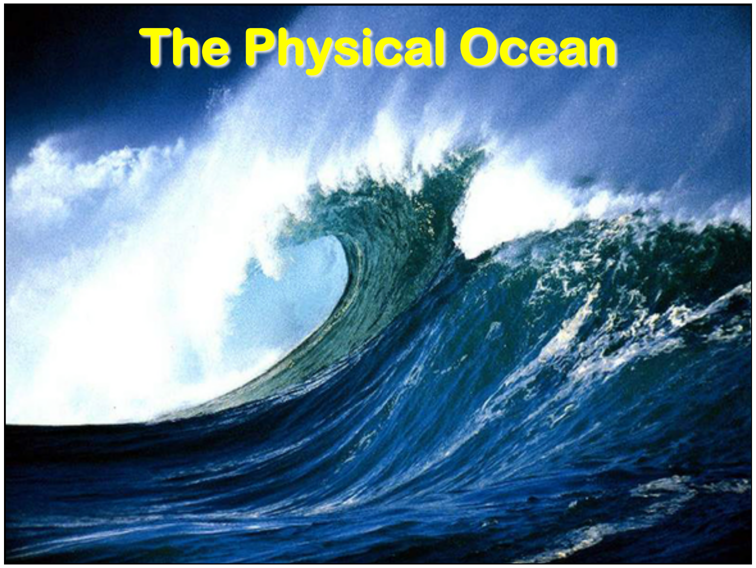
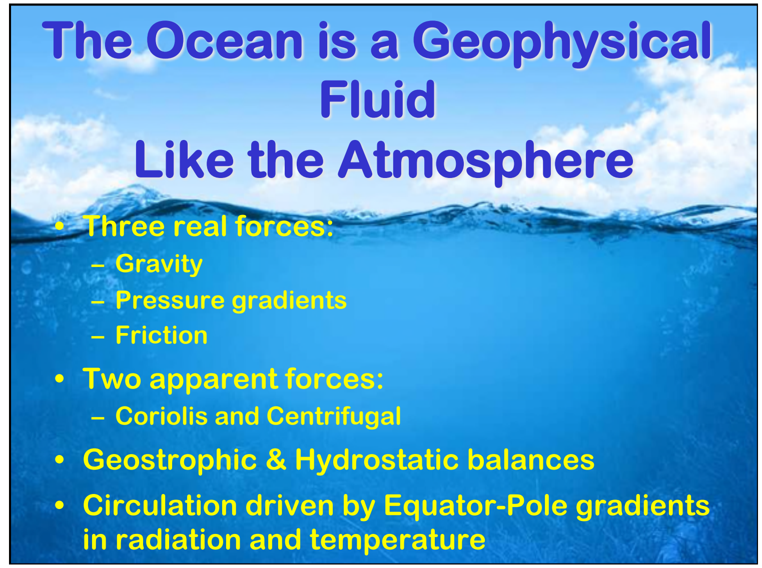
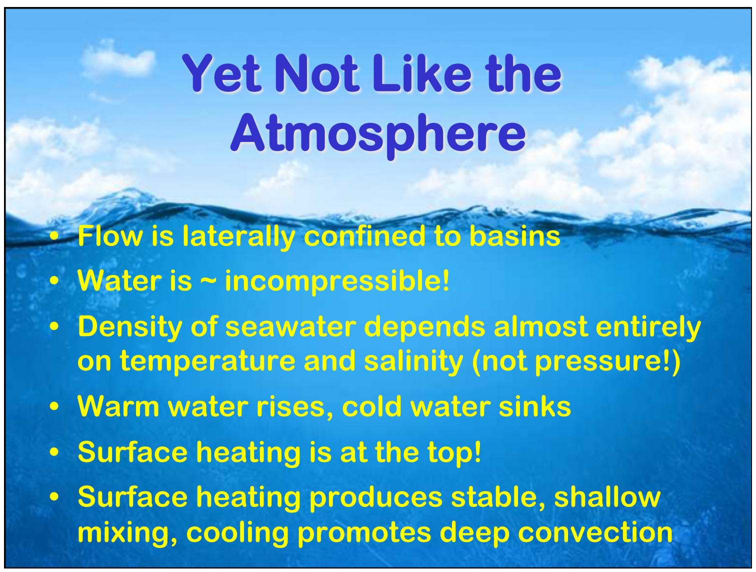

