Lecture 4: OCEANS (Outline)

- Basic Structures and Dynamics
  - Ekman transport
  - Geostrophic currents
- Surface Ocean Circulation
  - Subtropical gyre
  - Boundary current
- Deep Ocean Circulation
  - Thermohaline conveyor belt

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.

Basic Ocean Current Systems

- Upper Ocean
- Deep Ocean

The State of Oceans

- **Temperature**
  - warm on the upper ocean, cold in the deeper ocean.
- **Salinity**
  - variations determined by evaporation, precipitation, sea-ice formation and melt, and river runoff.
- **Density**
  - small in the upper ocean, large in the deeper ocean.
Potential Temperature

- Potential temperature is very close to temperature in the ocean.
- The average temperature of the world ocean is about 3.6°C.

Salinity

- Salinity is the mass of dissolved salts in a kilogram of seawater.
- Unit: ‰ (part per thousand, per mil).
- The average salinity of the world ocean is 34.7‰.
- Four major factors that affect salinity: evaporation, precipitation, inflow of river water, and sea-ice formation and melting.

Density

- Seawater is almost incompressible, so the density of seawater is always very close to 1000 kg/m³.
- Potential density is the density that seawater with a particular salinity and temperature would have at zero water pressure (or at surface air pressure).
- Potential density = density – 1000 kg/m³.
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

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.

Seasonal Variation of Mixed Layer

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

Two Circulation Systems

- **Wind-driven circulation**
- **Density-driven circulation**

(Figure from The Earth System)
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)

Characteristics of the Gyres
- Currents are in geostrophic 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 poleward (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 m³/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**

*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 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)

Formula for Ekman Transport

\[ U_E = \int_{-\infty}^{0} \mu_E \, dz = \frac{\tau_y}{\rho_0 f}; \quad V_E = \int_{-\infty}^{0} \nu_E \, dz = -\frac{\tau_x}{\rho_0 f} \]

How Deep is the Ekman Layer?

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

\( \nu = \) vertical diffusivity of momentum

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

(Figure from The Earth System)

(Figure from Climate System Modeling)
**Ekman Transport**

- Wind-driven gyre
- Westerlies

**Convergence/Divergence**

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

**Geostrophic Currents**

- Geostrophic Gyre Currents
- Thermocline
- Upwelling

**Step 3: Geostrophic Current**

(Pressure Gradient Force + Coriolis Force)

- NASA-TOPEX Observations of Sea-Level Height
- Thermocline
- Upwelling
- Convergence/divergence (in the center of the gyre)
- Pressure Gradient Force
- Geostrophic Currents

(Figure from *The Earth System*)

(Figure from *Oceanography* by Tom Garrison)
Step 4: Boundary Currents

Western boundary currents: narrow and strong

Eastern boundary currents: broad and weak

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

Costal Upwelling/Downwelling
- A result of Ekman transport and mass continuity.
Global Surface Currents

Equatorial Current System

The Equatorial Counter Current, which flows towards the east, is a partial return of water carried westward by the North and South Equatorial currents.

Equatorial Under Current

The most prominent of all eastward flows is the Equatorial Undercurrent (EUC).

It is a swift flowing ribbon of water extending over a distance of more than 14,000 km along the equator with a thickness of only 200 m and a width of at most 400 km.

The current core is found at 200 m depth in the west, rises to 40 m or less in the east and shows typical speeds of up to 1.5 m s⁻¹.

Its existence remained unknown to oceanographers until 1952.

Deep Ocean Circulation: Density-Driven

(Figure from Oceanography by Tom Garrison)
Thermohaline Circulation

Two Regions of Deep Water Formation

Two Processes to Increase Salinity in High Latitudes

- **Evaporation**: Extremely cold, dry winter air enhances evaporation from the relatively warm ocean \( \Rightarrow \) increase salinity in the ocean.

- **Formation of Sea Ice**: When sea ice forms, salts are left in the ocean \( \Rightarrow \) increase salinity

Ocean Water Mass

- **Surface Water**: to a depth of about 200 meters
- **Central Water**: to the bottom of the main thermocline
- **Intermediate Water**: to about 1500 meters
- **Deep Water**: below intermediate water but not in contact with the bottom
- **Bottom Water**: in contact with sea floor

- Ocean water masses possess distinct, identifiable properties and don’t often mix easily when they meet.
- Instead, they usually flow above or below each other.
- Ocean water mass can retain their identity for great distance and long periods of time.
- Oceanographers name water masses according to their relative position.
Formation of Water Mass

- Once a water parcel is removed from the surface layer its temperature and salinity do not change until it rises back up to the surface again, usually many years later.
- Water masses with well-defined temperature and salinity characteristics are created by surface processes in specific locations, which then sink and mix slowly with other water masses as they move along.
- Water masses are always identified by capitals. For example, "Bottom Water" can stand for Antarctic, Arctic, or other Bottom Water but always refers to a water mass, while water found at the bottom of an oceanic region may be referred to as "bottom water" without implying that it is a known and well defined water mass.

