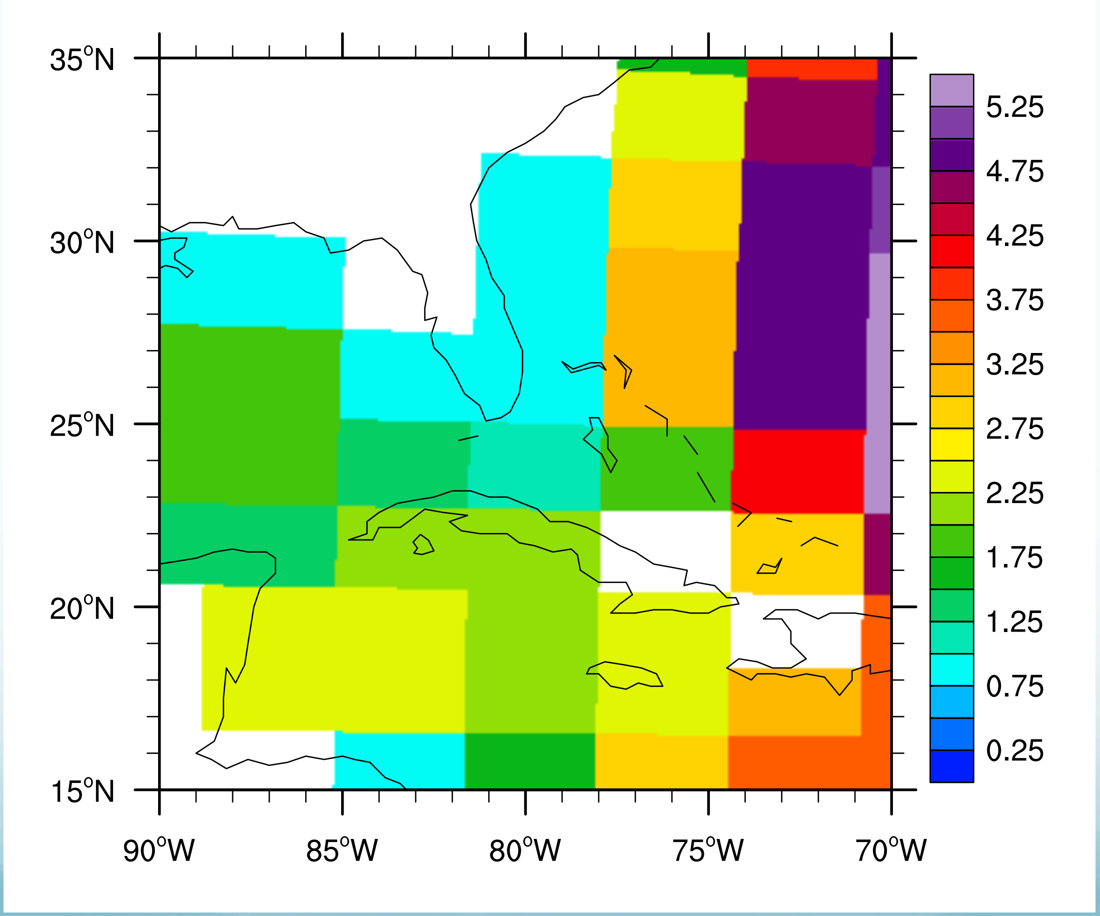
Ocean Modeling Challenges

Bathymetry (km), 1° model (gx1v6)



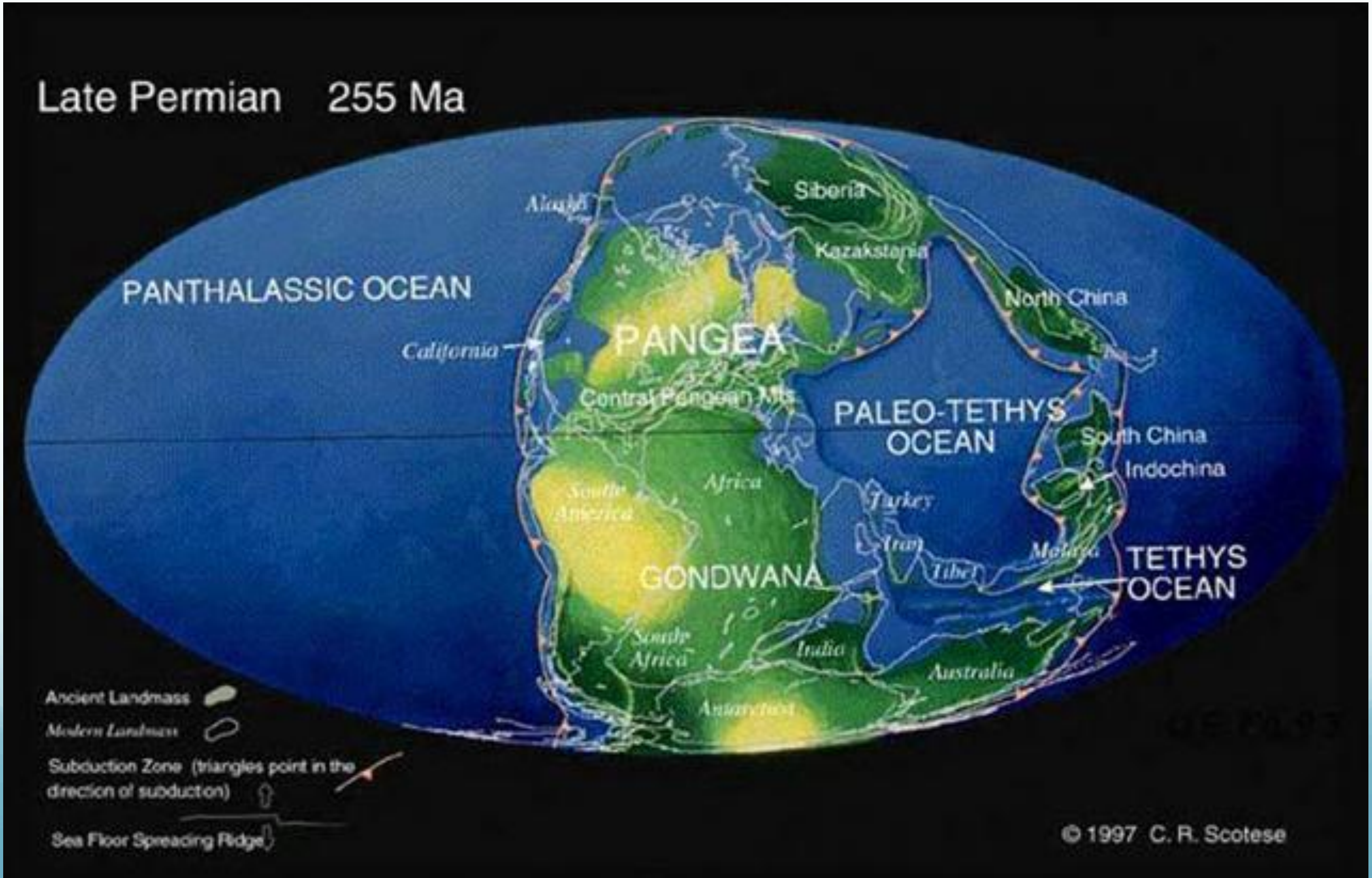
Ocean Modeling Challenges

Bathymetry (km), 3° model (gx3v7)

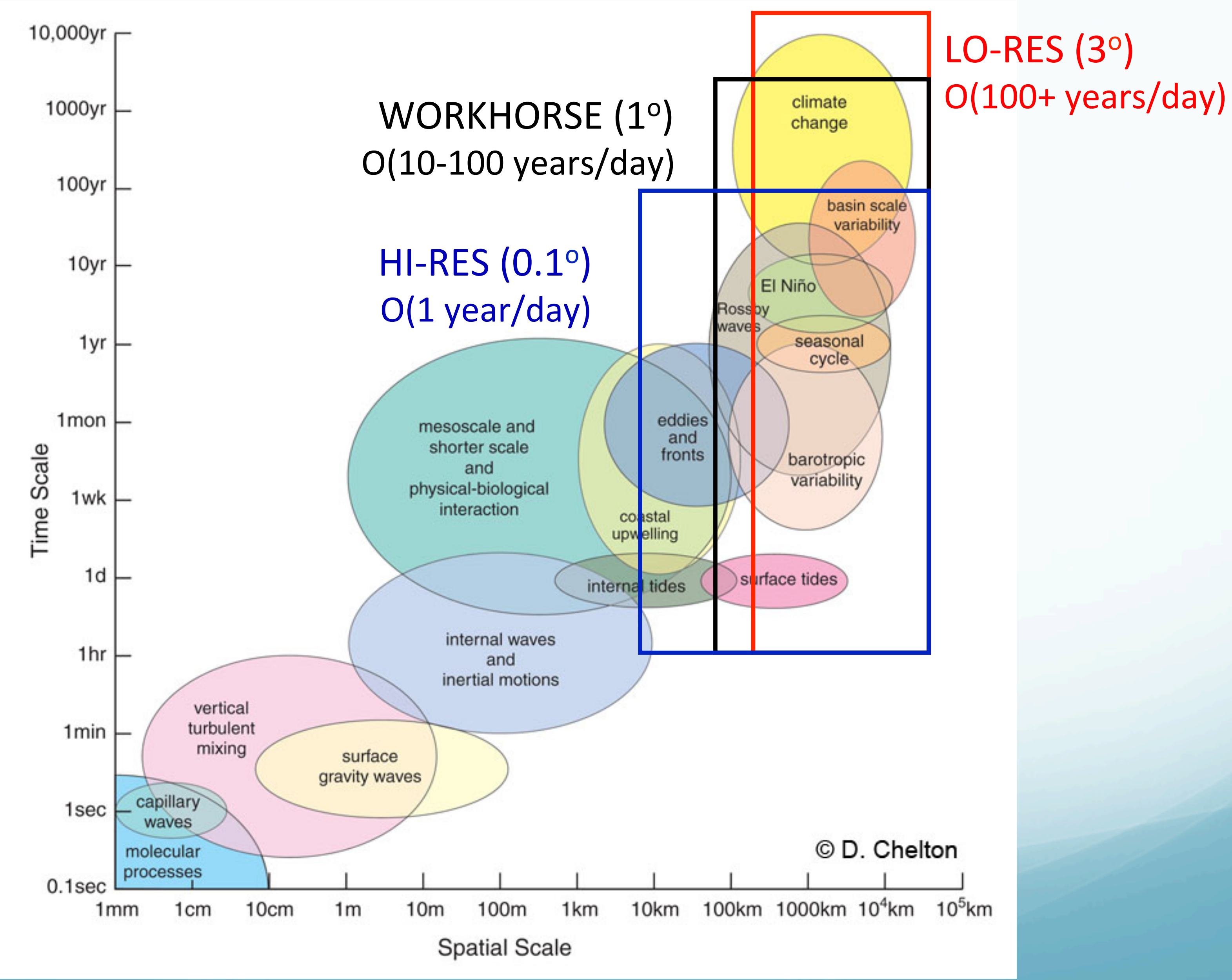


Ocean Modeling Challenges

Paleoclimate modeling can entail significant changes in ocean domain…



Ocean Modeling Challenges



Ocean Modeling Challenges

Oceanic deformation radius O(10-200) km << Atmospheric O(1000s) km,
➔ significantly higher resolution is needed O(0.1°) to resolve ocean "weather"

1st baroclinic Rossby radius (km) (< Eddy length scale)

