Lecture 10: Ocean Circulation

- Ekman Transport
- Ekman Pumping
- Wind-Driven Circulation
Basic Ocean Structures

- **Upper Ocean (~100 m)**
  Shallow, warm upper layer where light is abundant and where most marine life can be found.

- **Deep Ocean**
  Cold, dark, deep ocean where plenty supplies of nutrients and carbon exist.

Warm up by sunlight!

No sunlight!
Basic Ocean Current Systems

(from “Is The Temperature Rising?”)
Vertical Structure of Ocean

Mixed Layer: T and S well mixed by winds

Thermocline: large gradient of T and S

Deep Ocean: T and S independent of height
- cold
- salty
- high nutrient level

(from Climate System Modeling)
Mixed Layer Processes

- The depth of the mixed layer is determined by (1) the rate of buoyancy generation and (2) the rate of kinetic energy supply.
- The atmosphere can affect the mixed layer through three processes: heating, wind forcing, and freshening (P-E).
- The global-average depth of the mixed layer is about 70 m.
- The heat capacity of the mixed layer is about 30 times the heat capacity of the atmosphere.

(from *Global Physical Climatology*)
Seasonal Variation of Mixed Layer

- Summer: warm and thin.
- Winter: cold and deep (several hundred meters).

(from *Global Physical Climatology*)
Two Circulation Systems

(Figure from The Earth System)
Global Surface Currents

(from Climate System Modeling)
Six Great Current Circuits in the World Ocean

- 5 of them are geostrophic gyres:
  - North Pacific Gyre
  - South Pacific Gyre
  - North Atlantic Gyre
  - South Atlantic Gyre
  - Indian Ocean Gyre

- The 6th and the largest current:
  - Antarctic Circumpolar Current
    (also called West Wind Drift)

(Figure from *Oceanography* by Tom Garrison)
Characteristics of the Gyres

- **Currents are in geostropic balance**
- **Each gyre includes 4 current components:**
  - two boundary currents: western and eastern
  - two transverse currents: eastward and westward

**Western boundary current (jet stream of ocean)**
- the fast, deep, and narrow current moves warm water polarward (transport ~50 Sv or greater)

**Eastern boundary current**
- the slow, shallow, and broad current moves cold water equatorward (transport ~ 10-15 Sv)

**Trade wind-driven current**
- the moderately shallow and broad westward current (transport ~ 30 Sv)

**Westerly-driven current**
- the wider and slower (than the trade wind-driven current) eastward current

Volume transport unit:

1 sv = 1 Sverdrup = 1 million m$^3$/sec

(the Amazon river has a transport of ~0.17 Sv)
Major Current Names

- **Western Boundary Current**
  - Gulf Stream (in the North Atlantic)
  - Kuroshio Current (in the North Pacific)
  - Brazil Current (in the South Atlantic)
  - Eastern Australian Current (in the South Pacific)
  - Agulhas Current (in the Indian Ocean)

- **Trade Wind-Driven Current**
  - North Equatorial Current
  - South Equatorial Current

- **Eastern Boundary Current**
  - Canary Current (in the North Atlantic)
  - California Current (in the North Pacific)
  - Benguela Current (in the South Atlantic)
  - Peru Current (in the South Pacific)
  - Western Australian Current (in the Indian Ocean)

- **Westerly-Driven Current**
  - North Atlantic Current (in the North Atlantic)
  - North Pacific Current (in the North Pacific)
Gulf Stream

A river of current
Jet stream in the ocean

- Speed = 2 m/sec
- Depth = 450 m
- Width = 70 Km
- Color: clear and blue

(Figure from *Oceanography* by Tom Garrison)
Surface Current – Geostrophic Gyre

- **Mixed Layer**
  - Currents controlled by frictional force + Coriolis force
  - wind-driven circulation
  - Ekman transport (horizontal direction)
  - convergence/divergence
  - downwelling/upwelling at the bottom of mixed layer

- **Thermocline**
  - downwelling/upwelling in the mixed layer
  - pressure gradient force + Coriolis force
  - geostrophic current
  - Sverdrup transport (horizontal)
Step 1: Surface Winds

**Figure 9.1** Winds, driven by uneven solar heating and Earth’s spin, drive the movement of the ocean’s surface currents. The prime movers are the powerful westerlies and the persistent trade winds (easterlies).

**Figure 9.2** A combination of four forces—surface winds, the sun’s heat, the Coriolis effect, and gravity—circulates the ocean surface clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere, forming gyres.

(Figure from *Oceanography* by Tom Garrison)
Winds and Surface Currents

(Figure from The Earth System)
Step 2: Ekman Layer
(frictional force + Coriolis Force)

(Figure from Oceanography by Tom Garrison)
Ekman Spiral – A Result of Coriolis Force

(Figure from *The Earth System*)
Formula for Ekman Transport

\[
U_E = \int_{-\infty}^{0} u_E \, dz = \frac{\tau_y}{\rho_0 f}; \quad V_E = \int_{-\infty}^{0} v_E \, dz = -\frac{\tau_x}{\rho_0 f}
\]
How Deep is the Ekman Layer?

\[ D \propto \left(\frac{\nu}{f}\right)^{1/2} \]

\( \nu \) = vertical diffusivity of momentum

\( f \) = Coriolis parameter = \( 2\Omega \sin \phi \)

Fig. 4.4 (a) Vertical distribution of temperature and salinity at 50°N., 145°W. in early September, 1977. The solid lines are before a storm and the dotted lines are after a storm, which depict the vertical mixing above the seasonal thermocline. The main thermocline, or pycnocline in this area is between 110 m and 160 m depth.