The Physical Ocean

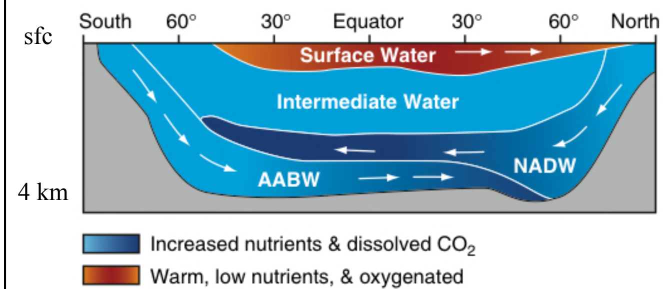

The Ocean is a Geophysical Fluid
Like the Atmosphere
• Three real forces:
– Gravity
– Pressure gradients
– Friction
• Two apparent forces:
– Coriolis and Centrifugal
• Geostrophic & Hydrostatic balances
• Circulation driven by Equator-Pole gradients in radiation and temperature


Yet Not Like the Atmosphere
• Flow is laterally confined to basins
• Water is ~ incompressible!
• Density of seawater depends almost entirely on temperature and salinity (not pressure!)
• Warm water rises, cold water sinks
• Surface heating is at the top!
• Surface heating produces stable, shallow mixing, cooling promotes deep convection


Dark and Deep
• Brightly colored equipment, fish, and corals at snorkel depths (10 – 20 feet)
• Red and orange go first, then yellow and green
• Below 50 feet, everything is progressively dimmer shades of blue …

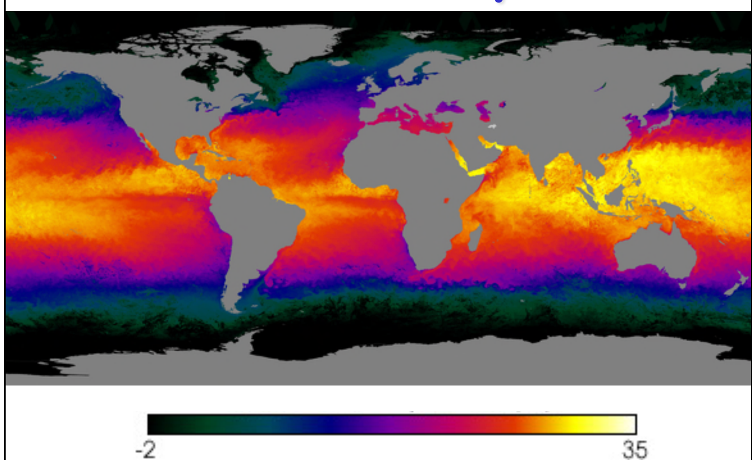
cold too!

Vertical Structure of the Oceans

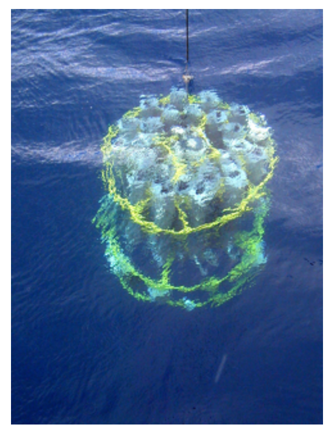


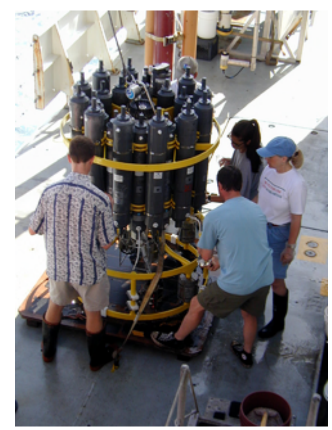
- Warm buoyant "raft" floats at surface
- Cold deep water is only "formed" at high latitudes
- Very stable, hard to mix, takes ~ 1000 years!
- Icy cold, inky black, most of the ocean doesn't know we're here yet!

