Topics

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

- Parameterizations => next talk
Ocean Modeling Challenges

Irregular Domain
Ocean Modeling Challenges

- **FAST**
  - $O(100-1000 \text{ years/day})$

- **WORKHORSE (CLIMATE)**
  - $O(10-100 \text{ years/day})$

- **HI-RES**
  - $O(<<10 \text{ years/day})$
Ocean Modeling Challenges

**Spatial Scales of Flow**
Eddy length scales <10km
Ocean Modeling Challenges

Spatial Scales of Flow

Eddies
Equilibration Timescale

Scaling argument for deep adjustment time:

\[ \frac{H^2}{\kappa} = \frac{(4000 \text{ m})^2}{(2 \times 10^{-5} \text{ m}^2/\text{s})} = 0 (>20,000 \text{ years}) \]

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°C

• The density change from top to bottom is much smaller than the atmosphere – 1.02 to 1.04 gr/cm³. 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. 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 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.
Smith et al. (2010)
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:

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

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

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

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

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

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

\[
\mathcal{F}_V(\alpha) = \frac{\partial}{\partial z} \mu \frac{\partial}{\partial z} \alpha \tag{2.7}
\]
Model Equations

Continuity equation:
\[ \mathcal{L}(1) = 0 \]  
(2.8)

Hydrostatic equation:
\[ \frac{\partial p}{\partial z} = -\rho g \]  
(2.9)

Equation of state:
\[ \rho = \rho(\Theta, S, p) \to \rho(\Theta, S, z) \]  
(2.10)

Tracer transport:
\[ \frac{\partial}{\partial t} \varphi + \mathcal{L}(\varphi) = D_H(\varphi) + D_V(\varphi) \]  
(2.11)

\[ D_H(\varphi) = A_H \nabla^2 \varphi \]  
(2.12)

\[ D_V(\varphi) = \frac{\partial}{\partial z} \kappa \frac{\partial}{\partial z} \varphi, \]  
(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°

Equatorial refinement
(0.3° / 0.9°)

Ex. T62_gx3v7
Model Grid

tripole

tx0.1
Finite Differencing Grid

B-grid

Top view
Model Grid

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

Top View

N

Land

T

T

T

T

Land

T

T

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T
# Model Grid

**B-grid**

\[ T = \text{tracer grid}, \ U = \text{velocity grid} \]

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**Side View**

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**Ocean bottom**

- kmt-1
- kmt

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**Notes:**

- The grid represents the interaction between tracer and velocity fields.
- The **T** grid denotes tracer concentrations, while **U** represents velocity vectors.
- The **Ocean bottom** regions are demarcated by green shading, indicating the interface between the grid and the sea floor.
Model Vertical Grid

[Graph showing depth vs. Δz for CCSM3 and 60-level CCSM4]
Advection

Current practice:

- Momentum: centered differencing (2\textsuperscript{nd} order)
- Tracers: upwind\textsuperscript{3} scheme (3\textsuperscript{rd} order)
  - Concerned with keeping within physical limits
Central Advection Discretization

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

\[
\begin{align*}
  u_E(i) &= (u_{i,j} \text{DYU}_{i,j} + u_{i,j-1} \text{DYU}_{i,j-1})/(2\text{DXT}_{i,j}) \\
  u_W(i) &= u_E(i - 1) \\
  v_N(j) &= (v_{i,j} \text{DXU}_{i,j} + v_{i-1,j} \text{DXU}_{i-1,j})/(2\text{DXT}_{i,j}) \\
  v_S(j) &= (v_{i,j-1} \text{DXU}_{i,j} + v_{i-1,j-1} \text{DXU}_{i-1,j})/(2\text{DXT})
\end{align*}
\]

\[
T^*_E = \frac{1}{2} \times (T_{i+1,j} + T_{i,j})
\]
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 \( \sqrt{gH} \sim 200 \text{ m/s} \)
- 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

\[ U = \langle U \rangle + U' \]

- \( \langle U \rangle \): 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
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)
  - Cooordinated Ocean-ice Reference Experiments (CORE)
    - Large and Yeager, NCAR Technical Note (2004)
    - Large and Yeager, Climate Dynamics (2009)
- Interannual forcing (IAF; 1948-2007)
- Normal Year Forcing (NYF): good for model testing and parameterization impact studies
Air-Sea Coupling

Atmosphere

Coupler

Land
Sea-ice
Land-ice

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

Air-Sea Coupling

Diurnal

- CCSM3
- C3H
- C1H
- C1D
- OBS
Model Biases
SST Differences from Observations

2° atmosphere
mean = 0.63°C
rms = 1.44°C

1° atmosphere
mean = -0.01°C
rms = 1.07°C

Obs: Levitus et al. (1998), Steele et al. (2001)
Model Biases
SST and Salinity Differences from Observations

CCSM3

CCSM4

Ocean – sea-ice coupled (G compset)
Model Biases

Annual Cycle of SST in the Equatorial Pacific
Model Biases

Mixed Layer Depth

a) OBS

b) CCSM4 - OBS

c) OCN - OBS

d) CCSM3 - OBS
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
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