Ocean Modeling I

The Parallel Ocean Program (POP)

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Topics

- Obstacles for ocean modeling
- Difference between ocean and atmosphere modeling
- What about the ocean is important to climate
- Equations of motion
- Ocean model grid
- Timescales of flow
- Advection schemes
- Air-sea coupling

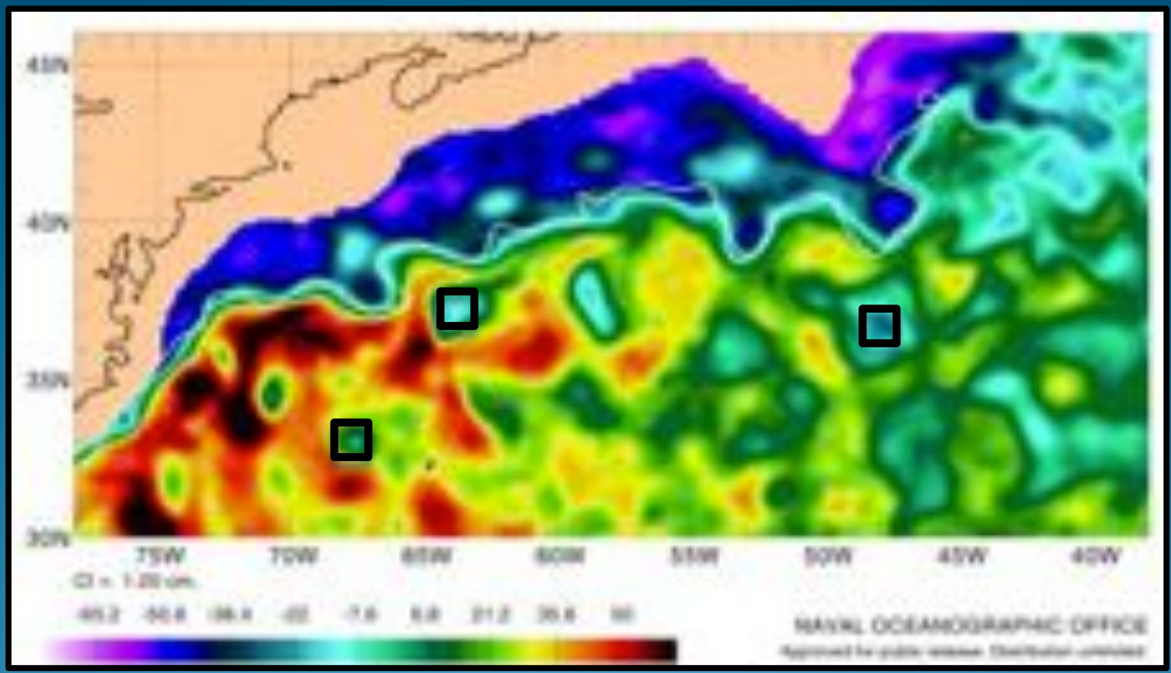
Ocean Modeling Obstacles

Irregular Domain

Ocean Modeling Obstacles

Spatial Scales of Flow

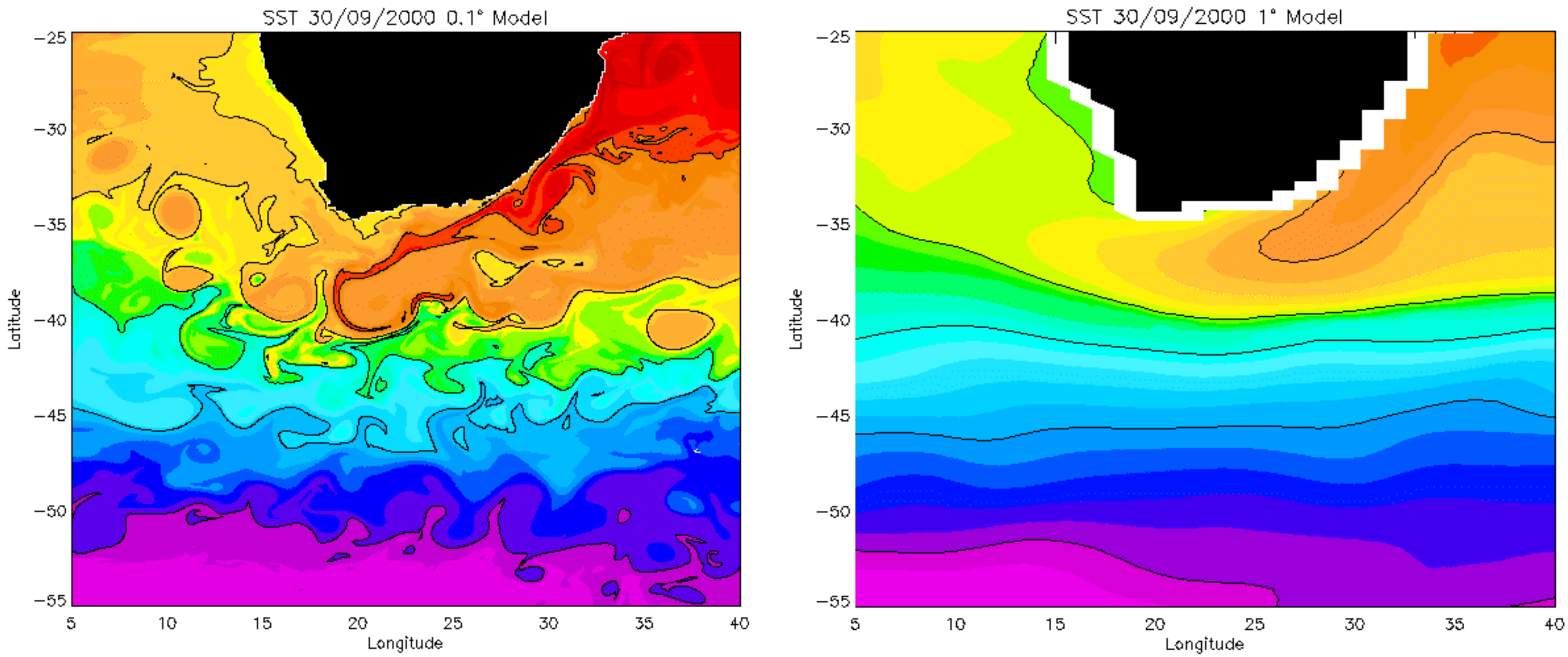
Eddy length scales <10km



Ocean Modeling Obstacles

Spatial Scales of Flow

Eddies



Ocean Modeling Obstacles

Equilibration Timescale

Scaling argument for deep adjustment time :

$$H^2/\kappa = (5000\text{m})^2 \;/\; (10^{-5}\ \text{m}^2/\text{s})$$
$$= O(10{,}000\ \text{years})$$

Bottom Line for Climate

-Equilibrium at eddy resolution can't be reached
- Must parameterize most energetic flow

Differences between Ocean and Atmosphere

- No change of state of seawater – makes it much easier. Just form ice when temperature <-1.8^{o}C
- The density change from top to bottom is much smaller – 1.02 to 1.04 gm/cc. This makes the Rossby radius much smaller – 100s to 10s km.
- The ocean is a 2 part density fluid (temp and salt).