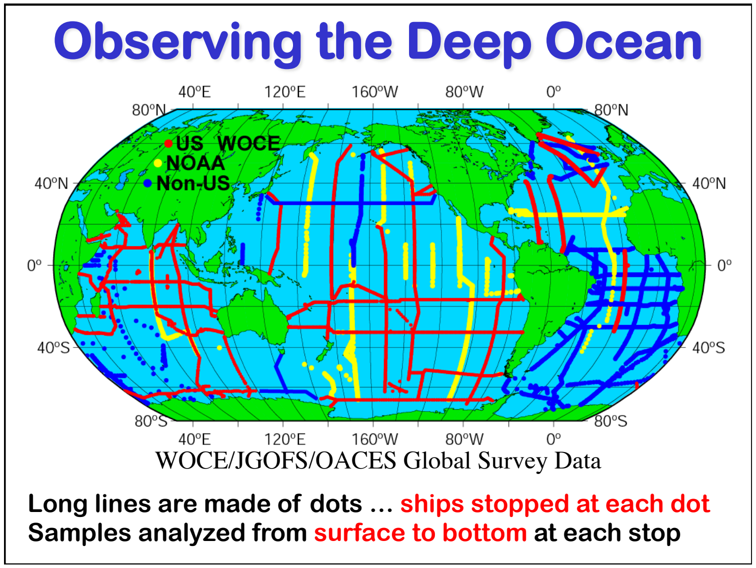
Sea Surface Temperature

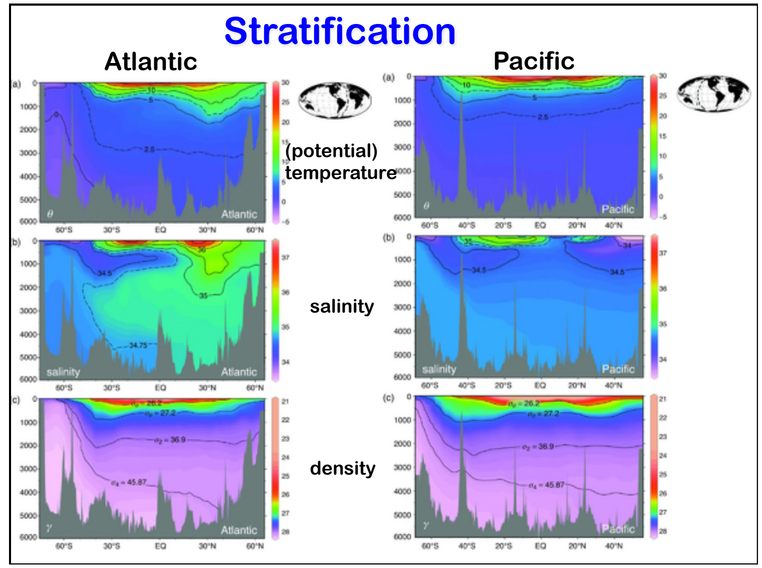


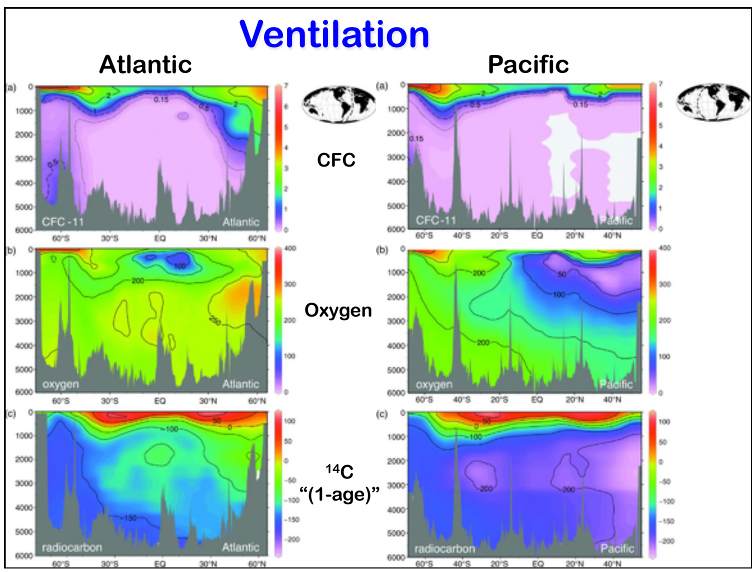
Observing the Deep Ocean

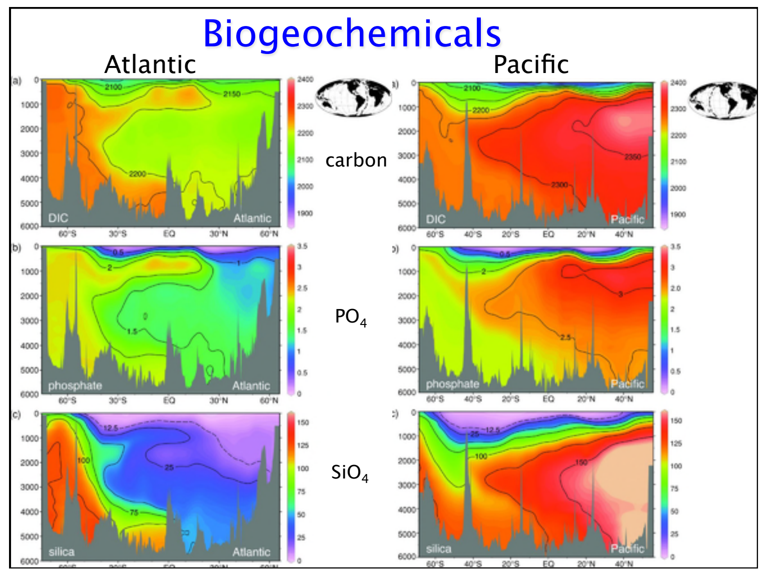





Observing the Deep Ocean
US WOCE
NOAA
Non-US
80°N
40°N
0°
40°S
80°S
40°E 120°E 160°W 80°W 0°
WOCE/JGOFS/OACES Global Survey Data
Long lines are made of dots … ships stopped at each dot
Samples analyzed from surface to bottom at each stop

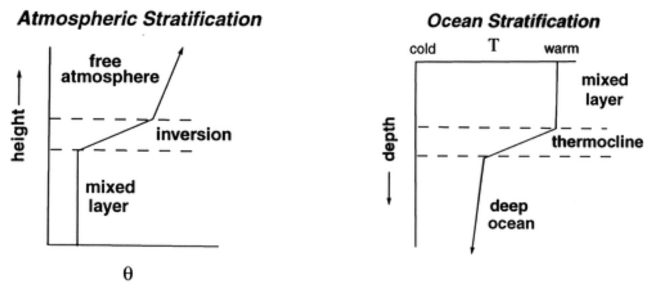

Stratification
Atlantic
Pacific
(potential) temperature
salinity
density


Ventilation
Atlantic
Pacific
CFC
Oxygen
14C "(1-age)"

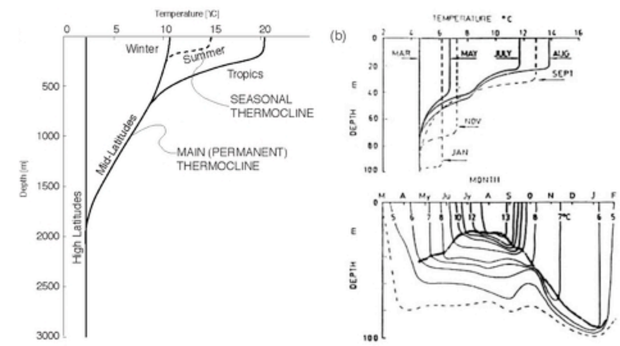

Biogeochemicals
Atlantic
Pacific
carbon
PO4
SiO4

Static Stability
and the formation of mixed layers

- Stable fluid is stratified by density, with the heaviest (coldest) sinking to the bottom
- If underlying layers become less dense, fluid becomes unstable and will spontaneously turn over and mix
- Fluid column that is uniformly dense is neutrally stratified and mixes freely