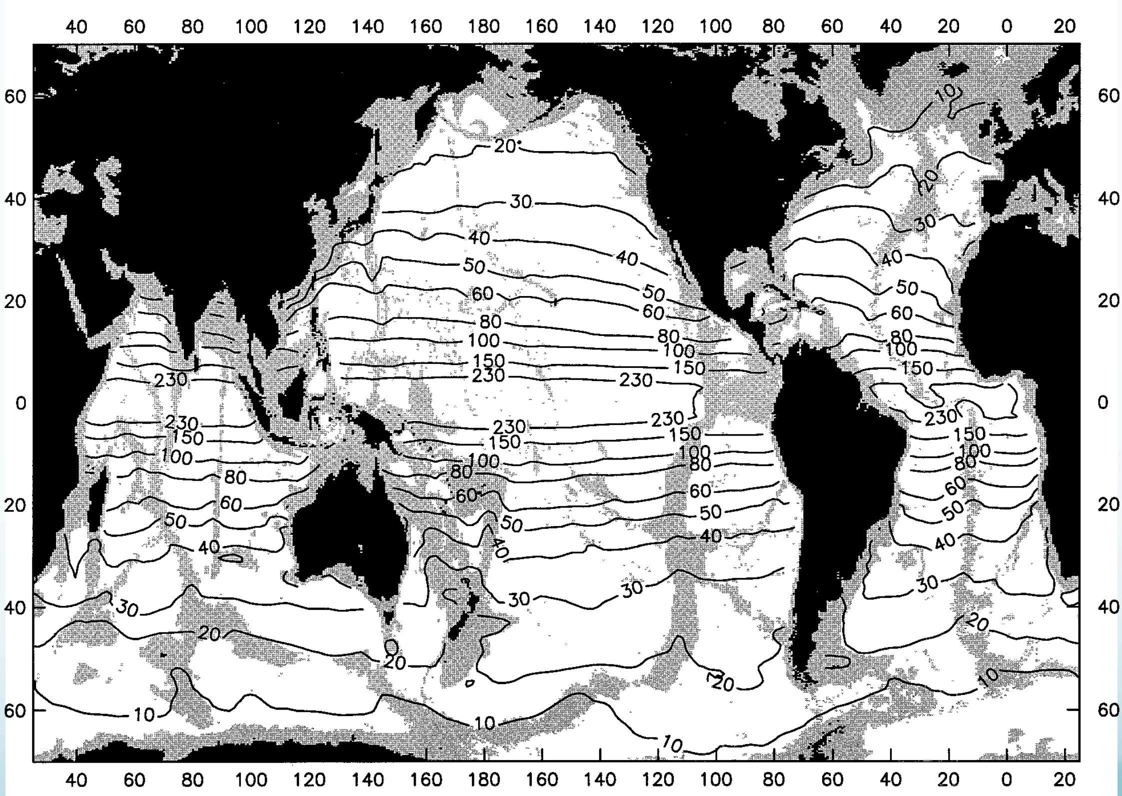


FIG. 6. Global contour map of the 1° × 1° first baroclinic Rossby radius of deformation λ_1 in kilometers computed by Eq. (2.3) from the first baroclinic gravity-wave phase speed shown in Fig. 2. Water depths shallower than 3500 m are shaded.

Chelton et al., JPO, (1998)

Ocean Modeling Challenges

…spheric O(1000s) km,
…o resolve ocean "weather"

…us (km) (< Eddy length scale)

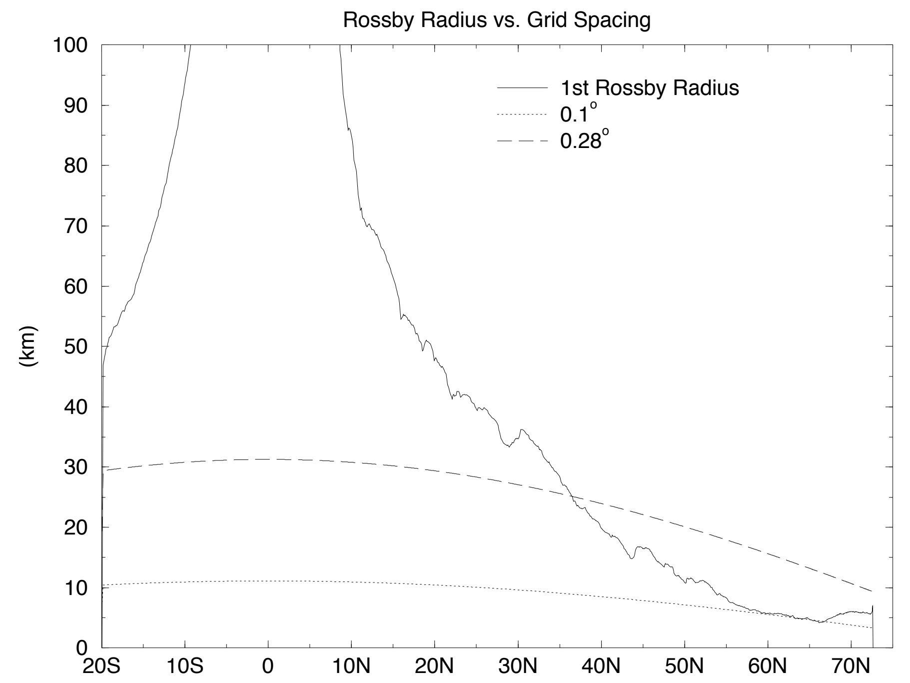
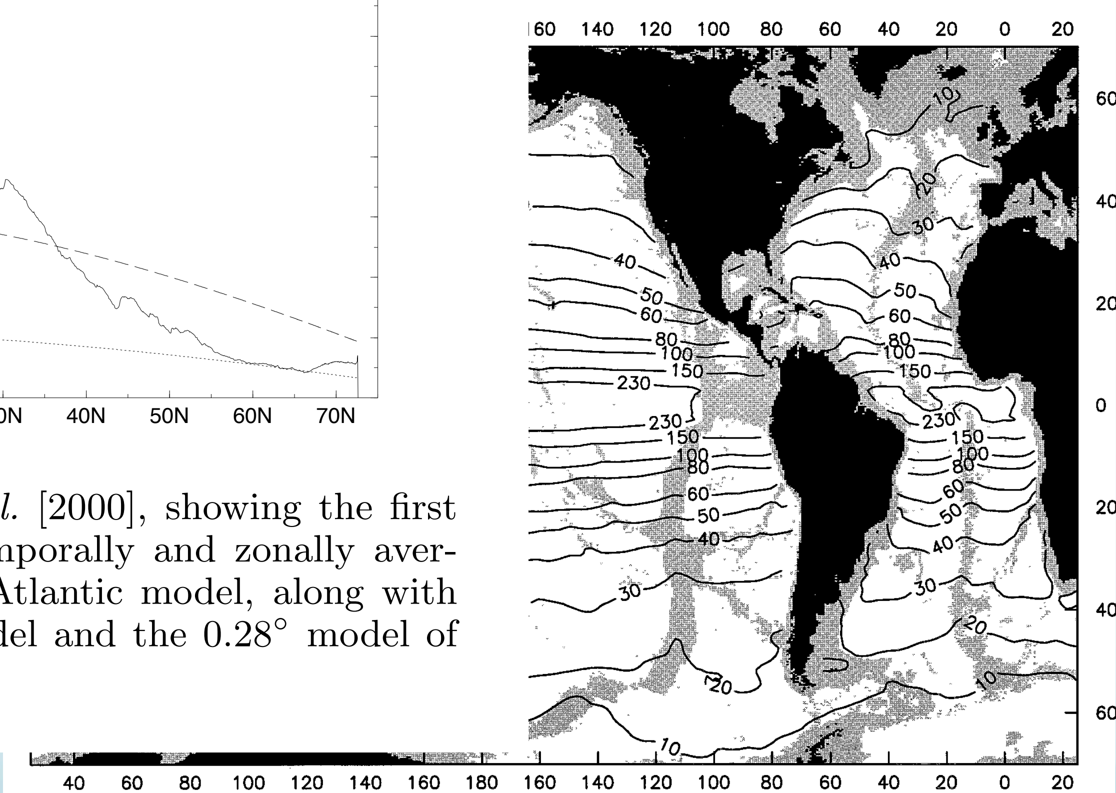


Figure 2. From *Smith et al.* [2000], showing the first baroclinic Rossby radius, temporally and zonally averaged from their 0.1° North Atlantic model, along with grid spacings of the 0.1° model and the 0.28° model of *Maltrud et al.* [1998].



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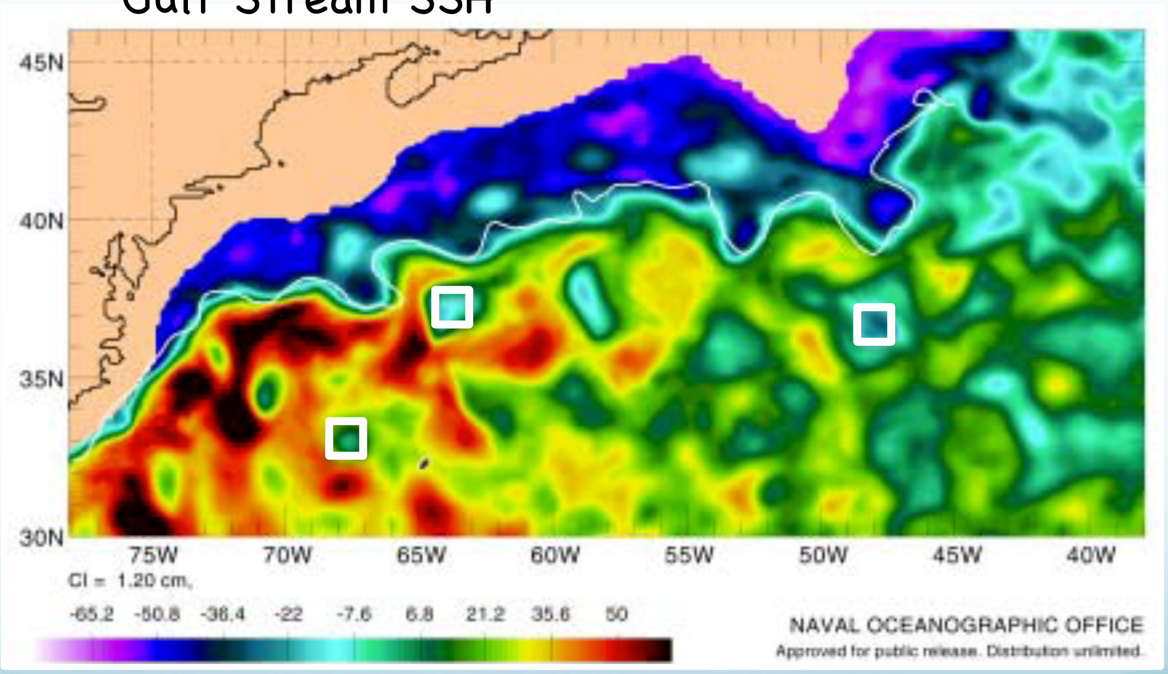
Chelton et al., JPO, (1998)

Ocean Modeling Challenges

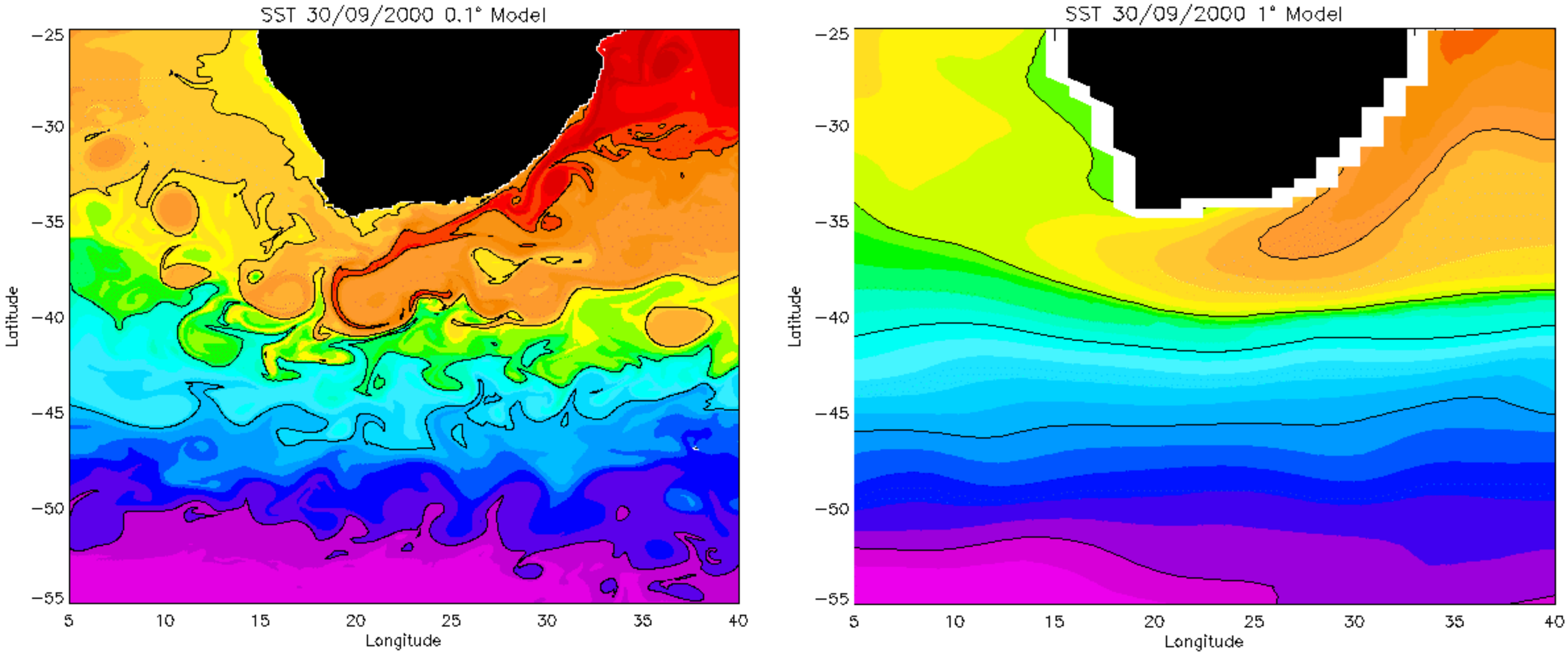
Workhorse (1° ≈ 100km) ocean models for climate research cannot reproduce the rich mesoscale eddy field observed in Nature...