Differences between Ocean and Atmosphere

- 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.
- Top to bottom lateral boundaries. Leads to WBC (heat transport) leaving little for eddies.
- The heat capacity of the ocean is much larger than the atmosphere. This makes it an important heat reservoir.
- The atmosphere contains more intrinsic variability than the ocean. The ocean is primarily forced by the atmosphere.

What is needed from the ocean to get climate change correct?

- Air-sea coupling (sst feedbacks).
- Need to get heat uptake correct.
- Need good representation of meridional transport of heat (and other properties): circulation, including the meridional overturning circulation (MOC).
- Representation of carbon cycle (storage of CO_2 (uptake), $CaCO_2$): Need a good vertical mixing scheme to get correct mixed layer depths and upwell nutrient rich water.

Primitive Equations

7 equations in 7 unknowns :

{u,v,w} ,	3 velocity components
θ,	potential temperature
S,	salinity
ρ,	density
p,	pressure

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

Primitive Equations

Momentum $$\frac{D}{Dt}\mathbf{u} + f\mathbf{k}\times\mathbf{u} + \nabla p = \nu_H\ \nabla^2\mathbf{u} + \nu_V\ \mathbf{u}_{zz}$$

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + \mathbf{u}\cdot\nabla + w\frac{\partial}{\partial z}$$

Hydrostatic $$p_z + g\rho/\rho_0 = 0$$

Continuity $$\nabla\cdot\mathbf{u} + w_z = 0$$

Temperature $$\frac{D}{Dt}\theta = \kappa_H\ \nabla^2\theta + \kappa_V\ \theta_{zz}$$

Salinity $$\frac{D}{Dt}S = \kappa_H\ \nabla^2 S + \kappa_V\ S_{zz}$$

Eqn of State $$\rho = \rho(p,\theta,S)$$

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

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

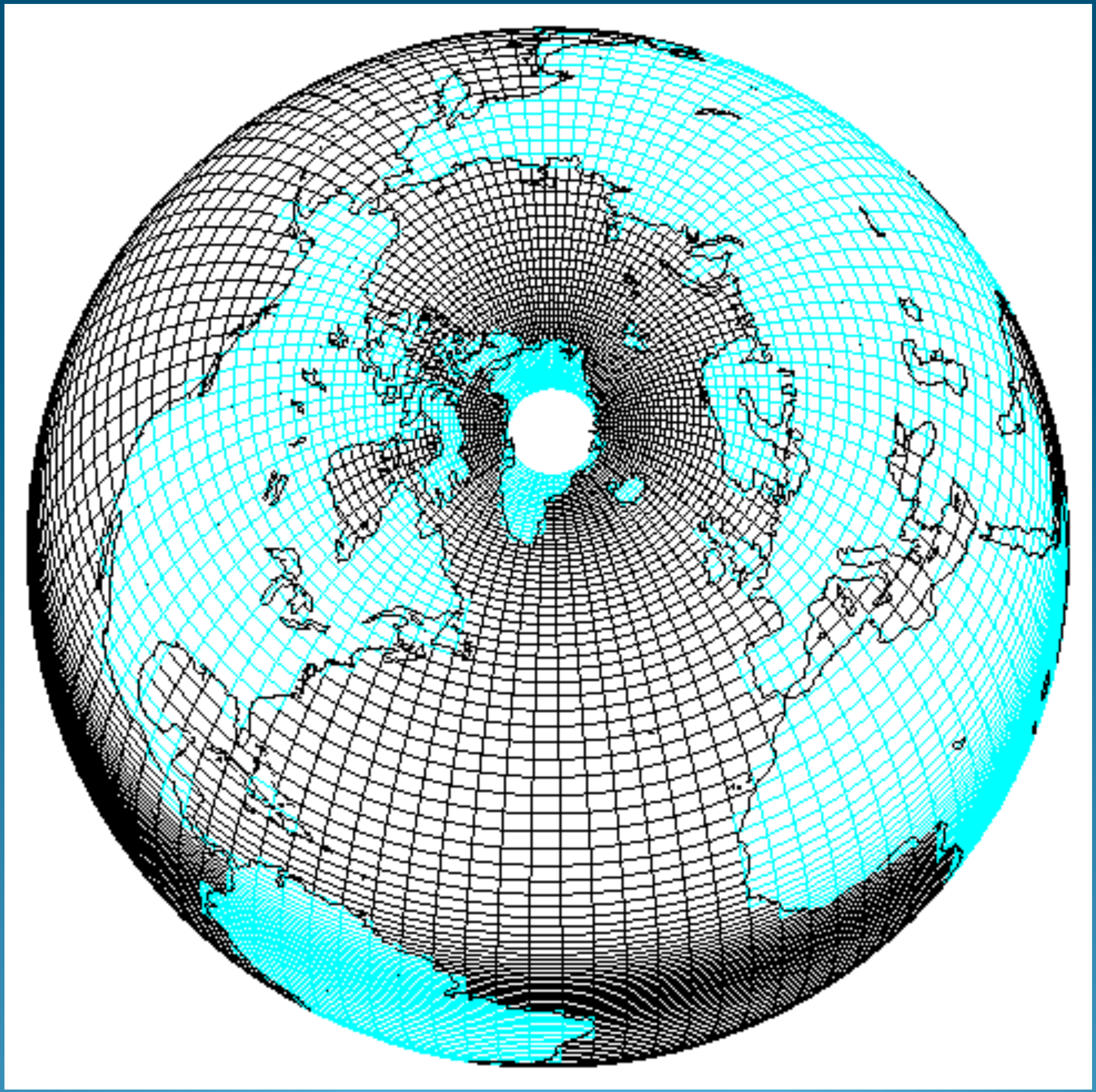
$$\mathcal{D}_V(\varphi) = \frac{\partial}{\partial z}\kappa\frac{\partial}{\partial z}\varphi,$$

Primitive Equations

- Continuity: can't deform seawater, so what flows into a control volume must flow out.
- Eqn of state: density dominated by T in upper tropical ocean; by S at high latitudes and deep.
- Hydrostatic: when ocean becomes statically unstable ($\rho_z > 0$) => vertical overturning should occur, but cannot because vertical acceleration has been excluded. This mixing is accomplished by a very large coefficient of vertical diffusion.