Five Types of Air Masses

- Theoretically, there should be 6 types of air masses (2 moisture types x 3 temperature types).
- But mA-type (maritime Arctic) does not exist.
- cA: continental Arctic
- cP: continental Polar
- cT: continental Tropical
- mP: maritime Polar
- mT: maritime Tropical

Distribution of Ekman Pumping

Subduction

(from Regional Oceanography)
Thermohaline Circulation

- Thermo: temperature
- Haline: salinity

Density-Driven Circulation

Cold and salty waters go down
Warm and fresh waters go up

Thermohaline Conveyor Belt

- Typical speed for deep ocean current: 0.03-0.06 km/hour.
- Antarctic Bottom Water takes some 250-1000 years to travel to North Atlantic and Pacific.
It Takes ~1000 Years for Deep Ocean Waters to Travel Around…

- If we date a water parcel from the time that it leaves the surface and sink into the deep ocean
- Then the youngest water is in the deep north Atlantic, and the oldest water is in the deep northern Pacific, where its age is estimated to be 1000 year.

The Most Unpolluted Waters are..

*the waters in the deep northern Pacific.*

- The man-released CFC and the chemical tritium and C¹⁴, which were released through atmospheric atomic bomb test in the 1950s and 1960s, entered the deep ocean in the northern Atlantic and are still moving southward slowly.
- Those pollutions just cross the equator in the Atlantic ➔ They have not reached the deep northern Pacific yet!!

Global Warming and Thermohaline Circulation

- *If the warming is slow*
  - The salinity is high enough to still produce a thermohaline circulation
  - The circulation will transfer the heat to deep ocean
  - The warming in the atmosphere will be deferred.

- *If the warming is fast*
  - Surface ocean becomes so warm (low water density)
  - No more thermohaline circulation
  - The rate of global warming in the atmosphere will increase.

Cryosphere

- The cryosphere is referred to all the ice near the surface of Earth: including sea ice and land ice.
- For climate, both the surface and the mass of ice are importance.
- At present, year-round ice covers 11% of the land area and 7%.
Seasonal Cycle of Antarctic Ice

Climate Roles of Sea Ice
- Atmosphere
- Albedo
- Insulation
- Sea Ice
- Salinity
- Ocean Circulation

Sea Ice

- One major climate effect of sea ice is to seal off the underlying ocean from interaction with the atmosphere.
- Without an ice cover, high-latitude oceans transfer large amounts of heat to the atmosphere, especially in winter.
- With an ice cover, the heat flux into the atmosphere is stopped. Winter air temperature can cool 30°C or more near a sea-ice cover.

Land Ice and Sea Level
- The Antarctic Ice Sheet holds the equivalent in seawater of 66 meters of global sea level.
- The Greenland Ice Sheet holds the equivalent of 6 meters of global seawater.

Ocean ice and sea level affect global climate and sea level change.
**Land Ice**

- **Continental Ice Sheets**:
  - Horizontal extend: 100-1000 km
  - Thickness: 1-4 km
  - Two large sheets: Antarctic Ice Sheet and Greenland Ice Sheet

- **Mountain Glaciers**: a few kilometers in length and 10-100 meters in width and thickness

**Glacial Ice**

- **Ice cores** retrieve climate records extending back thousands of years in small mountain glaciers to as much as hundreds of thousands of years in continental sized ice sheets.
- The Antarctic ice sheet has layers that extend back over 400,000 years.
- The Greenland ice sheet has layers that extended back 100,000 years.

**Interactions between Ice and Ocean**

- This hypothesis argues that millennial oscillations were produced by the internal interactions among various components of the climate system.
- One most likely internal interaction is the one associated with the deep-water formation in the North Atlantic.
- Millennial oscillations can be produced from changes in northward flow of warm, salty surface water along the conveyor belt.
- Stronger conveyor flow releases heat that melts ice and lowers the salinity of the North Atlantic, eventually slowing or stopping the formation of deep water.
- Weaker flow then causes salinity to rise, completing the cycle.

**Global Warming and Sea-Level Change**

- **Global Warming** (2.5°C by 2100)
- **Thermal Expansion** (11 inches)
- **Antarctic Ice Sheet** (-0.4 inches)
- **Glacier and Ice Caps** (6.3 inches)
- **Greenland Ice Sheet** (2.4 inches)
- **Sea Level Rise** (19.3 inches by 2100)
After a certain amount of land-supported ice melts, instead of saying the sea level will rise "so much", we should say the oceans will get "so much" deeper.

-- (Kivioja 2003, EOS)