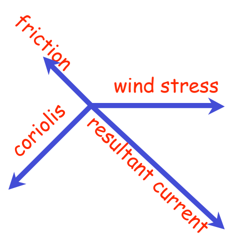
Wind-Driven Gyre Circulations and Boundary Currents

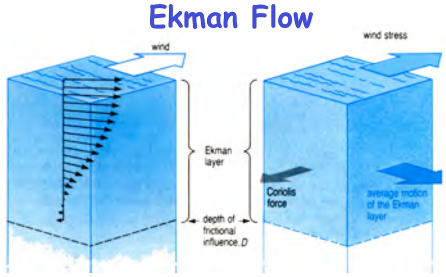
Surface Balance of Forces



- Wind stress accelerates surface water
- Friction couples surface to underlying water
- Friction always acts exactly opposite current motion
- Coriolis acceleration is always perpendicular to current motion

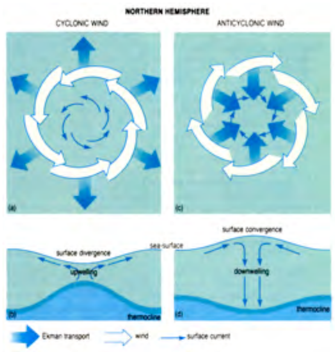
RESULT: Surface current directed about 45° (right/left) of wind in (NH/SH)

Ekman Flow



- Combined effects of Coriolis and friction on "stack" of thin layers
- Each layer moves more slowly and further right(left) than layer above ("spiral hodograph")
- Mass-weighted mean motion is 90° *cum sole* of wind

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

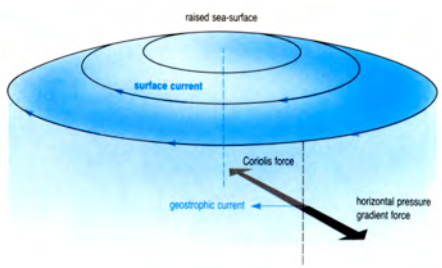


Figure 3.24 The generation of geostrophic current flow in a gyre driven by anticyclonic winds in the Northern Hemisphere. This current is driven by the wind only indirectly and persists below the wind-driven (Ekman) layer.

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

Asymmetric Gyre

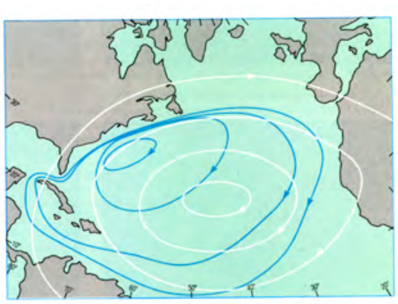
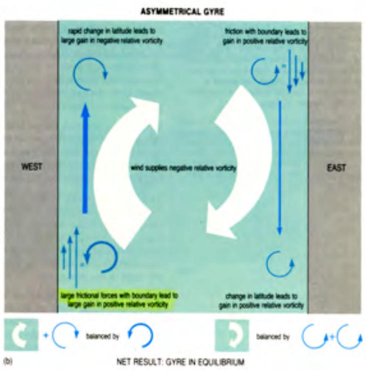


Figure 4.11 Schematic illustration of the asymmetrical North Atlantic gyre (blue) and the more or less symmetrical wind field which overlies it.

- Real world doesn't look like Sverdrup flow
- Boundary currents are not symmetric
- Why?

Stommel's Gyre Explained (part 2)

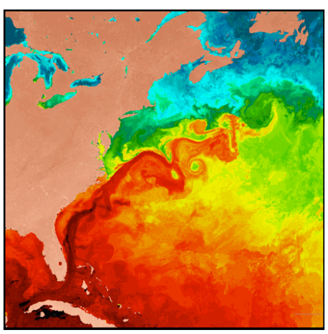


- Vorticity balance of asymmetric gyre
- Western boundary:
  - Fast current!
  - Friction ++
  - Latitude –
  - Balanced!
- Eastern boundary:
  - Slow current
  - Friction +
  - Latitude +
  - Balanced
- Overall balanced

Is there a Gulf Stream?