Model Grid

displaced pole



gx1
gx3

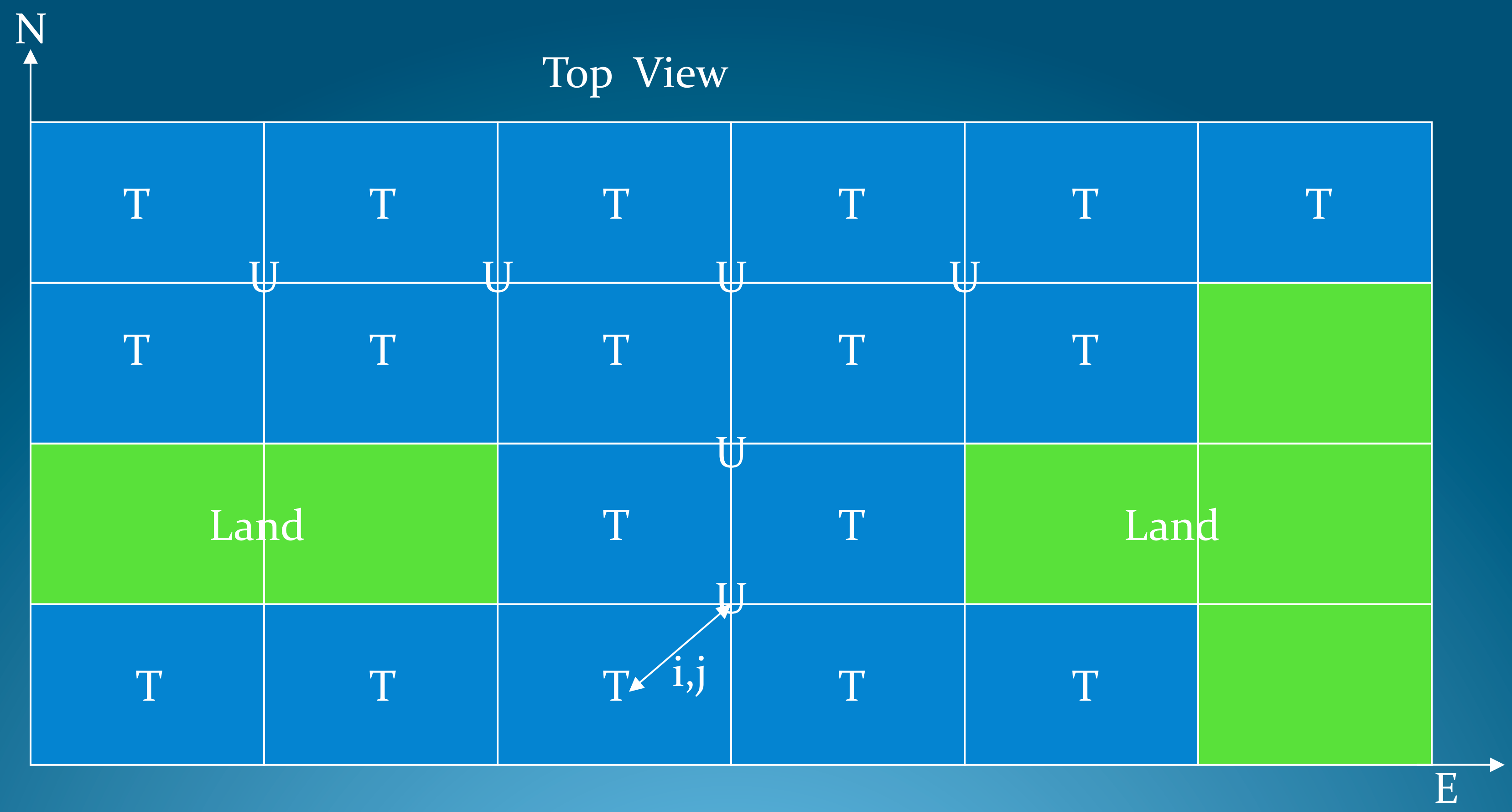
Model Grid

tripole

tx0.1

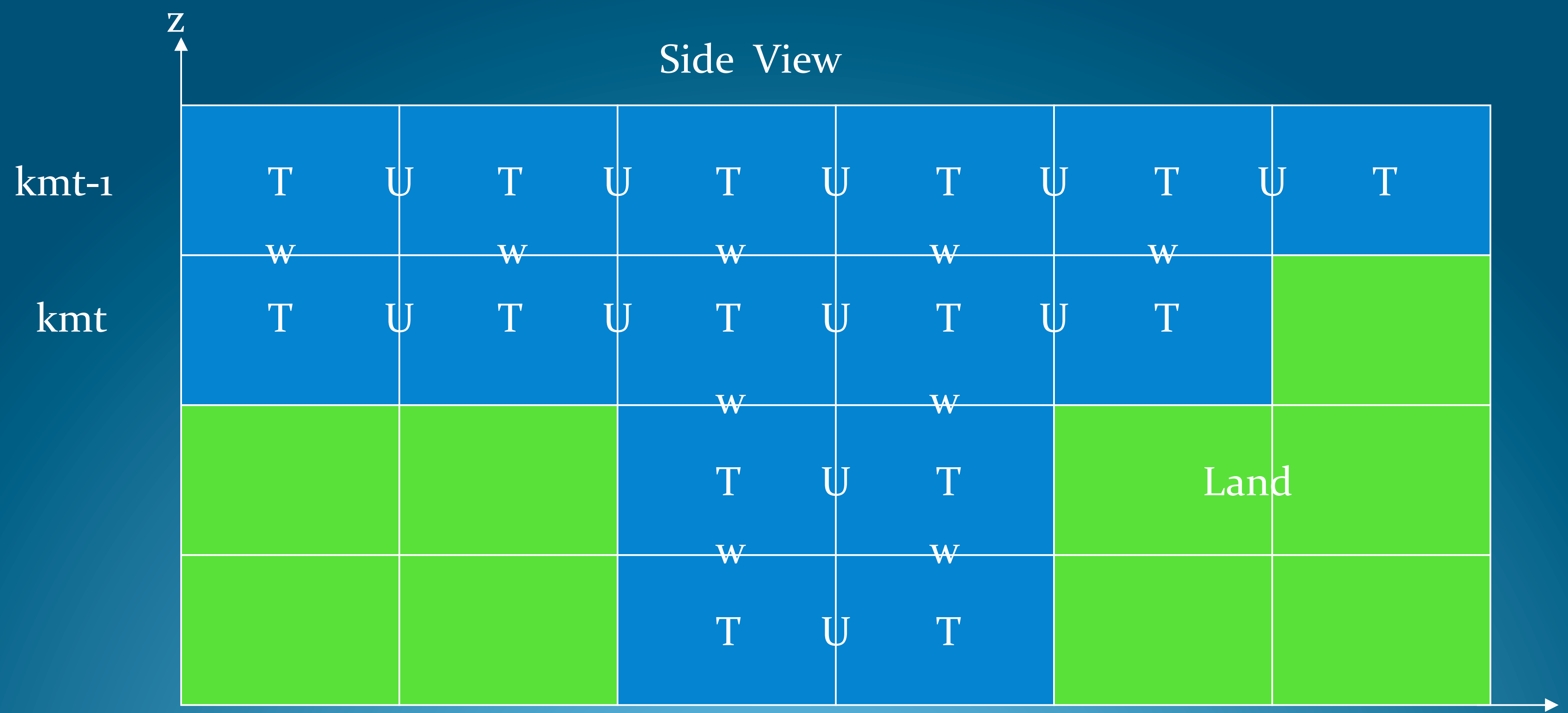
Model Grid

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

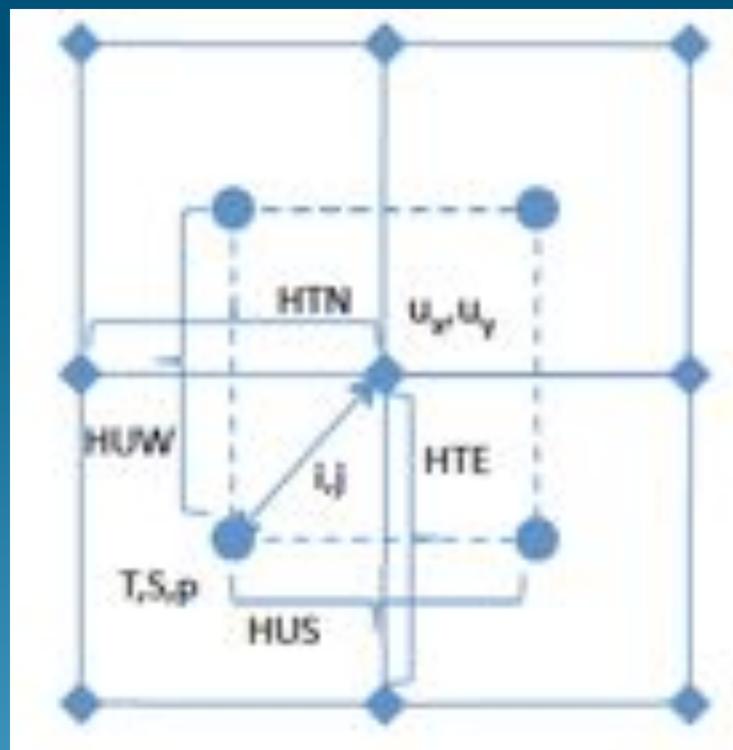


Model Grid

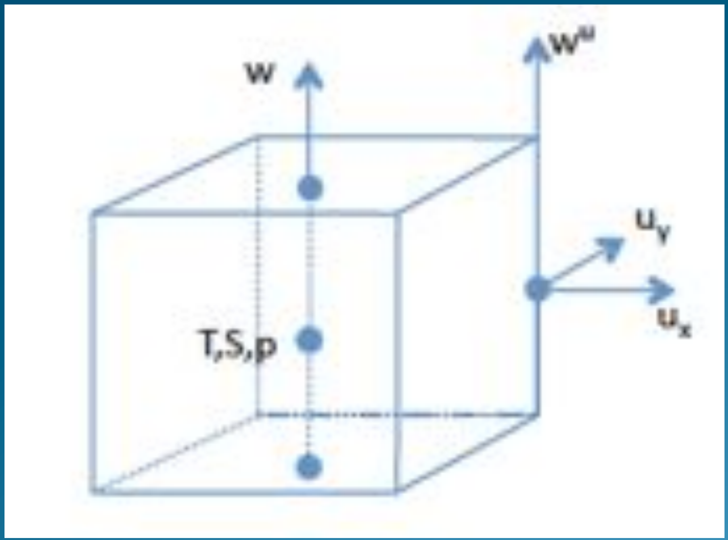
B-grid
T=tracer grid, U=velocity grid

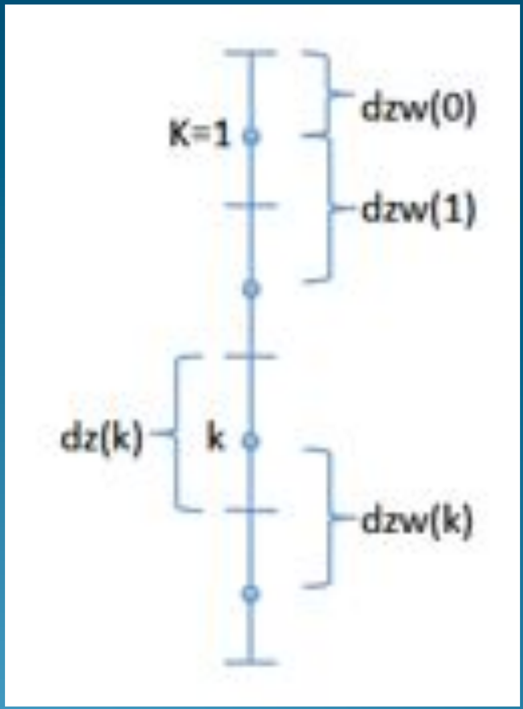


Model Grid



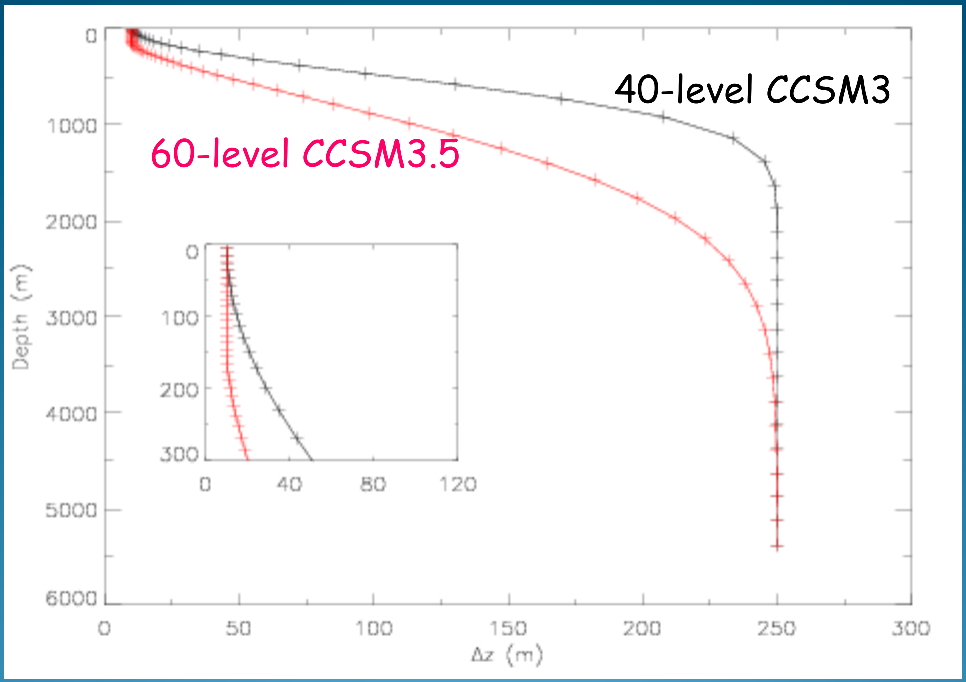
Model Grid





Model Grid

Vertical Grid



Baroclinic & Barotropic Flow

- Issue : CFL stability condition associated with fast surface gravity waves.
  - $u(\Delta t/\Delta x) \leq 1$
  - Barotropic mode $\sqrt{gH} \sim= 200m/s$

- Split flow into depth average barotropic plus vertically varying baroclinic

Baroclinic & Barotropic Flow

- Solve the vertically integrated momentum and continuity equations for the barotropic mode with new unknowns

η	sea surface height
<U>	depth averaged flow

- 1st internal mode in baroclinic equations is of the order 2m/s, which sets the model timestep.

Advection

- Conservative Flux Form $X = \{U, V, \theta, S, T\}$:
  >> $\mathbf{U} \cdot \nabla X = \partial_x (uX) + \partial_y (vX) + \partial_z (wX)$
  by adding $X \, \nabla \cdot \mathbf{U} = 0$.

