Ocean Mixing and Climate Change
Factors inducing seawater mixing

- Different densities
- Wind stirring
- Internal waves breaking
- Tidal
- Bottom topography
- Biogenic Mixing (??)

In general, any motion favoring turbulent activity between two layers of fluid with different densities
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5. Increased vertical mixing leads to increased meridional transport.
Buoyancy

upward acting force, caused by fluid pressure
(Archimedes' principle)
Convection

Heated fluids, due to their lower density, ascend and cooled fluids descend.
vertical mixing: Convection

Turbulence produced by destabilizing surface buoyancy fluxes

\[ \dot{b} (\cdot = 0) = \dot{b}_{p}^{\text{tot}} + \dot{b}_{0} \]

Moum and Smyth

Monday, November 30, 2009
Turbulence and Eddies

1. **Turbulence**: a fluid regime characterized by chaotic, stochastic property changes.

1. **Eddy**: swirling of a fluid and the reverse current created when the fluid flows past an obstacle. Ocean Eddies range: cm-100 km.

When two currents collide, they create eddies. Phytoplankton become concentrated along the boundaries of these eddies, tracing out the motions of the water.
Boundary stress mixing the whole water column

Strong surface friction: hurricanes

(MacKinnon and Gregg 03)

Strong bottom friction: tidal mixing fronts

(Rippeth et al 05)
The development and propagation of anomalously warm and cold eddies can be clearly seen in the Gulf Stream region. The transport of warm water northward by the mean flow of the Gulf Stream is also clearly visible.
modeled flow in the southern ocean

Ocean Surface Speed in NOAA/GFDL Southern Ocean Simulations

Fig. 6. Instantaneous surface speed in 1° and 1/6° models after 40 yr. Note that the large scale structure of the 1° model is quite similar to the 1/6° model (the currents have similar locations and have similar horizontal extents). The main difference is in the presence of intense jets and eddies in the 1/6° model.
Atmospheric Temperature Change Dependency on Oceanic Mixing Coefficients
Ocean Circulation

• Ultimately driven by solar energy
  – Distribution of solar energy drives global winds
  – Latitudinal wind belts produce ocean currents
    • Determine circulation patterns in upper ocean
  – Distribution of surface ocean temperatures strongly influence density structure
    • Density structure of oceans drives deep ocean circulation
• Negative feedback
  – Surface temperature gradients drive circulation
  – Net effect is to move warm water to poles and cold water towards tropics
Heat Transfer in Oceans

- Heating occurs in upper ocean
- Vertical mixing is minimal
  - Average mixed layer depth ~100 m
- Heat transfer from equator to pole by ocean currents
- Oceans redistribute about half as much heat at the atmosphere
Heat input per latitude band (PW)

1 PW = 1 “Petawatt” = $10^{15}$ W

Heat transport (PW)

(meridional integral of the above)

Models: If upper ocean mixing is enhanced everywhere within 30 of the equator, Poleward heat transport is increased. However, if mixing is enhanced solely in the subtropical bands, where tropical cyclones are observed, the poleward heat transport out of the deep tropics is decreased.
Heat transport

- Meridional heat transport across each latitude in PW
- Calculate either from and diagnose for ocean
- OR from velocity and temperature observations in the ocean. Must have net mass balance to compute this.
Surface Currents

- Surface circulation driven by winds
  - As a result of friction, winds drag ocean surface
- Water movement confined to upper ~100 m
  - Although well-developed currents ~1-2 km
  - Examples, Gulf Stream, Kuroshiro Current
- Coriolis effect influences ocean currents
  - Water deflected to right in N. hemisphere
  - Water deflected to left in S. hemisphere
Eckman Transport

• Observations confirm net transport of surface water is at a right angle to wind direction

• Net movement of water referred to as Eckman Transport
Gyre Circulation

- Wind driven and large scale
  - Sea level in center 2 m higher than edge
    - Eckman transport producing convergence
  - Circulation extends to 600-1000 m
  - Volume of water moved is 100 x transport of all Earth’s rivers
  - Flow towards equator balanced by flow toward pole on westward margin
    - In Atlantic, by Gulf Stream and North Atlantic Drift
The five major ocean gyres. Circulation is clockwise north of the equator & anticlockwise south of the equator.
Downwelling

- In areas of convergence
  - Surface water piles up in center of gyre
  - Sea level in the center of gyre increases
  - Surface layer of water thickens
    - Accumulation of water causes it to sink
    - Process known as downwelling
Equatorial Upwelling

- As surface water diverges, sea level falls, surface layer thins and cold water “upwells”
Eckman Transport Along Coasts

• Winds along a coast may result in Eckman transport that moves water towards or away from the coast
• Divergence from easterly winds and southward moving currents
  – SW coast of N. America
  – W coast of N. Africa
• Divergence from northward moving currents
  – West coasts of S. America and S. Africa
Coastal Upwelling

- Coastal divergence results in upwelling as cold water rises to replace surface water
Boundary Currents

• Gyre circulation pushes water to the west
• Flow of water around gyres is asymmetric
• In the western part of gyre water is confined to a narrow fast-moving flow
  – Western boundary current
• In the eastern part of gyre flow is diffuse, spread out and slow
  – Eastern boundary current
  – Eastern currents tend to be divergent
    • Eckman transport away from continent
Gulf Stream

- Western boundary current in Atlantic
  - Narrow, fast-moving from Cuba to Cape Hatteras
  - Decreases speed across N. Atlantic
  - Flow broadens and slows becoming N. Atlantic Drift
  - Movement to the south along the Canary Current is very slow, shallow and broad
Vertical Structure of Ocean