Gulf Stream SSH



Ocean Modeling Challenges

➔Mixing associated with sub-gridscale turbulence must be parameterized



Ocean Modeling Challenges

- Long equilibration timescale ➔ deep ocean will in general be characterized by drift.

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

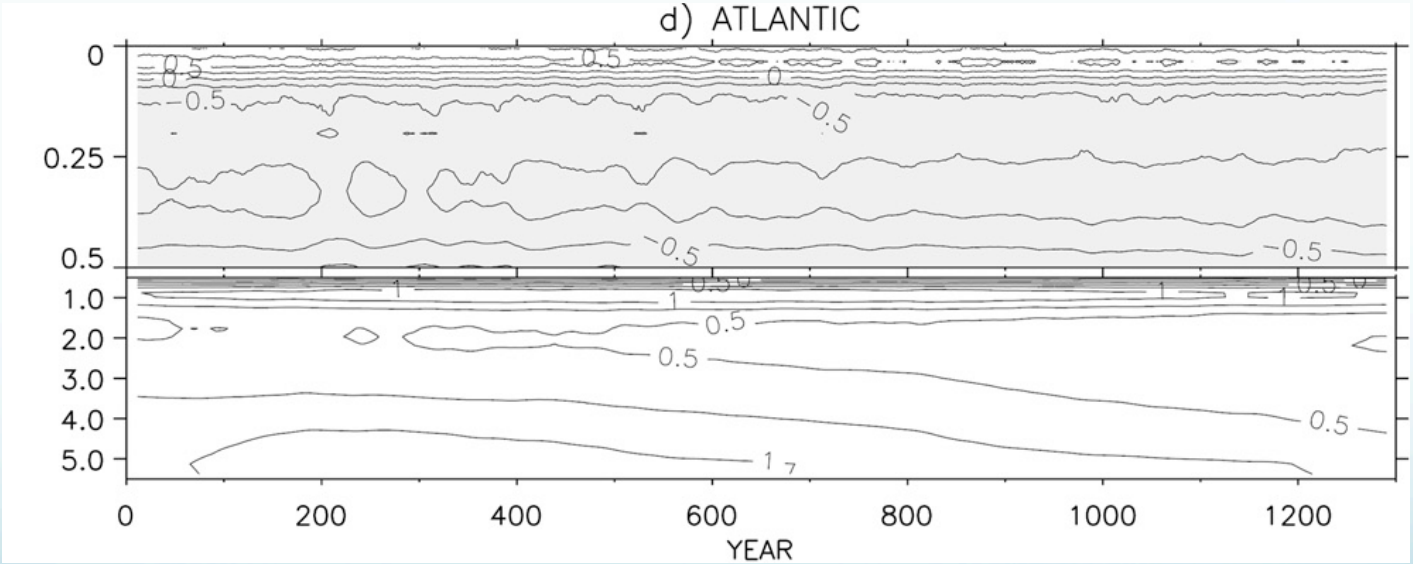


FIG. 2. Horizontal-mean potential temperature difference time series for 1850 CONTROL minus PHC2 observations: (a) global, (b) Pacific, (c) Indian, and (d) Atlantic Oceans. The contour intervals are 0.1°, 0.2°, 0.25°, and 0.25°C in (a),(b),(c),(d), respectively. The shaded regions indicate negative differences. The time series are based on annual-mean fields smoothed using a 10-yr running mean.

Danabasoglu et al., J Clim, (2012)

Important Ocean Properties

- 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 diapycnal mixing (across density surfaces) once water masses are subducted below the mixed layer. This is why water masses can be named and followed around the ocean.
- The ocean is a 2 part density fluid (temperature and salinity). Form ice when temperature <-1.8°C & resulting brine rejection increases salinity of adjacent water parcels.
- Top to bottom "lateral" boundaries. Leads to WBC heat transport leaving little role for eddies.
- 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).
- Descendant of the Bryan-Cox-Semtner class of models.
- Solves the 3-D primitive equations in general orthogonal coordinates with the hydrostatic and Boussinesq approximations.
- A linearized, implicit free-surface formulation is used for the barotropic mode (Dukowicz & Smith, 1994).
- Surface freshwater fluxes are treated as virtual salt fluxes, using a constant reference salinity ➔ net ocean volume remains constant (but not ocean mass).

CESM1.1: Parallel Ocean Program (POP2)

www.cesm.ucar.edu/models/cesm1.2/pop2/

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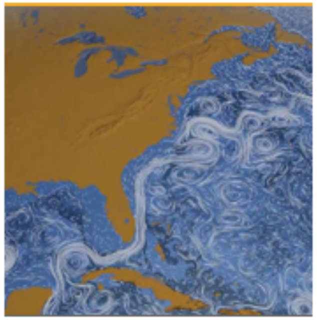
CESM1.1: PARALLEL OCEAN PROGRAM (POP2)

INTRODUCTION

The ocean component of the CESM1.1 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
- CESM1.1 POP2 User Guide
- CESM1.1 Ocean Ecosystem Model User Guide
- CESM1.1 POP2 FAQ

Smith et al. (2010)

POP2 PORT VALIDATION AND MODEL VERIFICATION

Before running any experiments with CESM1.1 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.

Journal of Climate CCSM4 / CESM1 Special Collection Papers
(doi:10.1175/JCLI-D-11-00091.1)

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SPECIAL
Community Climate System Model CCSM4
COLLECTION

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 additional passive tracer
(e.g. CFCs, Ideal Age)

POP Reference Manual (Smith et al. 2010):

Momentum equations:

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

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

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

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

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

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

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

POP Reference Manual (Smith et al. 2010):

Continuity equation:

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

Hydrostatic equation:

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

Equation of state:

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

Tracer transport:

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

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

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

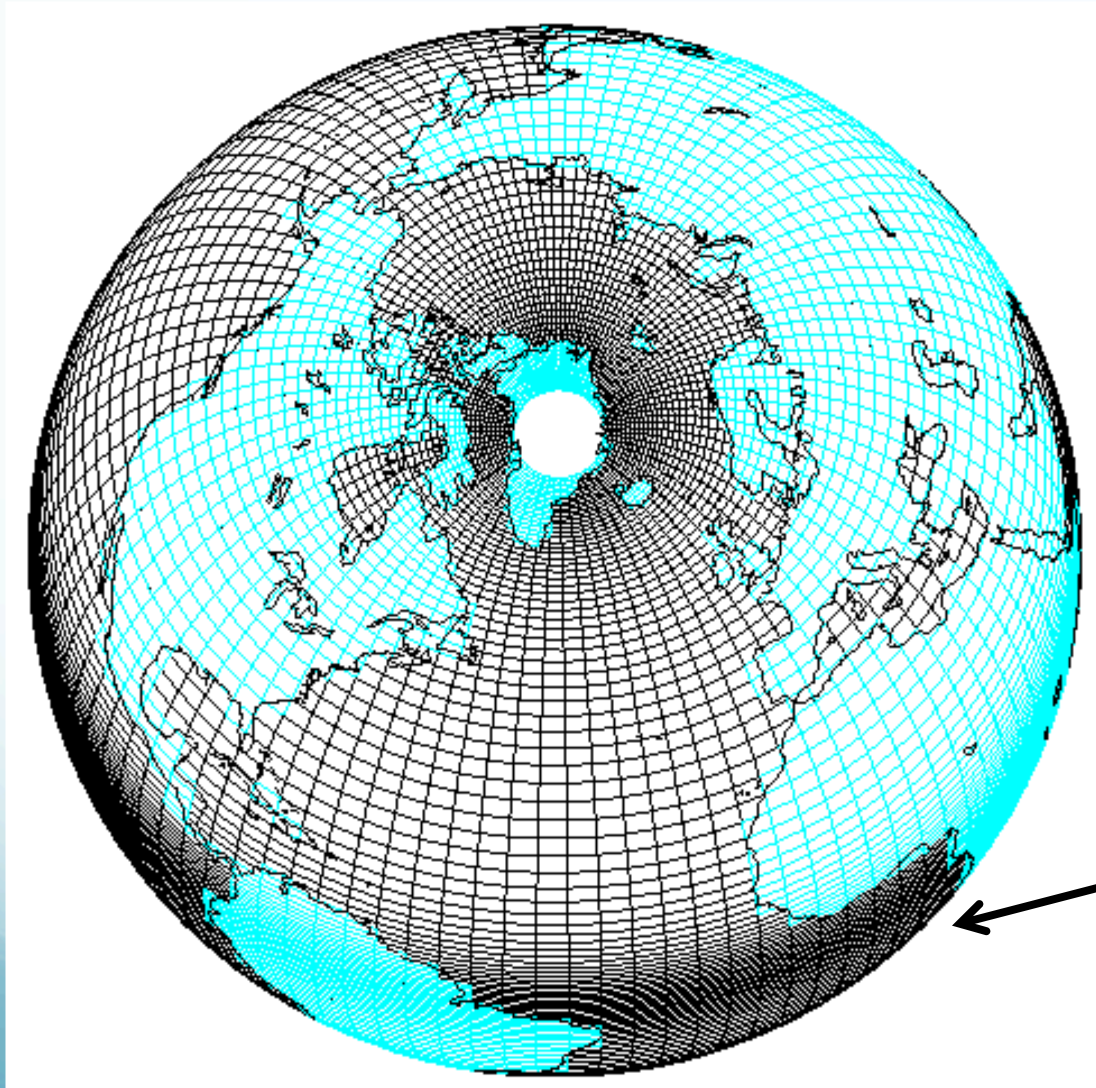
CESM Ocean Model

- Seawater ≈ incompressible, so 3-D flow field is non-divergent (Boussinesq)➔ vertical velocity is computed diagnostically from continuity eqn., rather than prognostically

- There should be vertical acceleration when ocean becomes statically unstable (ρ_z>0), but w tendency has been excluded by hydrostatic assumption. Therefore, vertical mixing must be parameterized by prognostic computation of vertical diffusivity (very large for an unstable column).