- $X = \sum A_n \cos(\omega_n \lambda + \psi_n)$
  centered discretization ==>> dispersion errors leading to "false extrema" of X

- Breaks 2nd law of thermodynamics :
  heat flows from colder to hotter

Advection

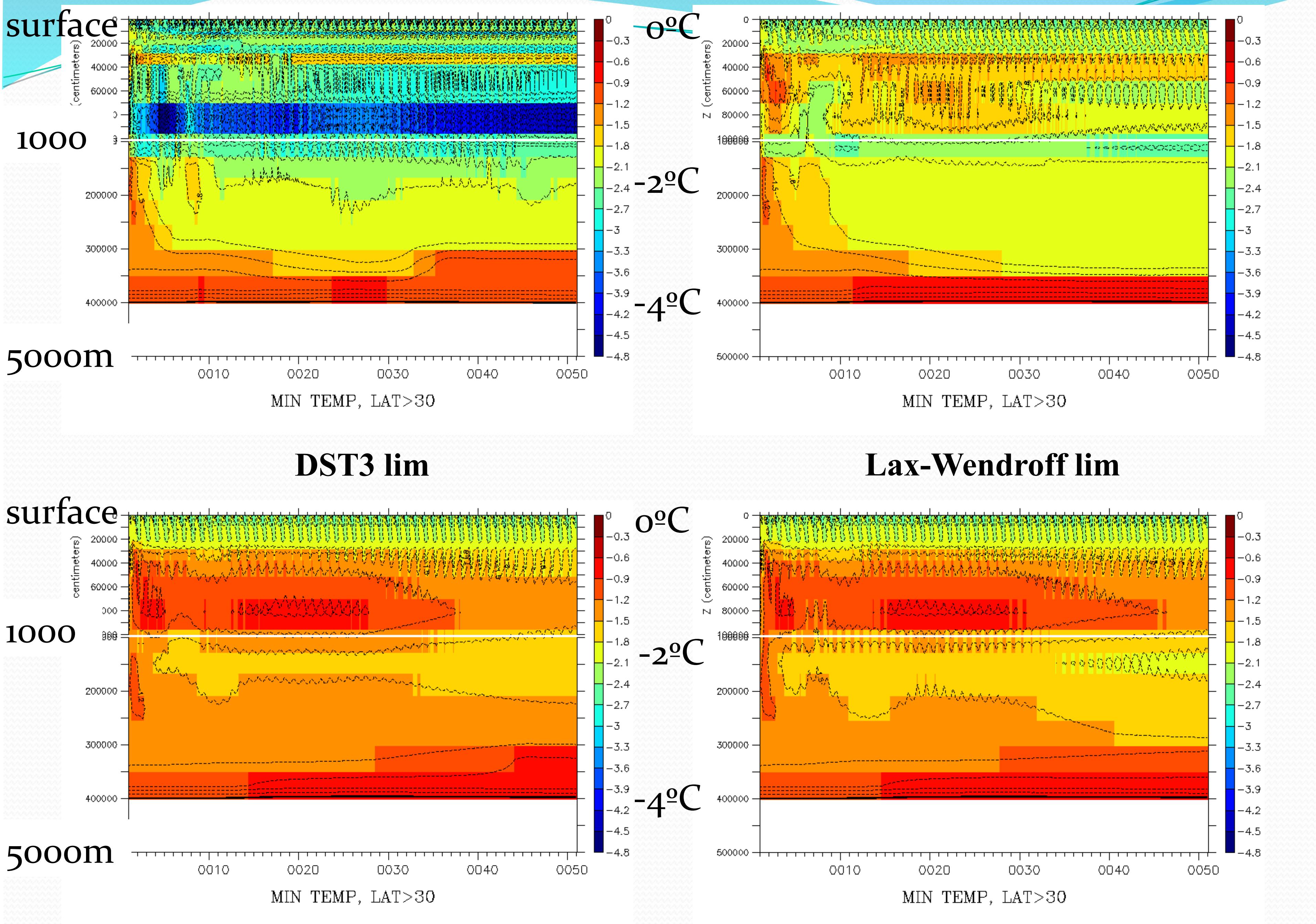
Options

- centered differencing: no diffusion, contains dispersion
- upwind3 scheme: diffusion and dispersion

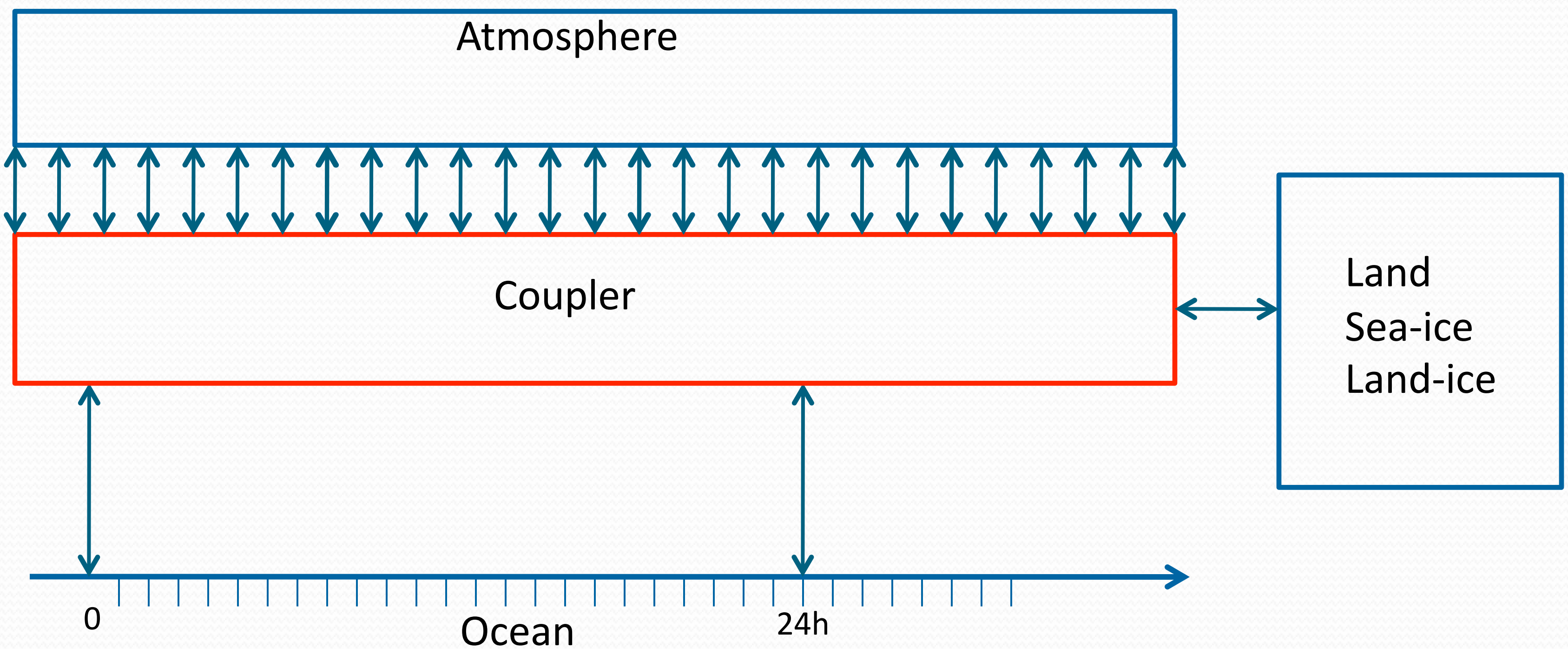
The goal: Reduce dispersion errors, evidenced by artificial extrema, while not creating excessive diffusive errors