- Pycnocline (~1 km)
  - Zone of transition between surface and deep water
  - Characterized by rapid increase in density
    - Some regions density change due to salinity changes – halocline
    - Most regions density change due to temperature change – thermocline
  - Steep density gradient stabilizes layer
Deep Atlantic Water Masses

- Deep Atlantic water comes from high latitude N. Atlantic, Southern Ocean and at shallower depth, the Mediterranean Sea
Ocean Circulation

- Surface water at high latitudes forms deep water
- Deep water sinks and flows at depth throughout the major ocean basins
- Deep water upwells to replace the surface water that sinks in polar regions
- Surface waters must flow to high latitudes to replace water sinking in polar regions
- Idealized circulation – Thermohaline Conveyer Belt
Thermohaline circulation: Vertical Structure

Diagram showing the vertical structure of thermohaline circulation. The diagram illustrates the flow of water in the ocean, with heating and cooling regions, surface flow, thermocline, deep spreading, and sinking. The equatorial regions are heated, leading to surface flow, while polar regions are cooled, causing sinking.
Thermohaline circulation: Other Names

- Thermohaline Circulation (THC)
- Ocean Global Conveyor Belt
- Meridional Overturning Circulation (MOC)

Blue: deep-water currents
Red: represent surface currents
Surface Temperature and Salinity
World Ocean Circulation: Water Masses

Figure 8.21 A three-dimensional perspective view of thermohaline flow. The red arrows show flow paths in the shallow and intermediate depths. Green and blue arrows show the paths for the deep ocean and bottom flows, respectively. Orange represents the very salty, warm water flowing out of the Red Sea, and purple indicates near-surface circulation. The ribbons and arrows in this diagram do not represent distinct currents but rather depict generalized flow pathways of salt and heat transport. Note especially the interlocked connections between ocean basins and depths, and the complex formation of Antarctic Bottom Water (AABW). This graphic represents decades of work by many researchers, but special mention should be made of the contributions of Wallace Broecker, William Schmitz, and Jack Cook.
Internal Waves

Wind

Internal waves

Horizontal currents

Overturning

Turbulent mixing

10m

1m

Internal waves

Tidal currents
Strength of surface and internal tide (SIO pier)
Eric Terill

**Barotropic tide:**
regular beating of semi-diurnal (12 hour) and diurnal (24 hour) signals

**Internal tide: a mess!**
Changing stratification, mesoscale currents, eddies, ....
When a layer of warm, salty water lies above a layer of colder, fresher water, the heat and salt will tend to diffuse (spread out) downwards to make a single layer with intermediate temperature and salinity values. However, because heat diffuses faster than salt, the process can lead to local instabilities in the density structure which cause mixing within a layer many meters thick.
Turbulent Mixing

Cross-section of the temperature field in Kelvin-Helmholtz billows before (a) and after (b) the transition to turbulence. © W.D. Smyth, College of Oceanic and Atmospheric Sciences, Oregon State University.
Wind-driven turbulence maintains the mixed layer by stirring the water near the ocean’s surface.
Surface Height
Oscillations due to Tides

Highest tidal ranges are found where continental coasts distort the tide wave
Mixing Due to Tides

Tide anomalies: around islands where the tide wave distorts most (NZ, Madagascar), and around deep sea ridges and chains of seamounts (Hawaii). They give rise to deep eddies that transport nutrients from the deep to the surface.
Tidal Mixing off Hawaii
Bottom Topography induced mixing
Biogenic Mixing
Total Mixing (mW/m$^2$)
The global carbon cycle shows the carbon reservoirs in GtC (gigatonne = one thousand million tonnes) and fluxes in GtC/year.
Air-sea CO2 fluxes: annual mean

Ocean gains CO2 from atm

Ocean loses CO2 to atm (upwelling areas mostly)
Carbon Concentration in the World Ocean

Sea-surface DIC [mmol C kg$^{-1}$]

1.8  1.85  1.9  1.95  2  2.05  2.1  2.15  2.2
Carbon Concentration in the World Ocean

Trouble!!!!…near saturation!
(Le Quere, Science 2007)
Mixing and Global Warming

Install mighty pumps to mix up the water:
Bring the nutrient-rich waters up, increase algal bloom,
consume CO2 + cloud formation
Anthropogenic vs. Natural causes for global warming

- Observations
- (Natural) volcano + solar
- (Anthropogenic + Natural) volcano + solar + greenhouse gas + sulfate + ozone
Experiment Setup

Cyclonic and anticyclonic circulation are induced by blowing air over the surface of a rotating tank of water using co-rotating fans.
The mass transport of the Ekman layer is directed to the right of the wind in the Northern Hemisphere.
The flow within the surface Ekman layer associated with the action of the wind is convergent in anticyclonic flow and divergent in cyclonic flow if the apparatus is rotating cyclonically ($\Omega > 0$, corresponding to the northern hemisphere). The convergent flow drives downward vertical motion (called Ekman pumping, left); the divergent flow drives upward vertical motion from beneath (called Ekman suction, right).
Vertical overturning circulation in an anticyclonic and in a cyclonic vortex.
Atlantic surface circulation

Note:

Subtropical gyres (anticyclonic)

Subpolar gyres (cyclonic)

Note: westward intensification of the currents - strong currents are all on the western boundary, regardless of hemisphere
Schematic of surface circulation

Why are there gyres? Why are the currents intensified in the west? (“western boundary currents”)
Observed asymmetry of wind-driven gyres

what one might expect

what one observes
Sverdrup transport

• Ekman pumping provides the squashing or stretching.

• The water columns must respond. They do this by changing latitude.

• (They do not spin up in place.)

Squashing -> equatorward movement  Stretching -> poleward

TRUE in both Northern and Southern hemisphere