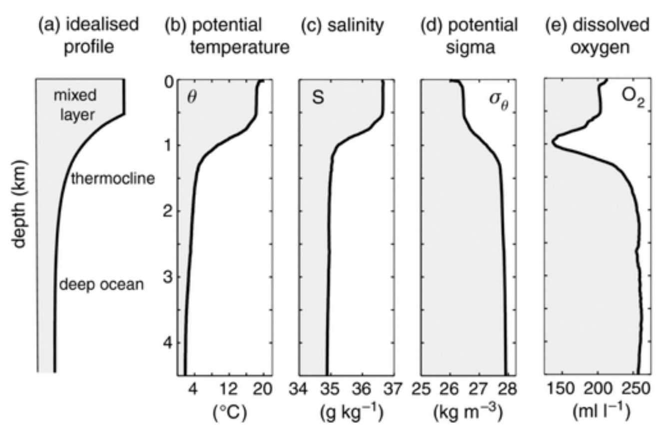


Seasonal Thermocline



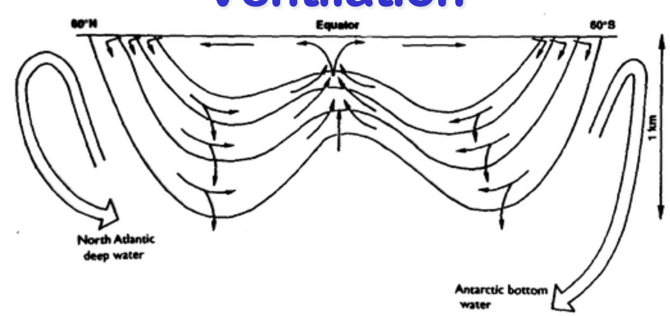
- Heating promotes stratification
- Cooling promotes deeper mixing

Vertical Profiles



Williams_Fig. 2.4

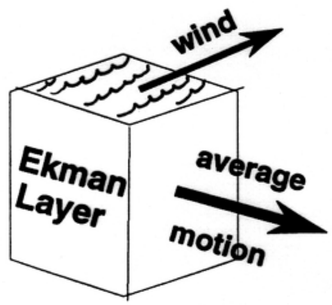
Ventilation



- High-latitude cooling causes deep convective mixing
- Stratified water can move along isopycnal (constant-density) surfaces
- Deep water "outcrops" at highest latitudes and thermocline water outcrops a little equatorward

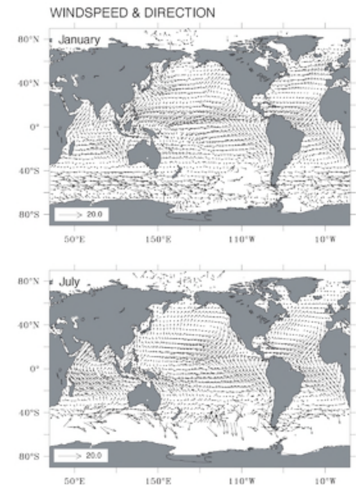
Coriolis Force and Ekman Pumping

- Surface wind stress "pushes" water through some depth that transmits the force by friction
- Water in this layer moves at right angles to wind forcing
  - Right of wind in NH
  - Left of wind in SH

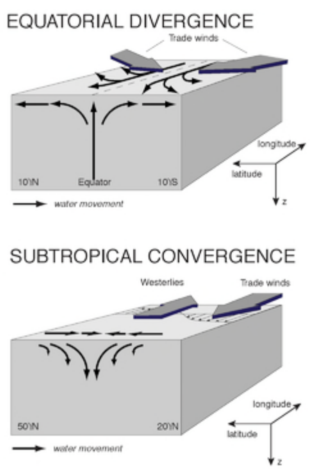


Sea-Surface Winds

- Westerlies in middle latitudes
- Easterlies ("Trade Winds") in tropics
- Seasonally-reversing Monsoon flow over Indian Ocean
- What do these patterns do to the water?