- Current practice :
  - 3º : 2nd order centered (as for all momentum)
  - 1º : Upwind3 (QUICK)

CENT2 MIN θ north of 30°N **UPWIND3**

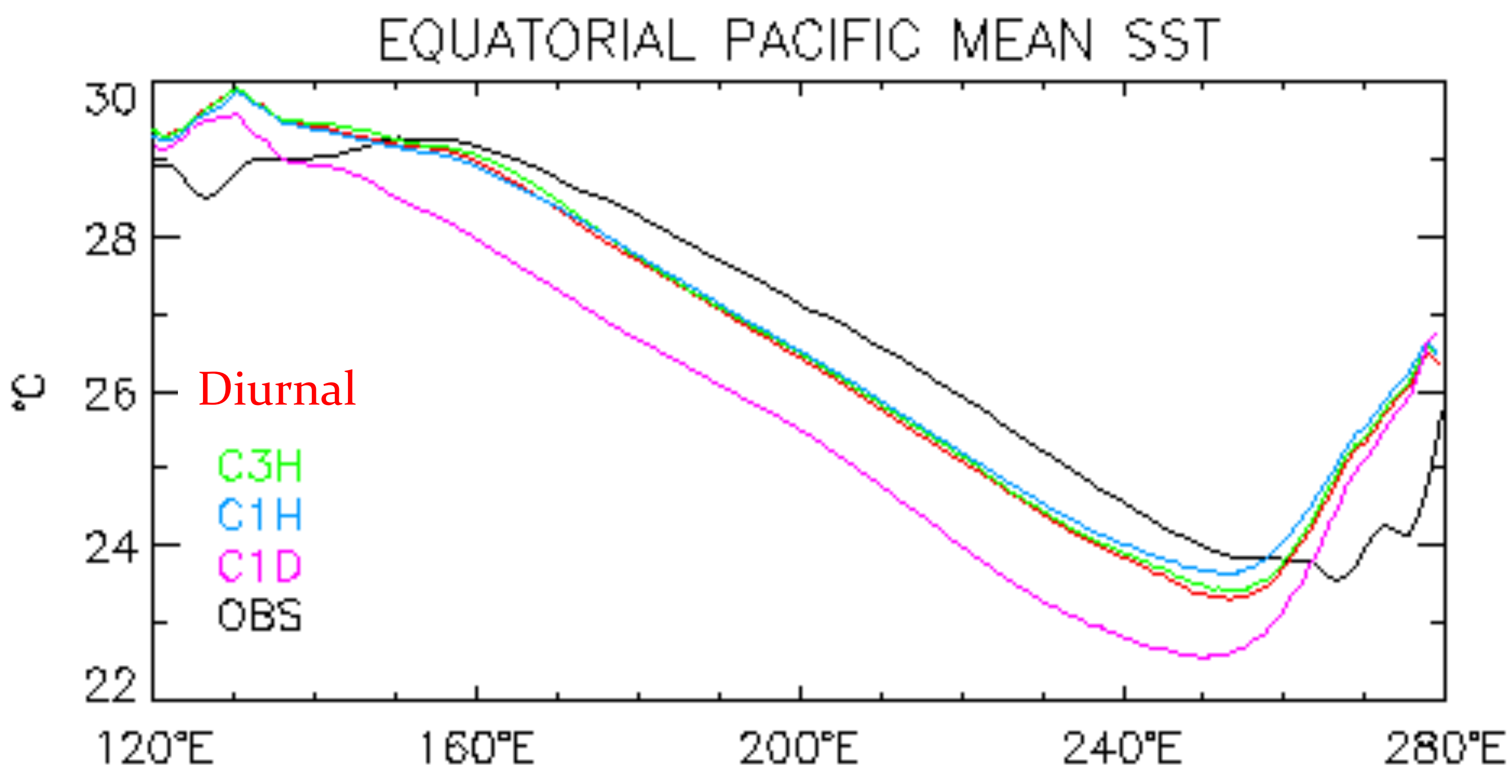


Air-Sea Coupling



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

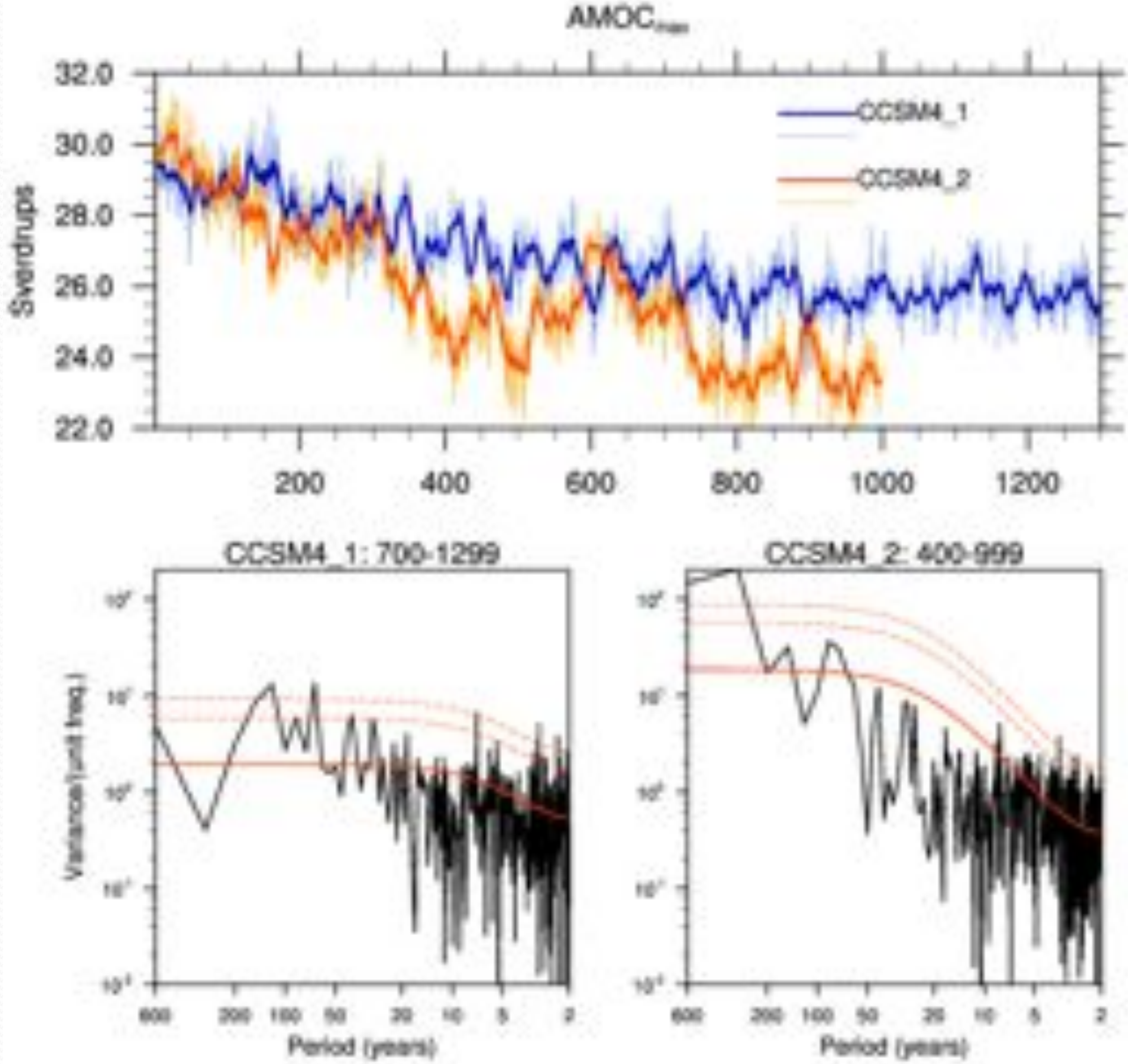
Air-Sea Coupling