CESM Ocean Model Grids

displaced pole



gx1v6: climate workhorse
nominal 1°
gx3v7: testing, paleo apps
nominal 3°

Ex. T62_gx3v7

Equatorial refinement
(0.3° / 0.9°)

CESM Ocean Model Grids

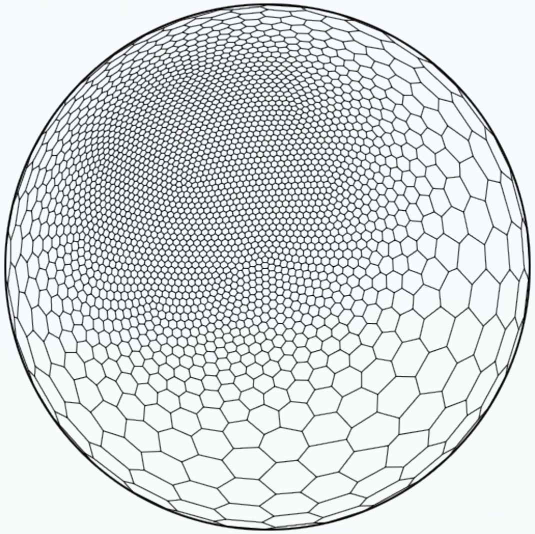
tripole

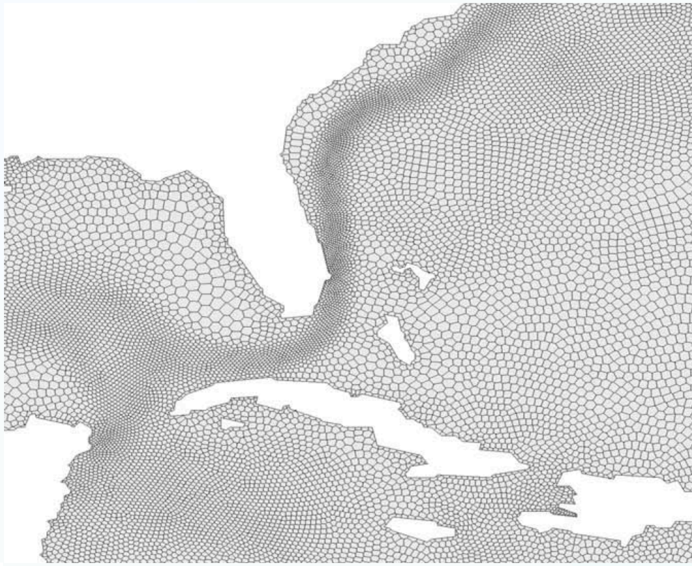
tx0.1: “eddy-resolving”
nominal 0.1°

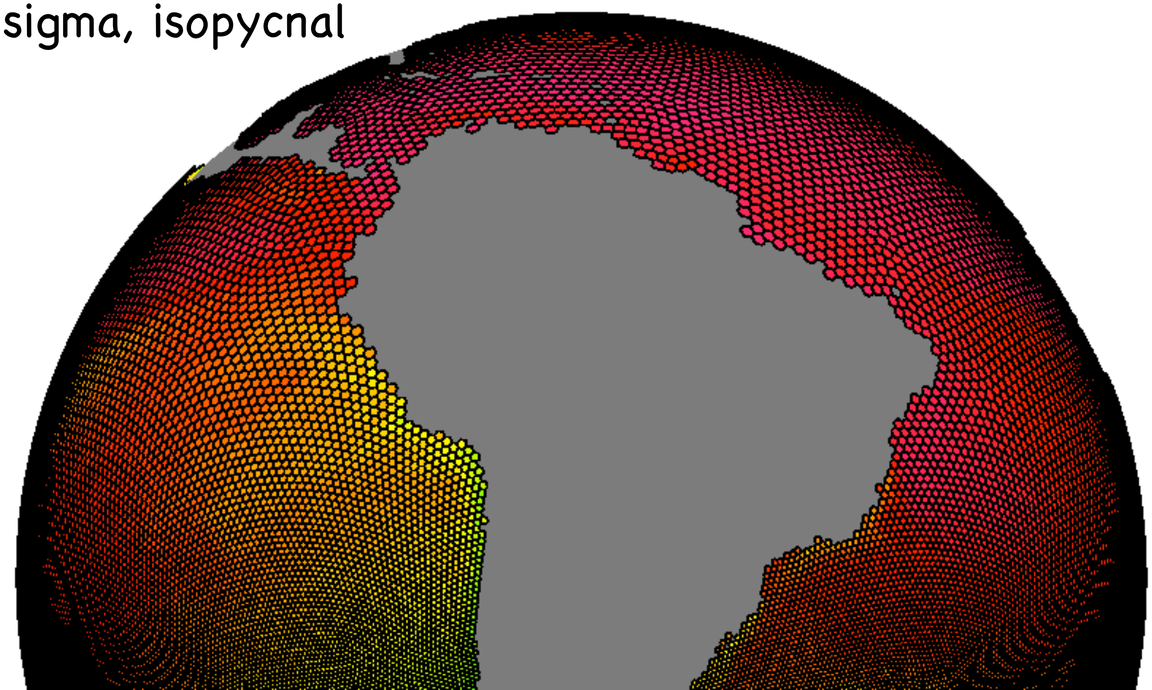
MPAS-Ocean model grids (future of CESM)

Horizontal:
unstructured
quasi-uniform or variable resolution
Voronoi Tesselations
4, 5, or 6-sided cells

Vertical: Arbitrary Lagrangian-Eulerian (ALE): z-level, z-star, sigma, isopycnal

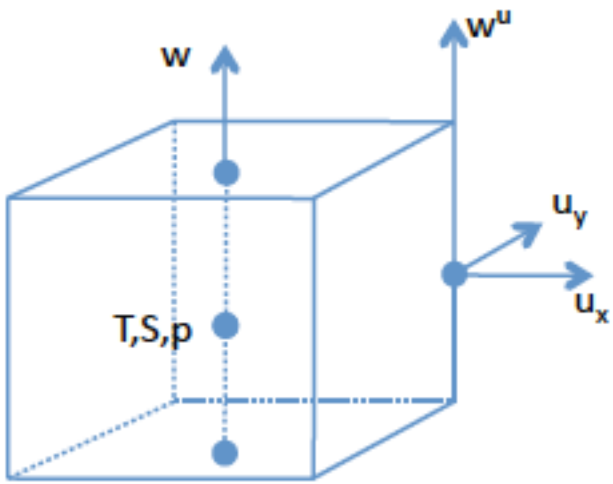






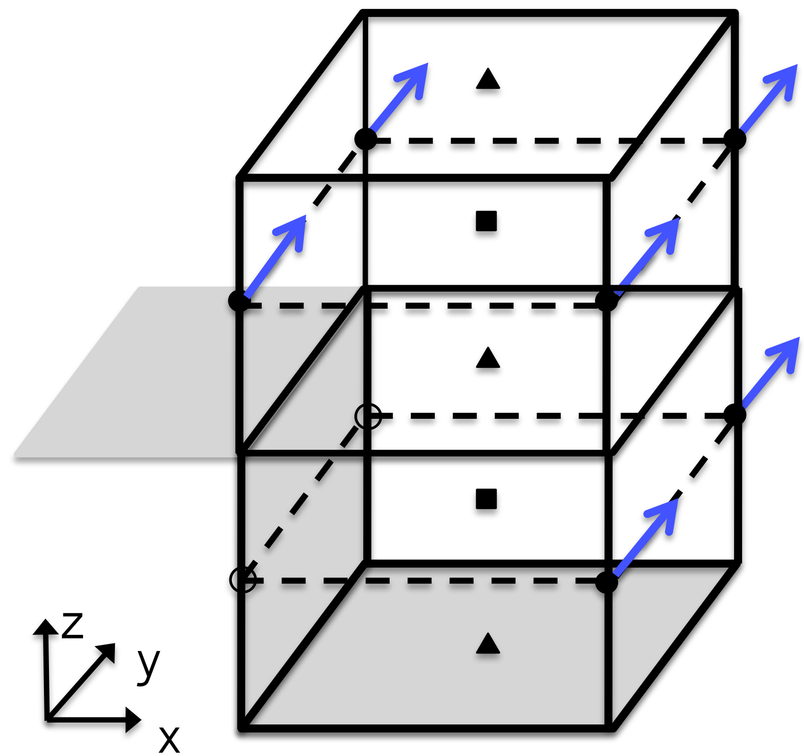
Figures courtesy of Mark Petersen (LANL)

POP Spatial Discretization



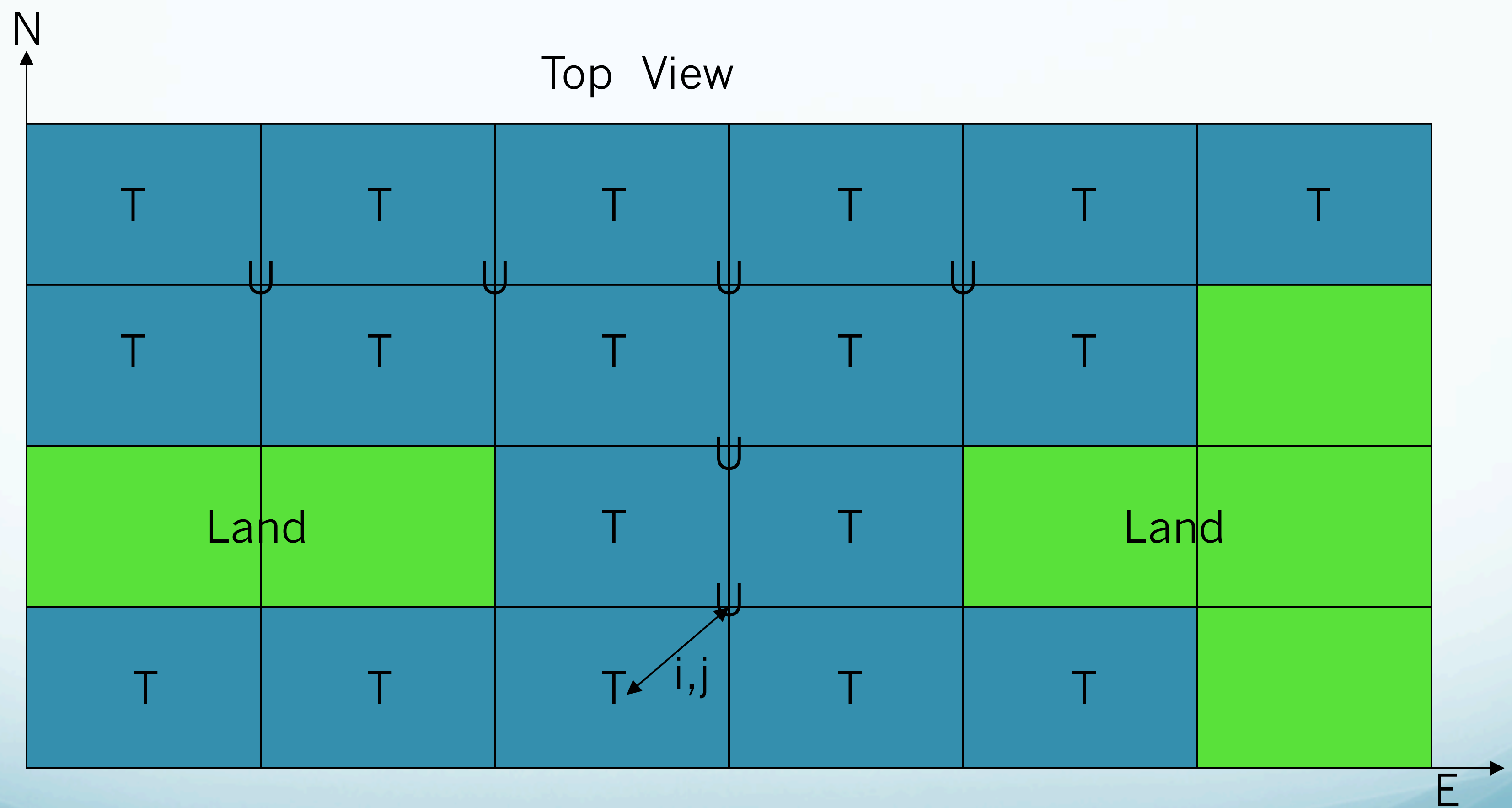
- Quadrilateral horizontal mesh (B-grid)
- fixed $\Delta z(z)$
- See POP reference manual for finite difference operators (div, curl, etc) used in model eqns

● Horizontal velocity
○ No-slip condition on sidewalls
■ Tracers (T, S, ρ, etc)
▲ Vertical velocity