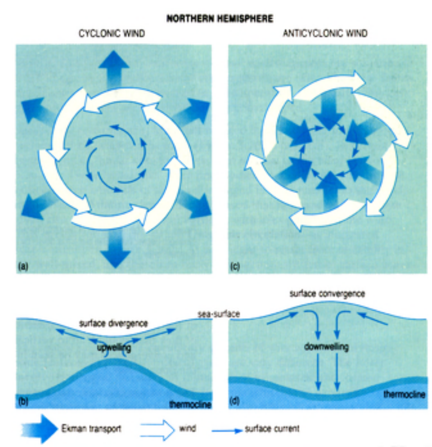


Winds and Vertical Motion



- Divergent Ekman flow along Equator in response to converging Trade Winds -> upwelling
- Convergent Ekman flow in subtropical gyres in response to diverging surface winds -> downwelling

Ekman Pumping



- Ekman flow in NH is 90° to the right of the wind stress
- Cyclonic wind forces divergence in water, and upwelling
- Anticyclonic wind forces convergence and downwelling

Idealized Geostrophic Gyre

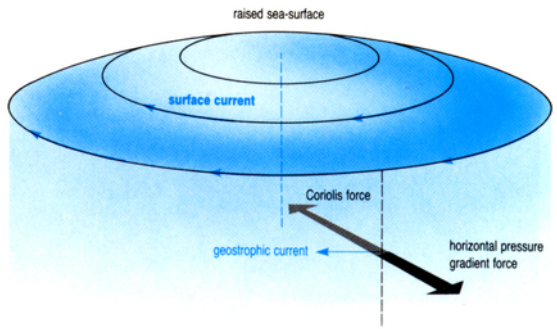
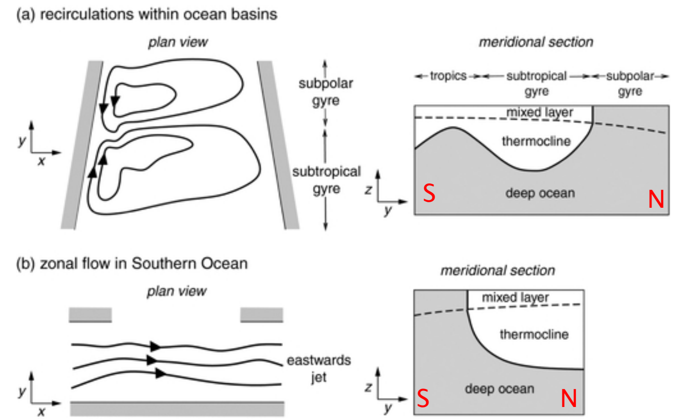


Figure 3.24 The generation of geostrophic current flow in a gyre driven by anticyclonic winds in the Northern Hemisphere. This current is driven by the wind only indirectly and persists below the wind-driven (Ekman) layer.

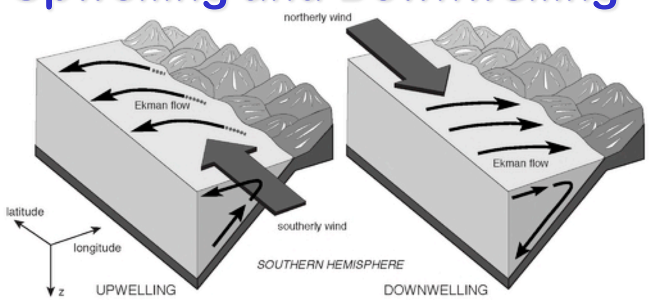
- **Convergence of Ekman flow raises sea surface**
- **Rotating "dome" results**