Representation of the AMOC

CCSM4_1: 1º : blue line

CCSM4_2: 2º red line



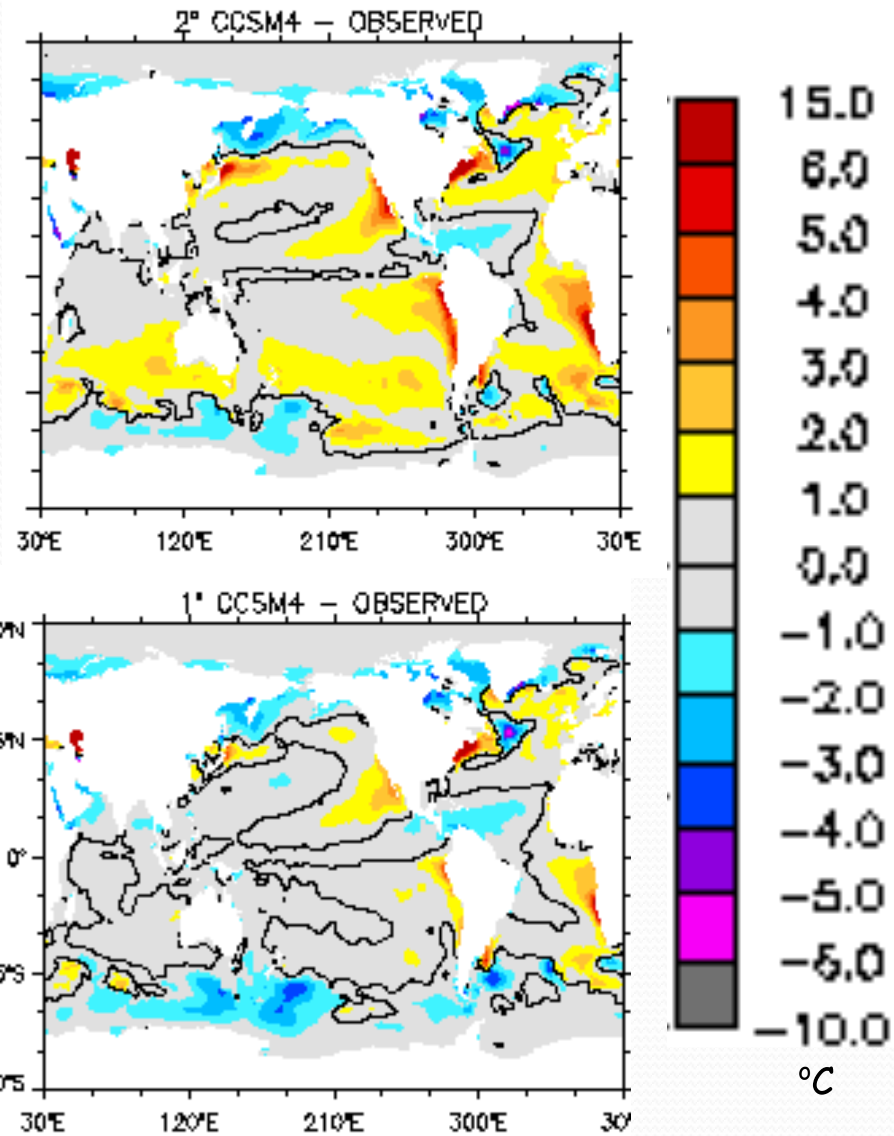
SST Differences from Observations

mean= 0.63°C

rms= 1.44°C

mean= -0.01°C

rms= 1.07°C

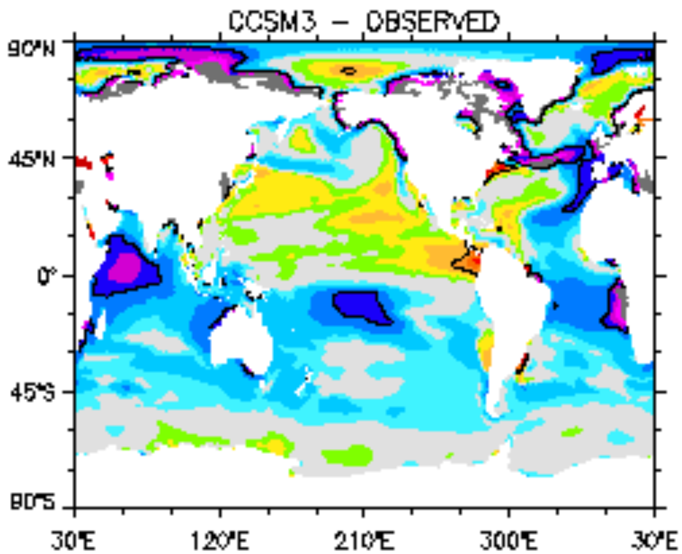


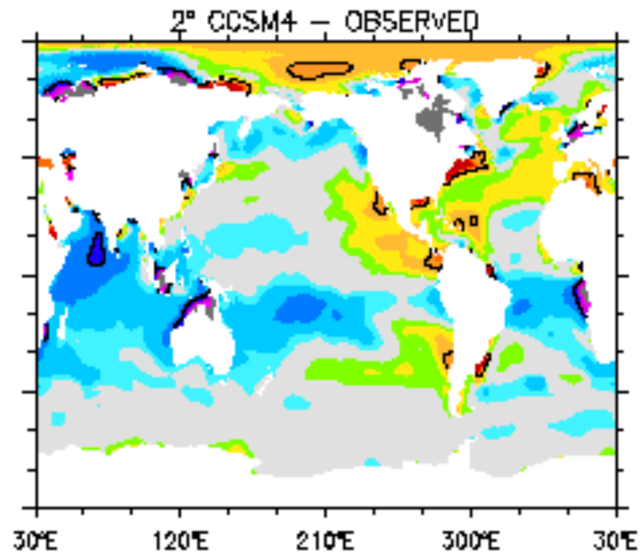
Obs: Levitus et al. (1998),
Steele et al. (2001)