(b) Time-averaged velocity for a 25 day summer period at an open ocean site southwest of Bermuda. Current meter measured velocity is referenced to 70 m. The topmost dashed vector is the time-averaged wind stress (Price et al., 1986).
Ekman Transport

(Figure from *The Earth System*)
Step 3: Geostrophic Current
(Pressure Gradient Force + Coriolis Force)

NASA-TOPEX Observations of Sea-Level Height

(from Oceanography by Tom Garrison)
Ekman Transport $\rightarrow$ Convergence/Divergence

(Figure from *The Earth System*)

- Surface wind + Coriolis Force
- Ekman Transport
- Convergence/divergence (in the center of the gyre)
- Pressure Gradient Force
- Geostrophic Currents

Thermocline

Mass convergence $\rightarrow$

Geostrophic current

Surface layer thickens

Mass convergence

Upwelling

Mass divergence $\rightarrow$

Surface layer thins

Divergence zone

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Geostrophic Current

Forces

- Westerly winds
- Eastward-flowing current
- Ekman transport causes water to pile up in the gyre
- Northeast trade winds

Geostrophic Gyre Currents

- Clockwise gyre resulting from geostrophic flow

(Figure from *The Earth System*)
Sverdrup Transport

\[ V = \hat{k} \cdot \frac{\nabla \times \tau}{\beta} \]

- Continuity equation for an incompressible flow:
  \[
  \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0
  \]

- Assume the horizontal flows are geostrophic:
  \[
  \frac{\partial u_g}{\partial x} + \frac{\partial v_g}{\partial y} + \frac{\partial w}{\partial z} = 0
  \]

- Replace the geostrophic flow pressure gradients:
  \[
  f u_g = -\frac{1}{\rho} \frac{\partial P}{\partial y}
  \]
  \[
  f v_g = \frac{1}{\rho} \frac{\partial P}{\partial y}
  \]

- The continuity equation becomes:
  \[
  -\frac{\beta}{f} v_g + \frac{\partial w}{\partial z} = 0 \quad \Rightarrow \quad \beta v_g = f \frac{\partial w}{\partial z}
  \]

Ekman layer pumping
- vertical depth decreases
- move equatorward to conserve absolute vorticity.

Ekman layer suction
- vertical depth increases
- move poleward to conserve absolute vorticity.
Continuity equation for an incompressible flow:
\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0
\]

Assume the horizontal flows are geostrophic:
\[
\frac{\partial u_g}{\partial x} + \frac{\partial v_g}{\partial y} + \frac{\partial w}{\partial z} = 0
\]

Replace the geostrophic flow pressure gradients:
\[
f u_g = -\frac{1}{\rho} \frac{\partial P}{\partial y}
\]
\[
f v_g = \frac{1}{\rho} \frac{\partial P}{\partial y}
\]

The continuity equation becomes:
\[
-\frac{\beta}{f} v_g + \frac{\partial w}{\partial z} = 0
\]

Integrate the equation from the bottom of the upper ocean \(D_w\) to the bottom of the Ekman layer \(D_E\):
\[
\begin{aligned}
\beta \int_{z=-D_E}^{z=-D_w} v \, dz &= f \left[ w_E - w(-D_w) \right]
\end{aligned}
\]

Ekman pumping \(w_E\) is related to the convergence of the Ekman transport:
\[
w(-D_w) \frac{\partial}{\partial x} \left( \frac{\tau_y}{\rho f} \right) - \frac{\partial}{\partial y} \left( \frac{\tau_x}{\rho f} \right)
\]

Therefore, we obtain:
\[
\begin{aligned}
\int_{z=-D_w}^{z=-D_E} v \, dz &= \frac{1}{\rho f} \left( \frac{\partial \tau_{y_w}}{\partial x} - \frac{\partial \tau_{x_w}}{\partial y} \right) + \frac{1}{\rho f} \tau_{x_w}
\end{aligned}
\]

Therefore,
\[
\text{Sverdrup transport} = \text{Geostrophic transport} + \text{Ekman transport}
\]
Ekman and Sverdrup Transports

Ekman Layer

- **Ekman Pumping** (w<0)
  - Equatorward Sverdrup Transport

- **Ekman Suction** (w>0)
  - Poleward Sverdrup Transport

Subtropical Gyre

\[ V_E = -\frac{\tau_x}{\rho_0 f} \]
Conservation of Potential Vorticity

- Potential Vorticity
  \[ PV = f + \zeta \]
  \[ f = \text{planetary vorticity} = 2\Omega \sin \phi \]
  \[ \zeta = \text{relative vorticity} = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \]

- \[ f_1 + \zeta_1 = f_2 + \zeta_2 \]
  Since \( f_1 > f_2 \) \( \Rightarrow \) \( \zeta_1 < \zeta_2 \)

- If \( \zeta < 0 \), the vortex decreases rotation when moves toward lower latitudes and increases rotation when moves toward higher latitudes.
Boundary Currents

(Figure from *The Earth System*)

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Step 4: Boundary Currents

(Figure from *Oceanography* by Tom Garrison)
Boundary Currents

Eastern boundary currents: broad and weak

Western boundary currents: narrow and strong
Eastern Boundary Current

- Cold water from higher latitude ocean.
- Coastal upwelling associated with subtropical high pressure system.
- Atmospheric subsidence produce persistent stratiform clouds, which further cool down SSTs by blocking solar radiation.

(from Global Physical Climatology)
Costal Upwelling/Downwelling

- A result of Ekman transport and mass continuity.

(Figure from *Oceanography* by Tom Garrison)
Global Surface Currents

[Diagram showing various global surface currents]

- Warm-water current
- Cold-water current

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