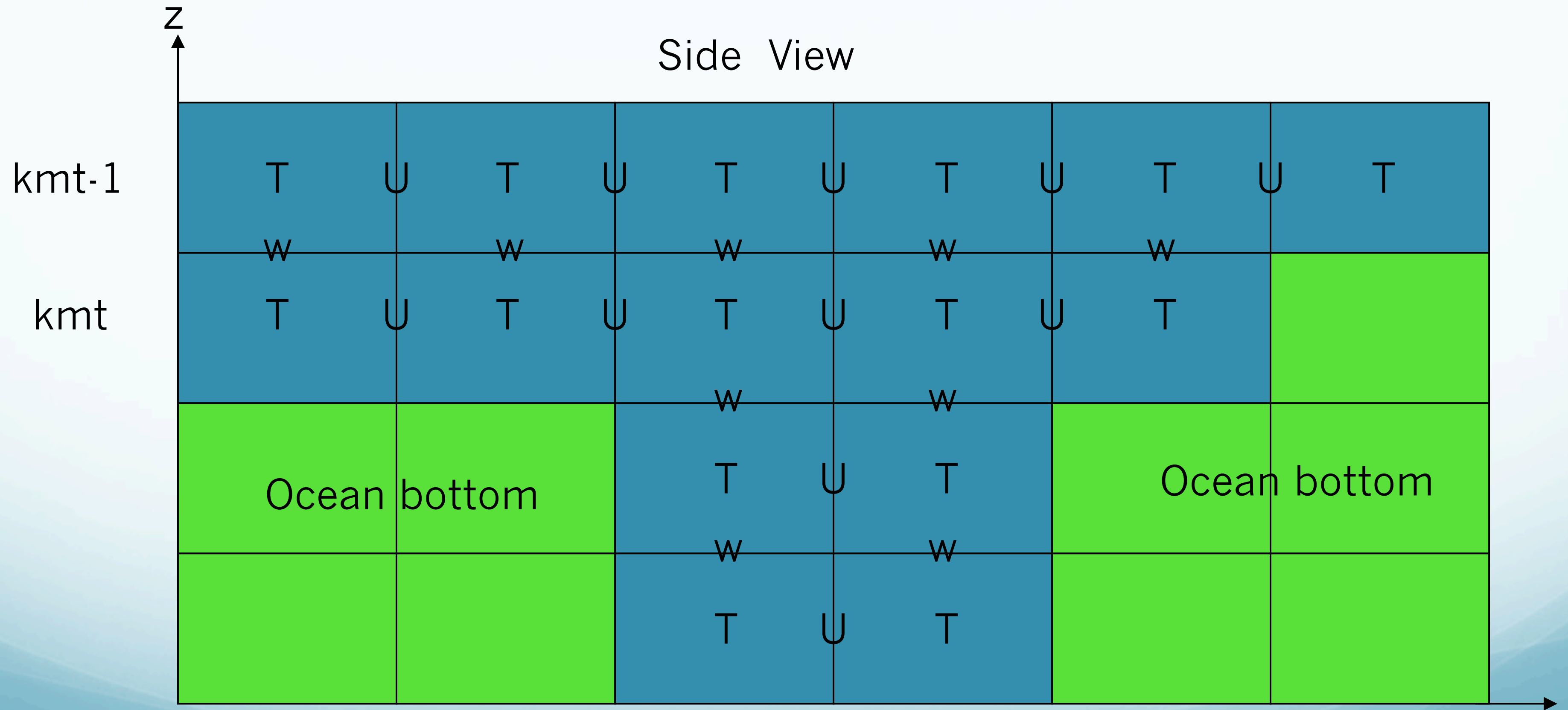
POP Spatial Discretization

- At least 2 adjacent active ocean T-cells are required for flow through channels



T=tracer grid, U=velocity grid

POP Spatial Discretization



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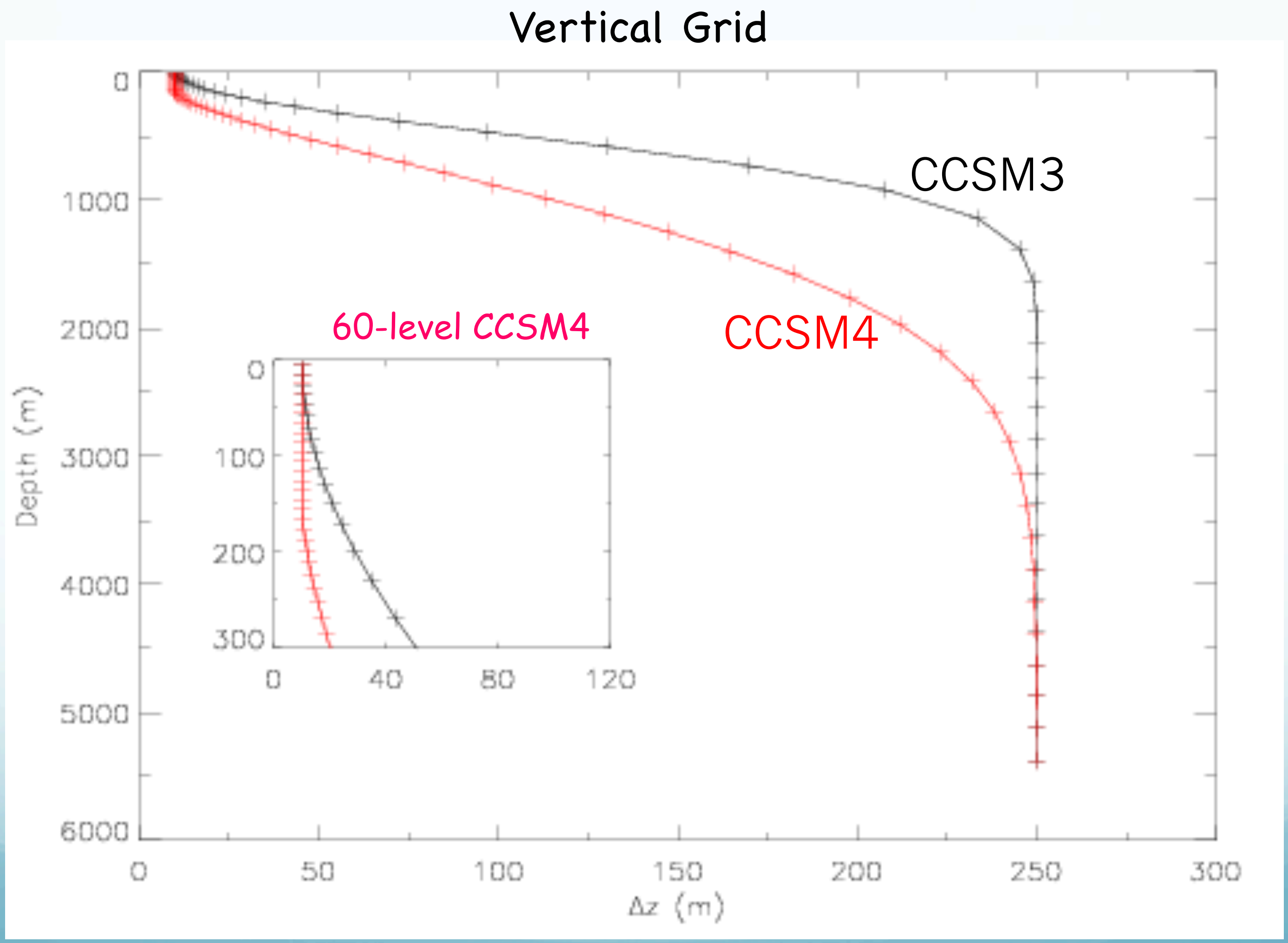
POP Spatial Discretization



POP numerics in a nutshell

Finite difference advection

- Momentum: centered differencing (2nd order)
- Tracer: upwind3 scheme (3rd order)
  - Stronger conservation & monotonicity requirements
  - Other alternatives for tracers (e.g., flux-limited Lax-Wendroff scheme), but more expensive

Barotropic/Baroclinic Split

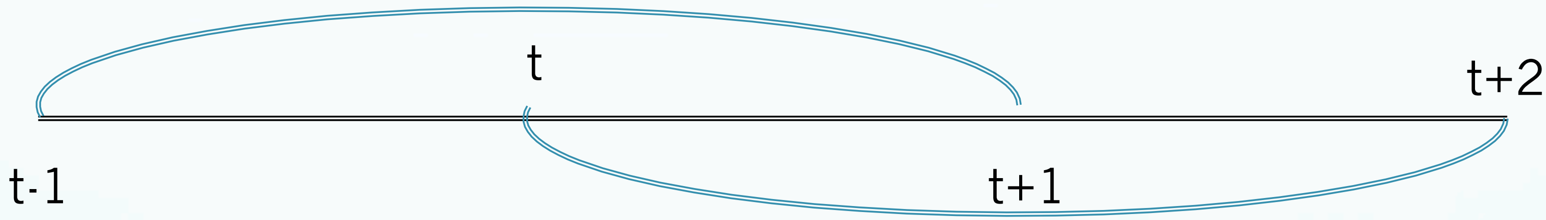
- U = <U> + U′, where <U> is depth-average (barotropic mode)
- Explicitly resolving fast barotropic gravity waves ($\sqrt{gH}$ ~200 m/s) would place severe limitations on model timestep
- Courant-Friedrichs-Lewy (CFL) stability condition: $u(\Delta t/\Delta x) \leq 1$
- Therefore, barotropic gravity waves are filtered out by solving for <U> as separate 2D system using implicit free-surface formulation
- Explicitly solve for U′ from momentum eqns without surface pressure gradient
- ➔ $\Delta t \approx 1$ hour in 1° POP

POP numerics in a nutshell

Time Discretization

- 3-time-level modified leapfrog scheme (2nd order)
- Occasional averaging timestep to suppress the computational mode associated with decoupled even/odd timestep solutions

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



Refer to POP reference manual for further details!

POP surface forcing options

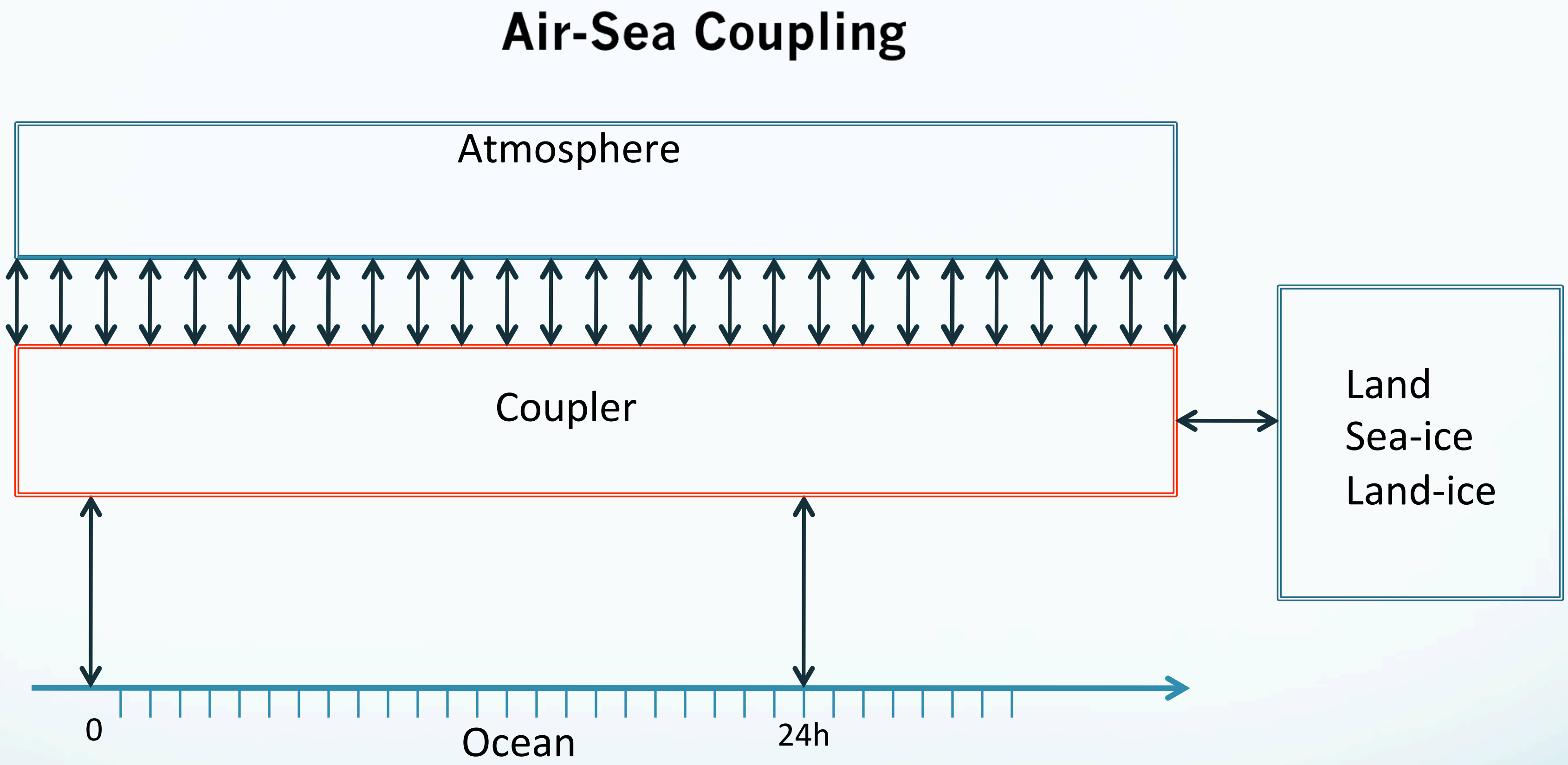
- Fully coupled mode (B compset): active atmospheric model
- Forced ocean (C compset) or ocean_sea-ice (G compset): data atmosphere
  - Generally use CORE atmospheric state fields for surface b.c.'s
  - http://data1.gfdl.noaa.gov/nomads/forms/core.html
  - Interannual (1948-2009) as well as Normal Year Forcing (NYF) are available and described in:

    Large and Yeager, NCAR Tech Note 460 (2004)

    Large and Yeager, *Climate Dynamics* (2009), doi:10.1007/s00382-008-0441-3

- Default is for POP to "couple" to surface b.c.'s once per day
- Quality of POP model solution is strongly tied to quality of surface b.c.'s

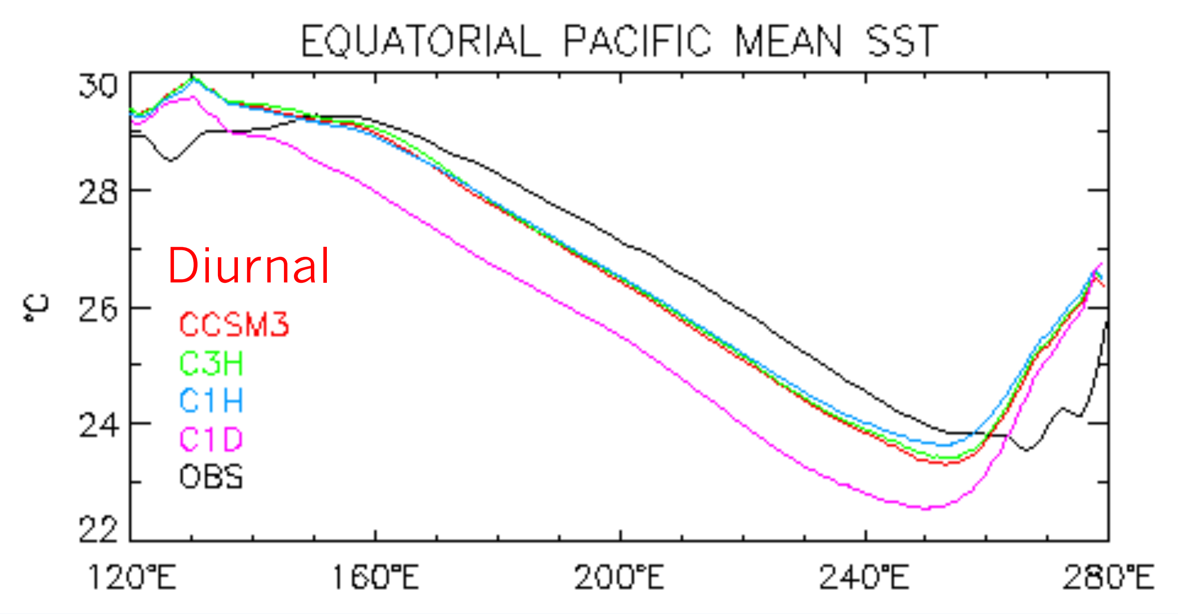
POP diurnal cycle



➔ Need to parameterize the diurnal cycle of (shortwave) radiative heat flux (ie., night & day). This is done with a zenith-angle dependent SW(lat, lon, hour, day of year) heat flux parameterization.