Surface Salinity Differences from Observations

mean= -0.39

rms= 1.12



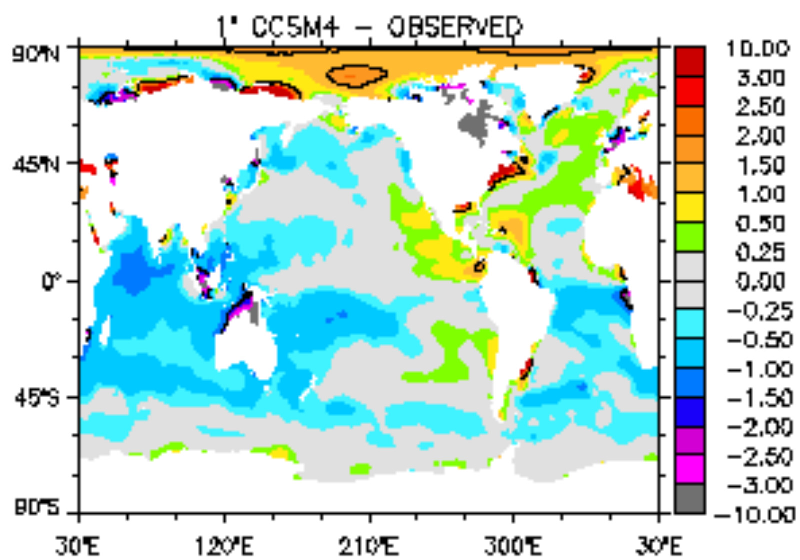


mean= -0.13

rms= 0.80

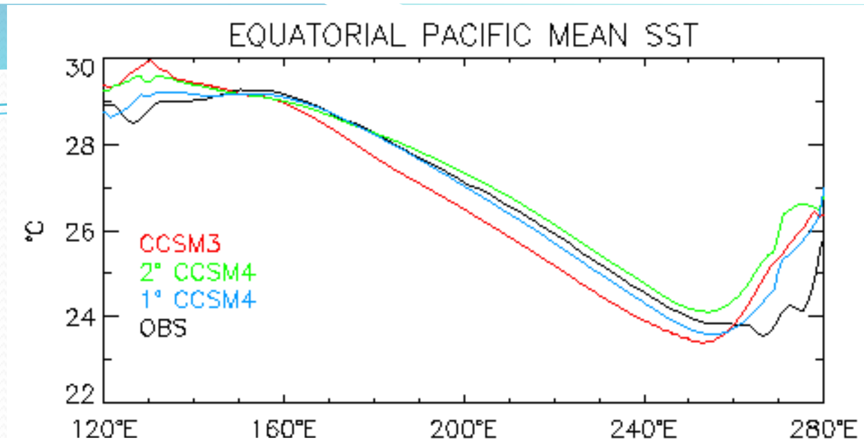
mean= -0.19

rms= 0.75

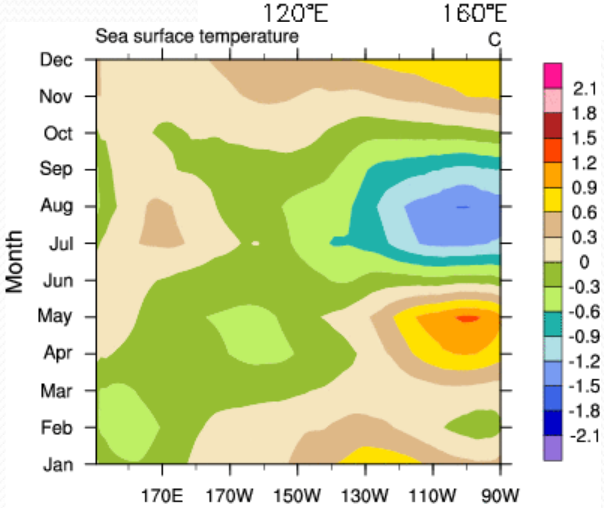


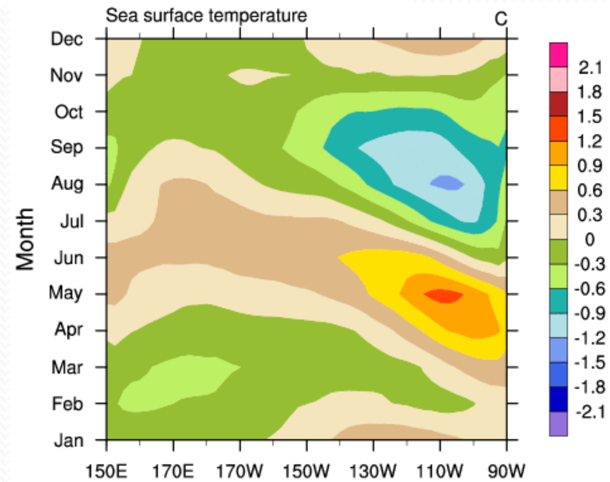
psu

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



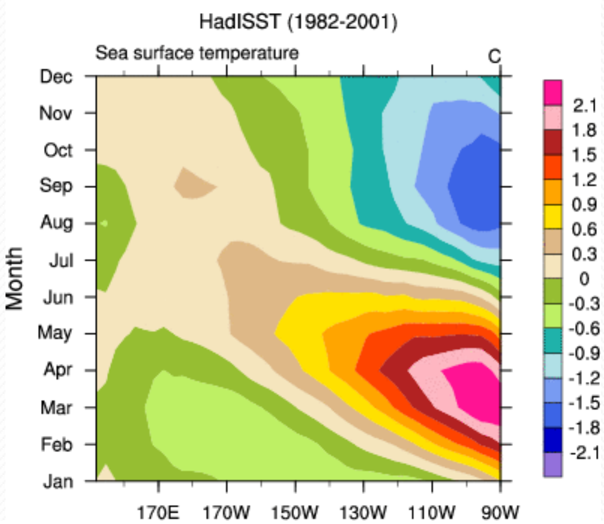
CCSM3

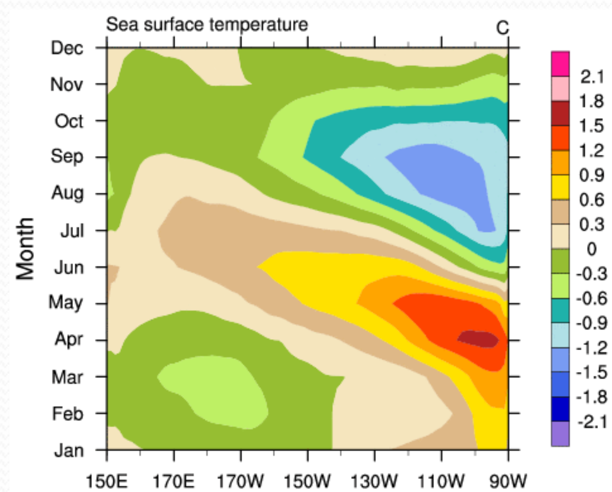




2° CCSM4

Observations





1° CCSM4

Summary

- Obstacles for ocean modeling
- What is different between ocean and atmosphere modeling
- What do we need to get right for climate
- Equations of motion: salinity, equation of state, and tracer equations
- POP Ocean model grid
- Barotropic and Baroclinic splitting
- Advection schemes
- Air-sea coupling: importance of coupling strategy and good forcing