Currents and Mixing



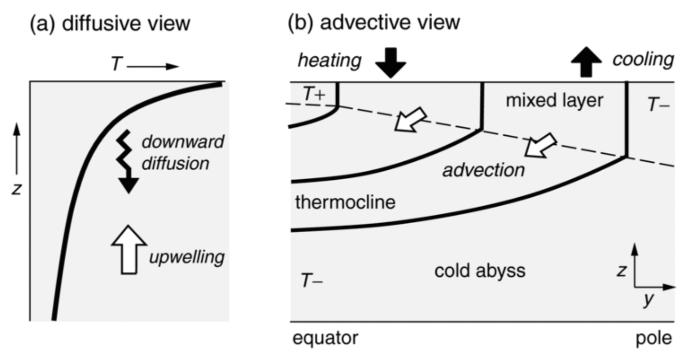
Williams_Fig. 2.3

Coastal Upwelling and Downwelling



- **Ekman flow in response to along-shore winds**
- **Typically upwelling along eastern margins (west coasts, e.g., California, Peru, Namibia)**
- **Nutrients from depth supply rich marine ecosystems**

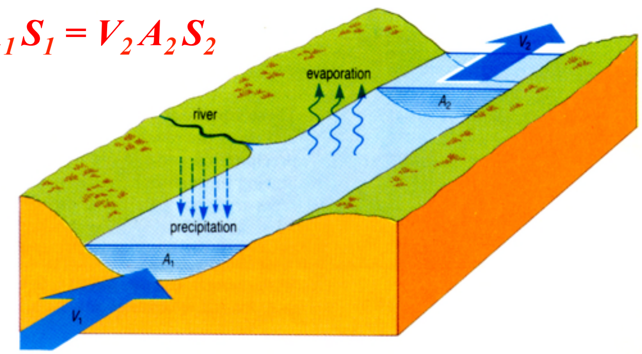
Vertical Temperature & Density Gradients



Williams_Fig. 2.5

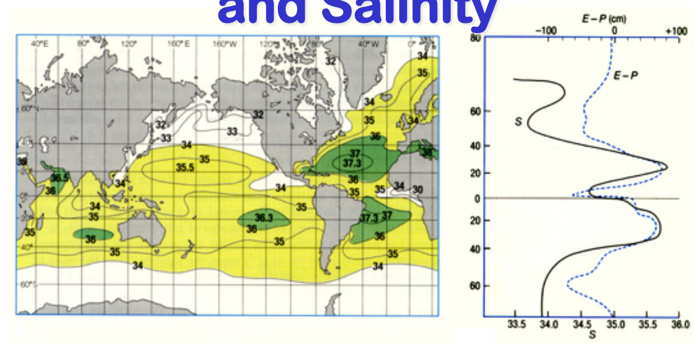
"Conservation of Salt"

$V_1 A_1 S_1 = V_2 A_2 S_2$



- Really just conservation of water (mass)
- Salt is used as an easily measured tracer of changes in water volume

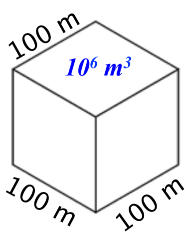
Evaporation, Precipitation, and Salinity



- Westerlies: more vapor leaves Atlantic drainage basin over Europe than arrives over Rockies
- Trades: more vapor leaves over Caribbean than arrives over Sahara
- Result: Atlantic is much more saline than Pacific

What's a Sverdrup?

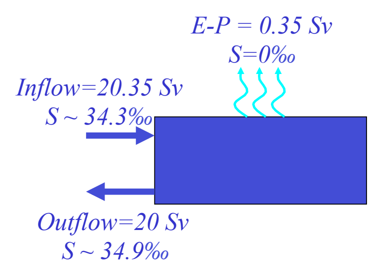
Harald Ulrik Sverdrup
(1888 –1957)
Norwegian oceanographer



- 1 Sv = 10^6 m^3 s^{-1}
- Unit of water flow in the ocean
- Biggest river on Earth (Amazon) flows at about 0.18 Sv
- Gulf Stream off of Florida flows about 30 Sv

North Atlantic Mass Balance

- Water vapor loss (E-P) from North Atlantic drainage basin estimated from meteorological data 0.35 +/- 0.12 Sv (salinity = 0‰)
- Outflow ~ 20 Sv estimated from ^{14}C residence time (salinity ~ 34.9‰)
- Inflow of (20+0.35) Sv with salinity ~34.3‰ required for mass balance



"Measly 0.35 Sv vapor loss drives a mighty 20 Sv current!"