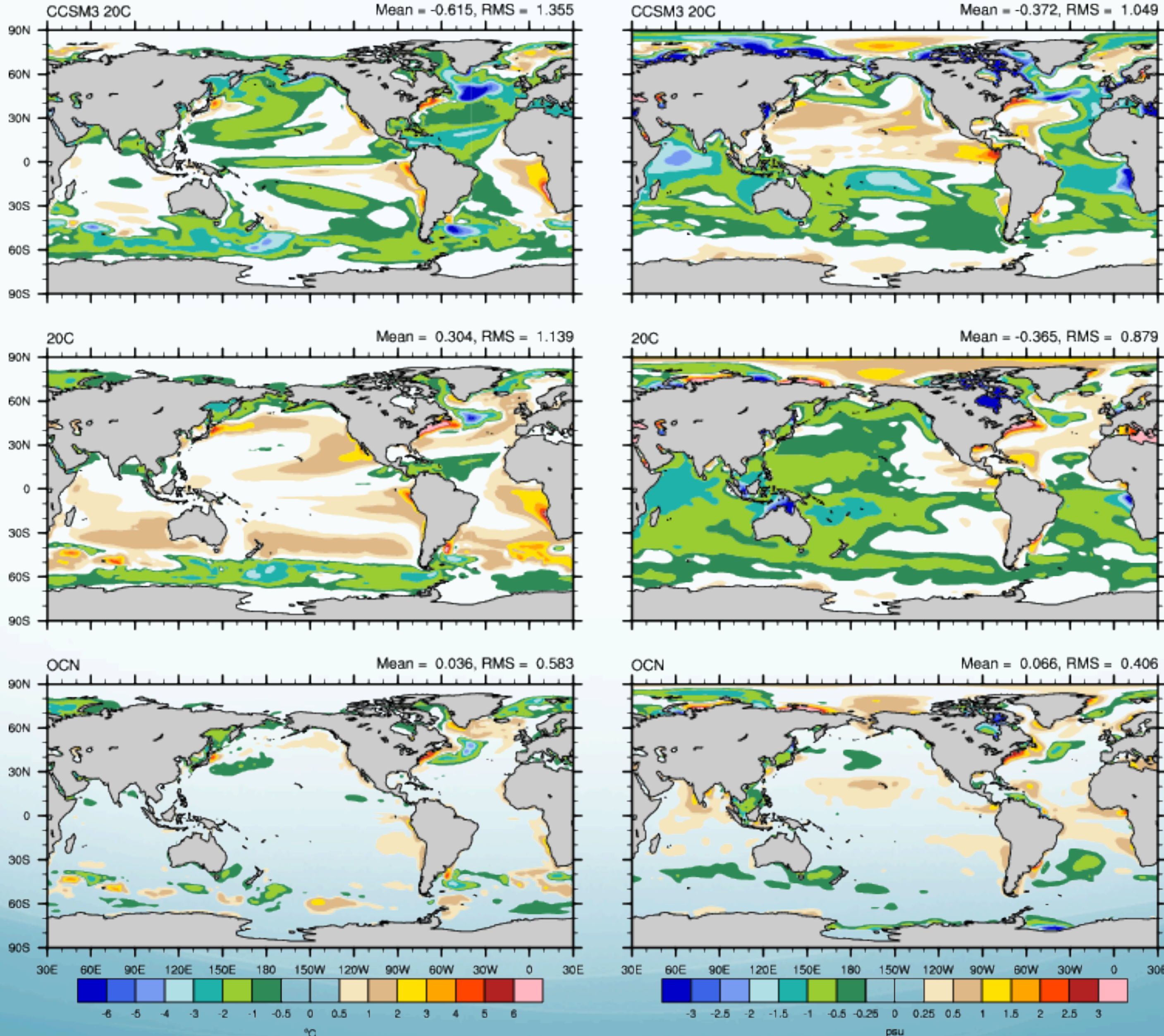
POP diurnal cycle

Air-Sea Coupling



➔ The SW diurnal cycle results in dramatically improved equatorial SST

SST and Salinity Differences from Observations

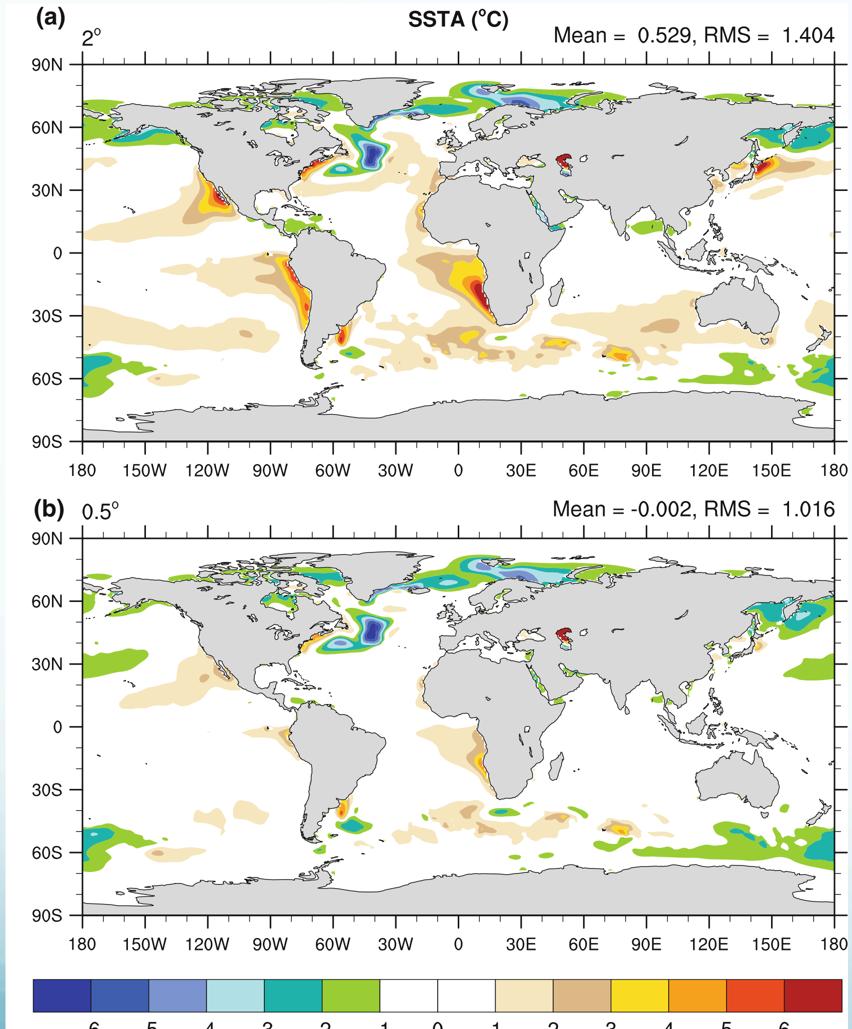


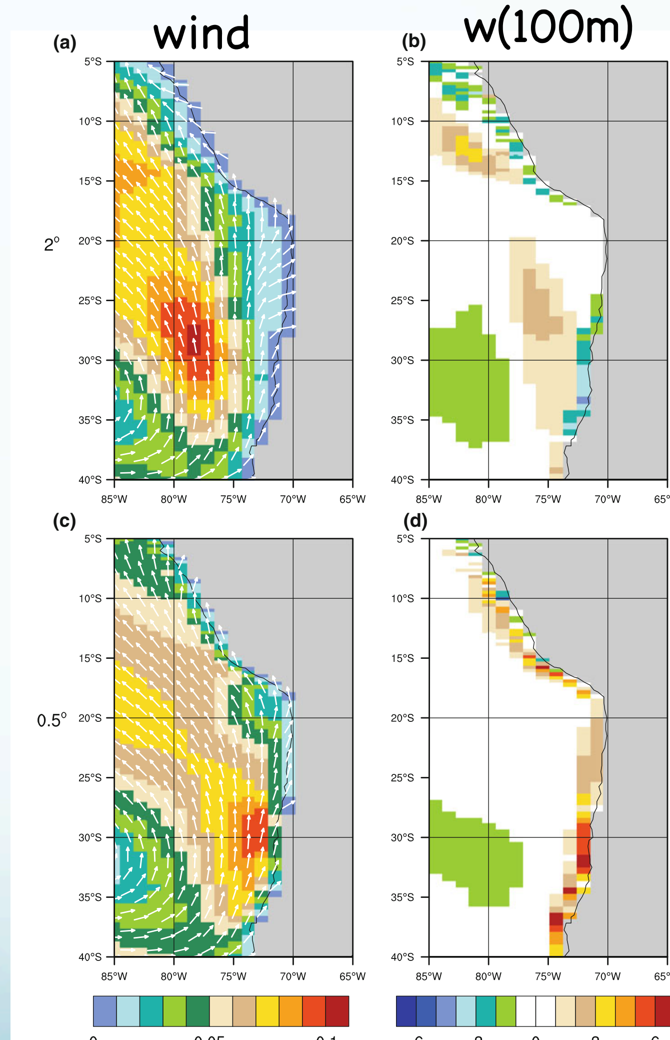
coupled CCSM3

coupled CCSM4

Forced ocean-ice CCSM4

Coupled CCSM4 SST bias as a function of atmospheric resolution

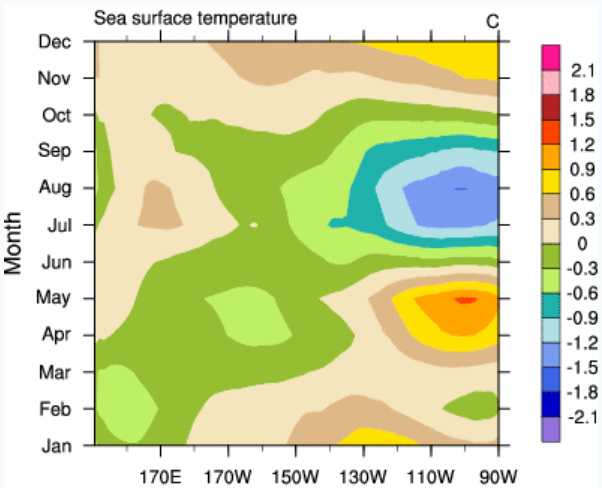




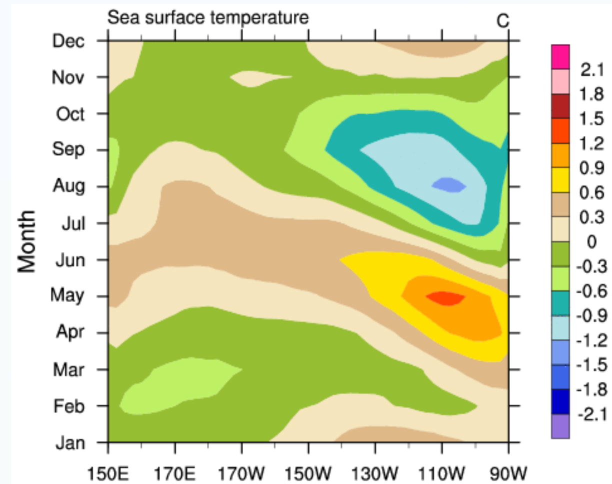
Gent et al., *Clim Dyn*, 2010

Annual Cycle of SST in the Equatorial Pacific

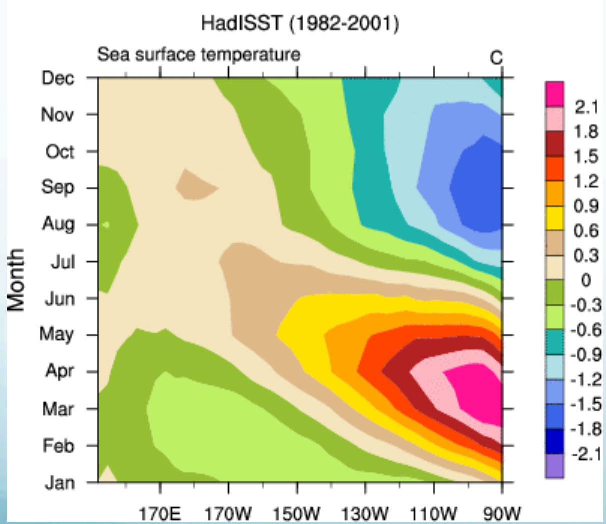
CCSM3



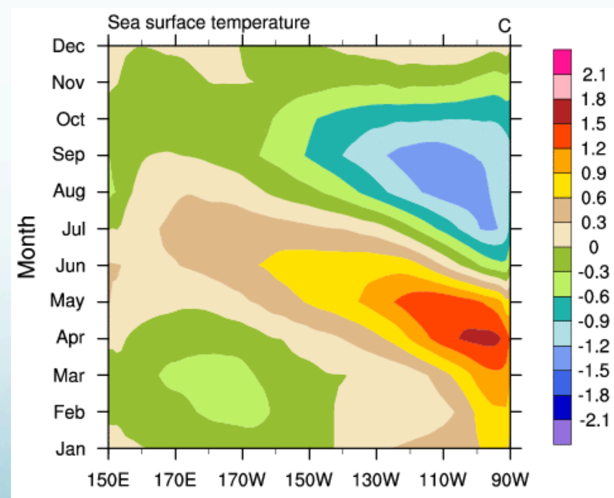
2° CCSM4



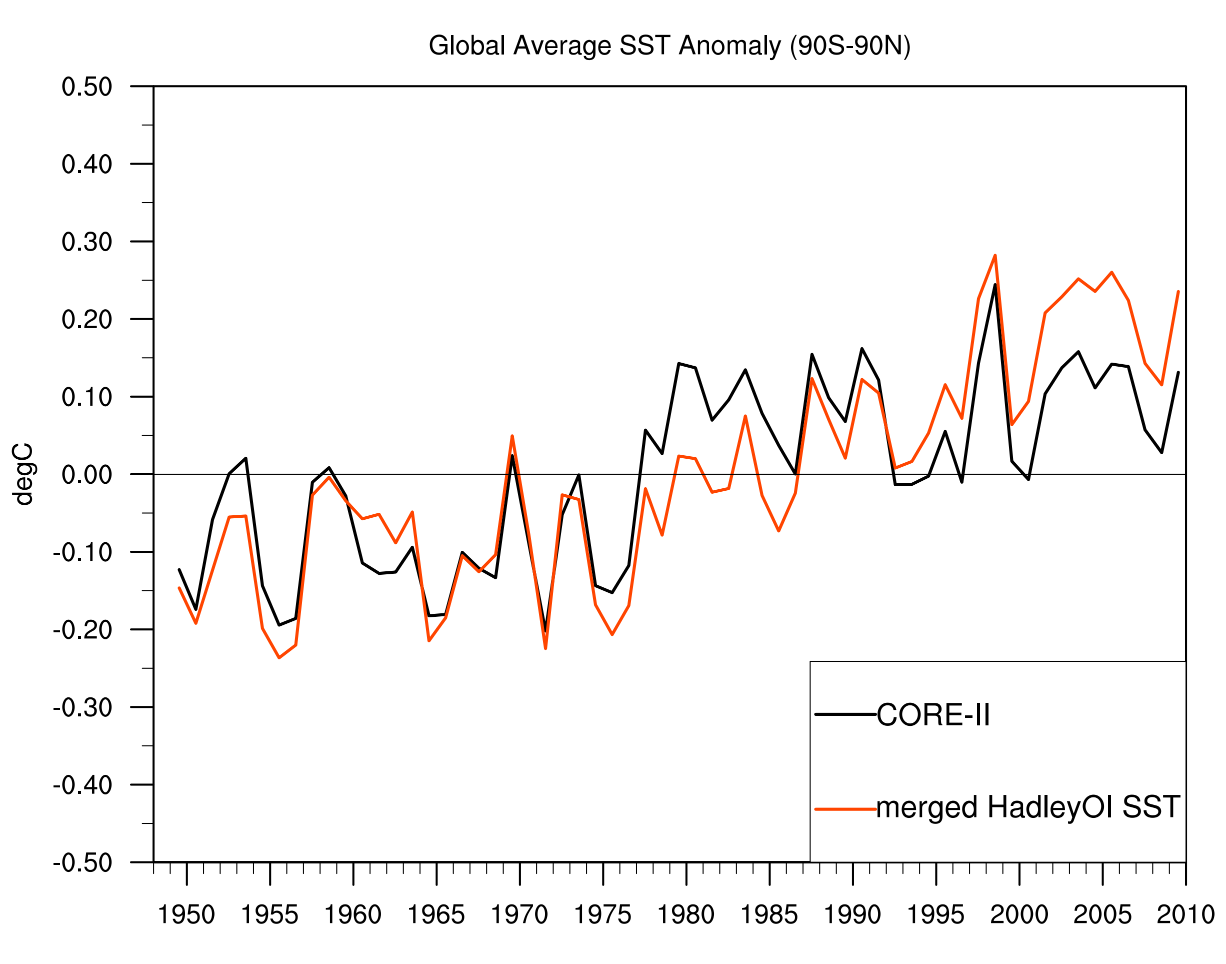
Observations



1° CCSM4



Interannual variability of Global mean SST



- CORE-forced ocean-ice hindcast simulation with 1° POP yields good reproduction of observed global SST change over late 20^{th} century

Interannual variability of North Atlantic Heat Content

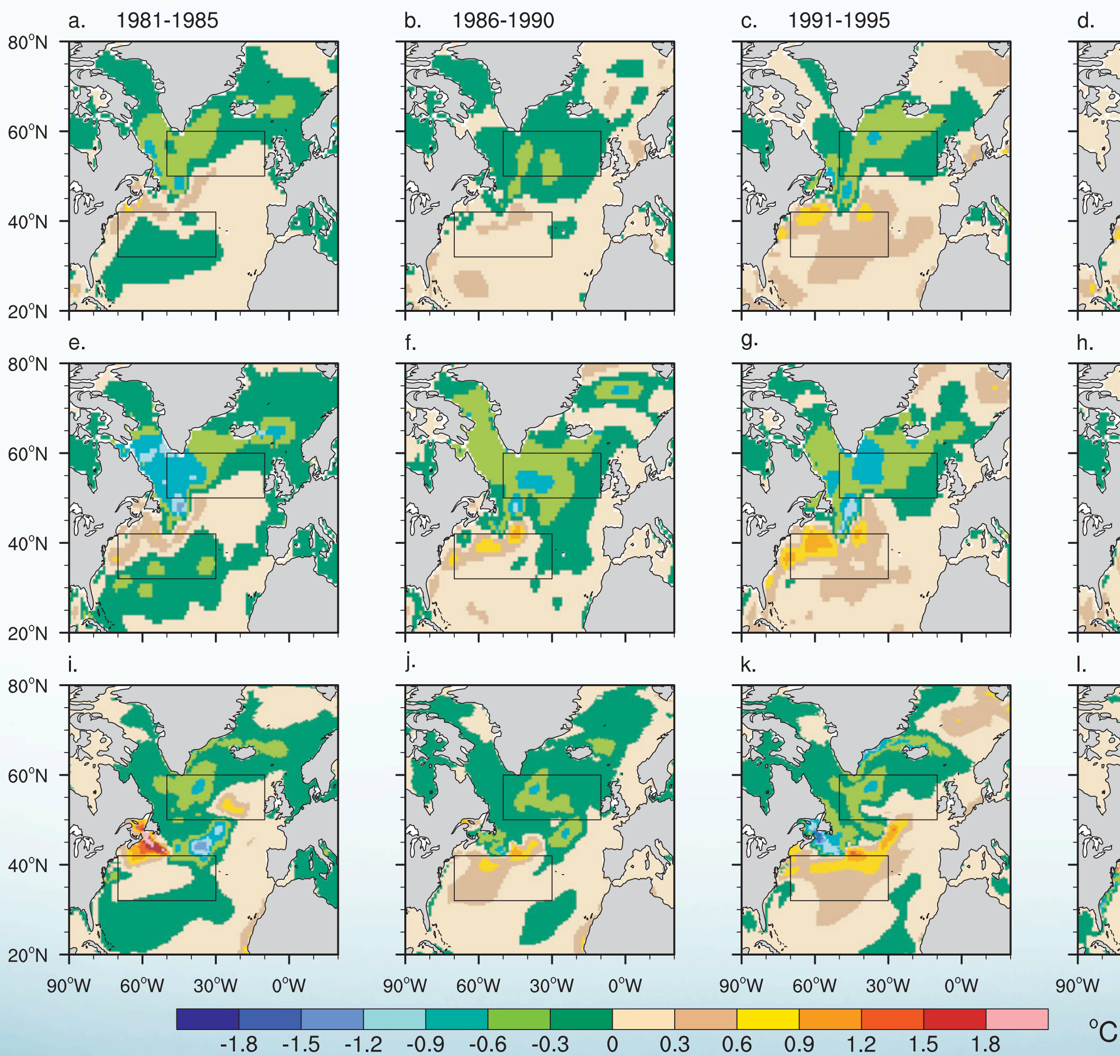
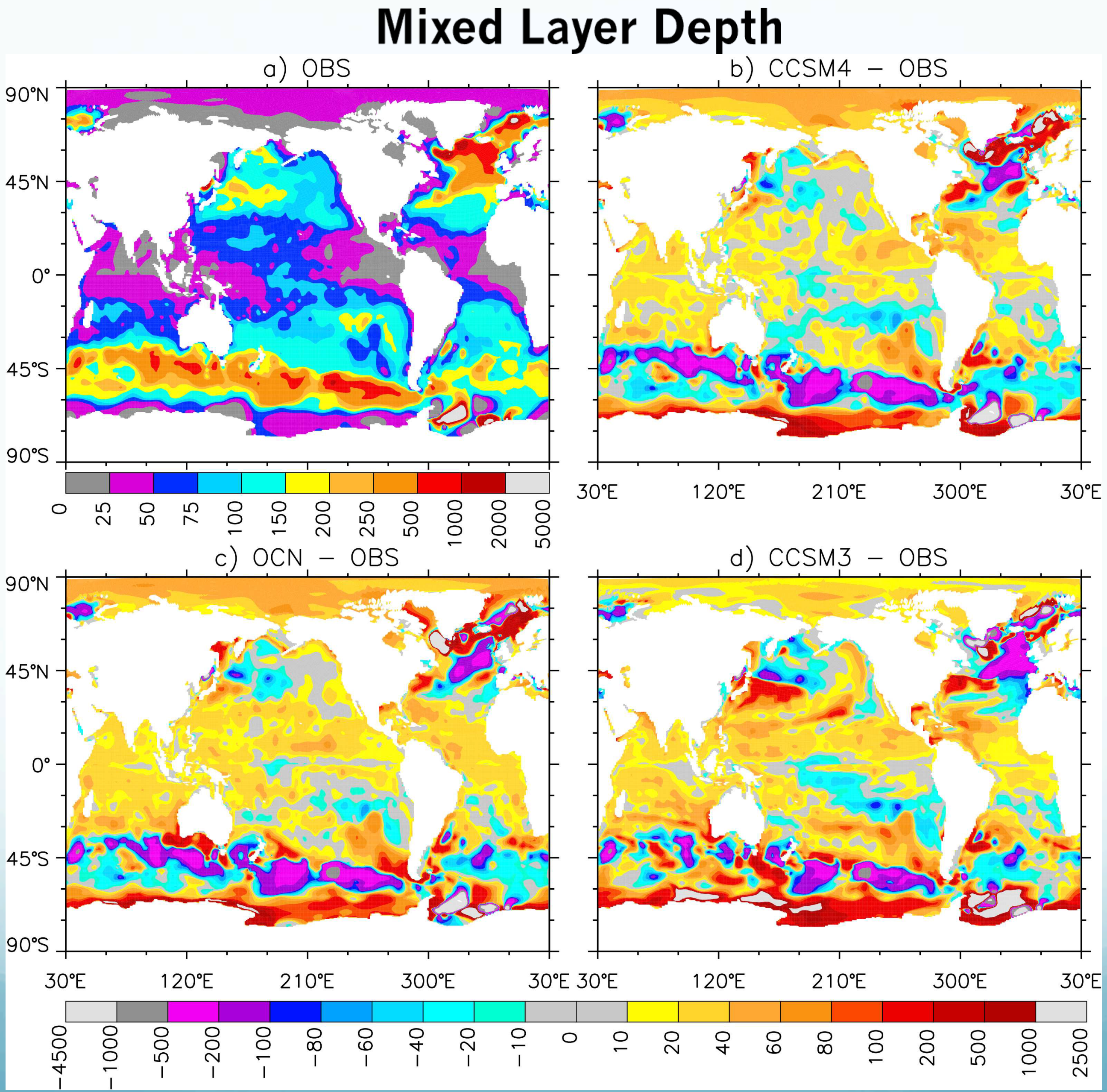


FIG. 1. Pentadal-mean heat content anomalies expressed as the 275-m depth-averaged temperature anomaly relative to 1957–90 climatology from (a)–(d) Ishii and Kimoto (2009), (e)–(h) Levitus et al. (2009), and (i)–(l) CORE-IA. The boxes in each panel demarcate the SPG (50°–10°W, 50°–60°N) and STG (70°–30°W, 32°–42°N) regions.

Yeager et al., *J Clim*, 2012

Questions?

Model Biases



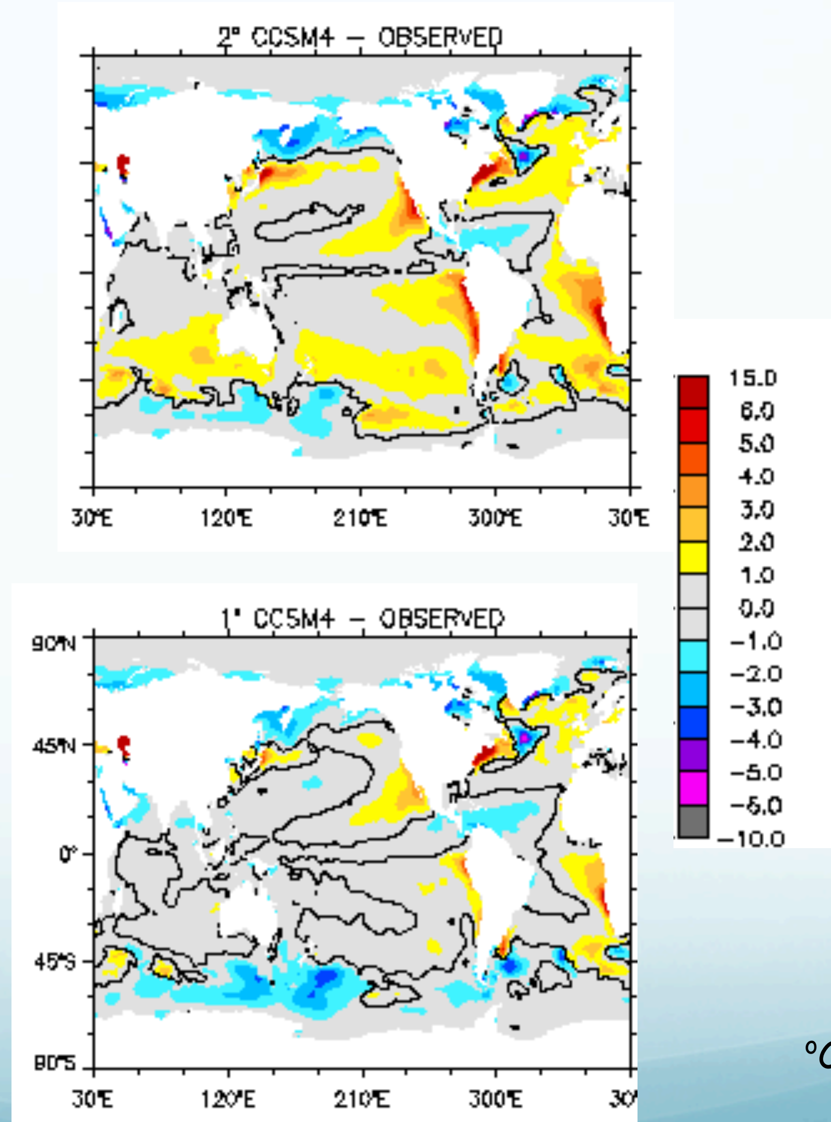
Model Biases

SST Differences from Observations

2° atmosphere

mean= 0.63°C

rms= 1.44°C



°C

1° atmosphere

mean= -0.01°C

rms= 1.07°C

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

Helpful Guides

http://www.cesm.ucar.edu/models/cesm1.2/pop2/

CESM Webpage for POP

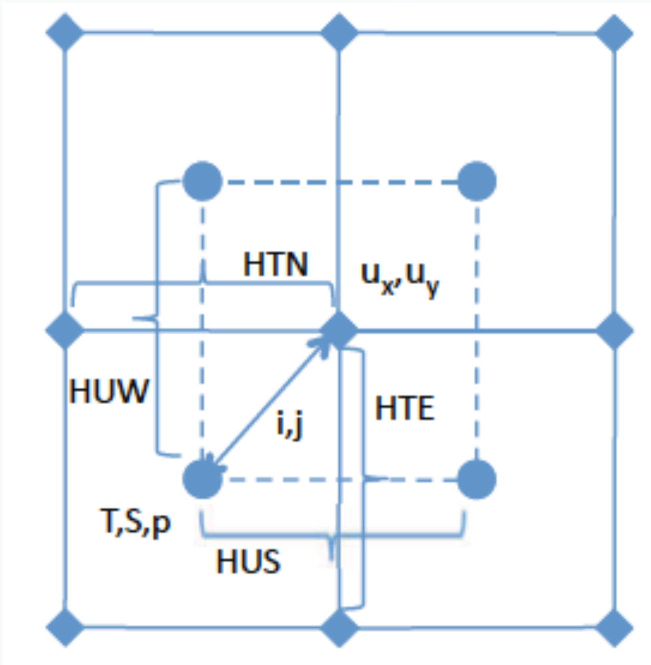
- POP2 User Guide
- Ocean Ecosystem Model User Guide
- POP Reference Manual
- Ocean Ecosystem Reference Manual

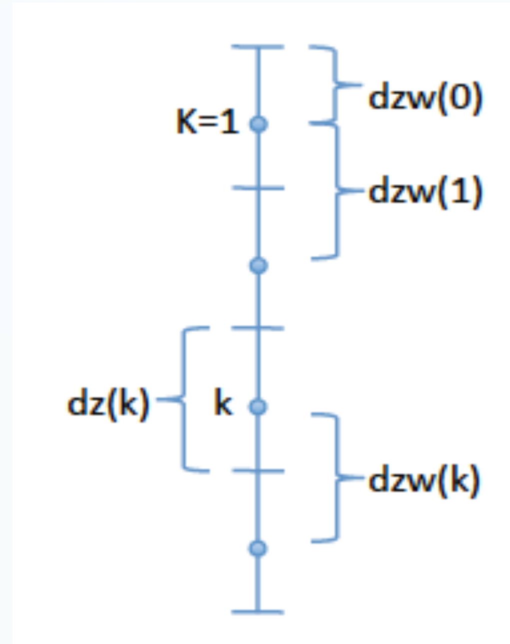
Friday's breakout session

Sea-ice, Ocean, and Land-ice

- Create and run a low-resolution ice-ocean
- Change the namelists
  - turn off the overflow parameterization
  - change snow and sea ice albedo
- Advanced exercises: changing wind stress forcing within the source code
- Data Analysis using nco commands and ncview

Central Advection Discretization





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

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

$$T^*_E = \tfrac{1}{2} * (T_{i+1,j} + T_{i,j})$$

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 ($\langle U \rangle$) plus vertically varying baroclinic (U')
- Fast moving gravity waves are filtered out, but that's okay because they don't impact climate

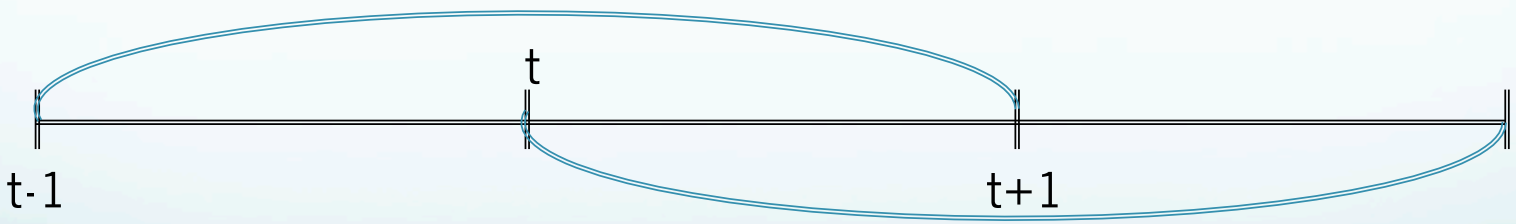
Barotropic and Baroclinic Flow

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

- $\langle U \rangle$: 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