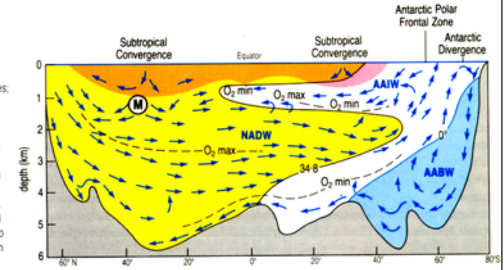
If not for slightly unbalanced inflow/ outflows, salinity of N. Atlantic would build without bound

Thermohaline Heat Pump

- Upper limb inflow to North Atlantic ~ 10° C
- Lower limb outflow ~ 3°C
- dQ = c DT ~ 3 x 10^7 J of heat released by each m^3 of water during conversion from upper limb to lower limb water mass
- 20 Sv = 20 x 10^6 m^3 s^{-1} of water makes this transition, releasing 6 x 10^{14} J s^{-1} (= 0.6 Pw) of heat to the atmosphere
- This is 35% of solar heating of North Atlantic north of 40° N latitude!

Atlantic Water Masses

Figure 6.15 Meridional cross-section of the Atlantic Ocean, showing movement of the major water masses; NADW = North Atlantic Deep Water; AAIW = Antarctic Intermediate Water; AABW = Antarctic Bottom Water. Water with salinity greater than 34.8 is shown yellow; note how the low salinity tongue of AAIW extends northwards from the Antarctic Polar Frontal Zone, to overlie the more saline NADW. The M at about 35°N indicates the inflow of water from the Mediterranean. Water warmer than 10 °C is shown pink/orange, and the cooler than 0 °C (corresponding approximately to the distribution of AABW) is shown blue. The oxygen maxima and minima will be explained in Section 6.5.

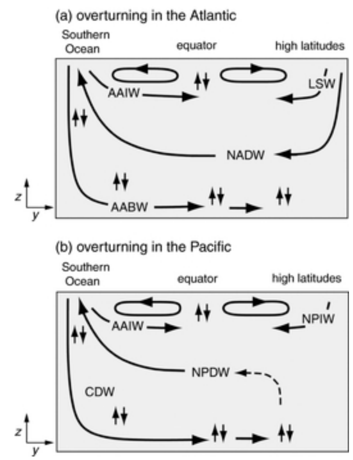


- Deep water formation in North Atlantic
- Bottom water formation in Antarctic
- Ekman convergence in subtropical gyres forces water down against buoyancy

Bottom Water Flow

Deep water formed off Greenland and Norway flows south to fill Atlantic Basin

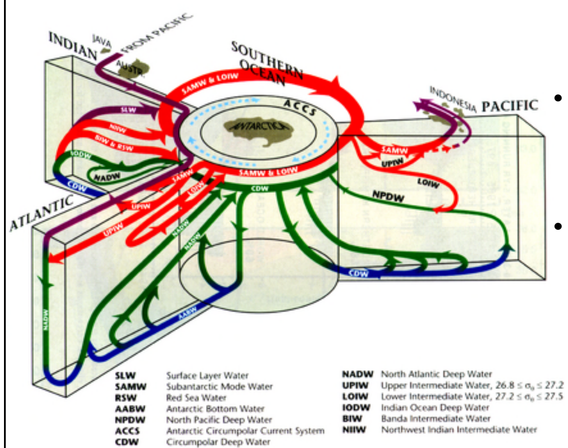
Meridional Overturning



Williams_Fig. 2.9

- North Atlantic Deep water forms around Greenland
- North Pacific much less salty, no deep water formed there
- Antarctic bottom water is heavier than NADW, also fills deep North Pacific

The Mix-Master



- **Water masses form in each ocean basin**
- **Circumpolar "mixmaster" resets properties**