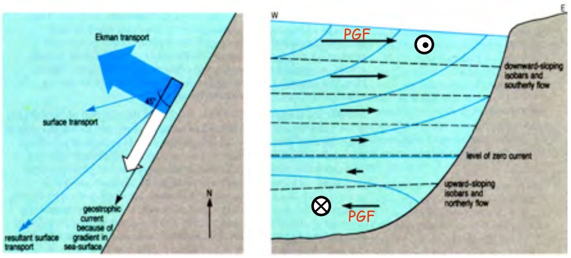
Trajectories of derelict (drifting) ships (19th century)

Sea-Surface Temperature from Space



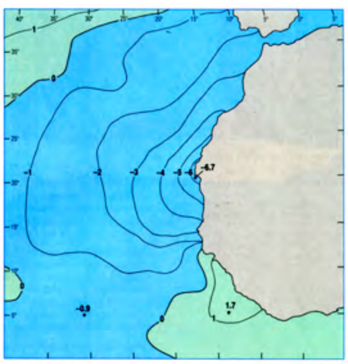
- Note baroclinic eddies and "rings" in Gulf Stream

Eastern Boundary Currents (NH)



- Sloping sea-surface in upwelling regions produces equatorward geostrophic current
- Strongly baroclinic conditions eliminate and even reverse pressure gradient at depth (countercurrent)

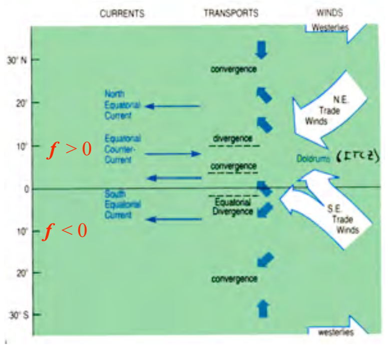
Coastal Upwelling Effect on SST



- Deviation from zonal mean SST
- Cold coastal water due to upwelling and cold geostrophic currents
- Interaction with desert climate on land

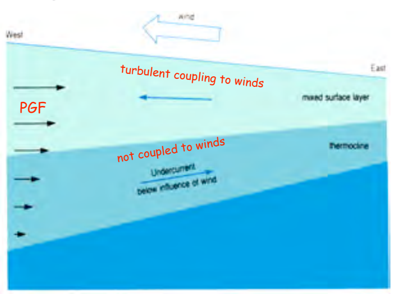
Tropical Oceans and El Nino

Tropical Winds and Currents



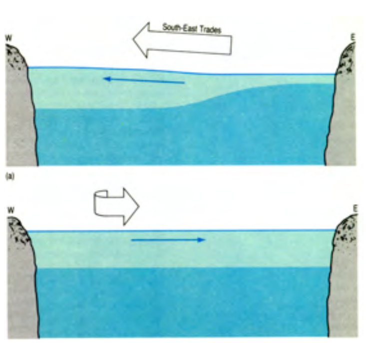
- Atmospheric convergence produces ocean divergence
- Vertical motions associated with divergent currents control SST

Equatorial Cross-Section

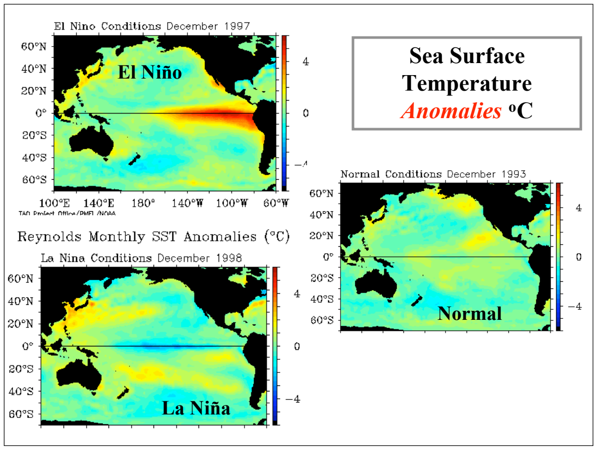


- Because f ~ 0, wind stress pushes water west
- Recall thermocline displacement is ~ 100 x surface because restoring force is "reduced gravity"

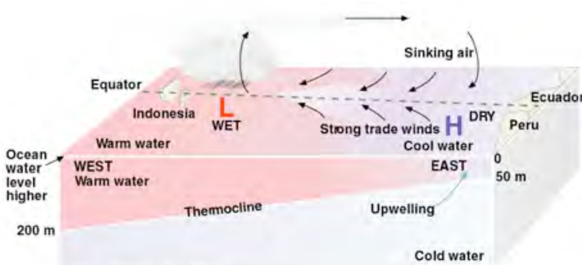
El Niño



- Normal conditions: Huge accumulation of deep warm water in W. Pacific
- El Nino: Relaxation of Trade Wind forcing allows warm water to flow eastward

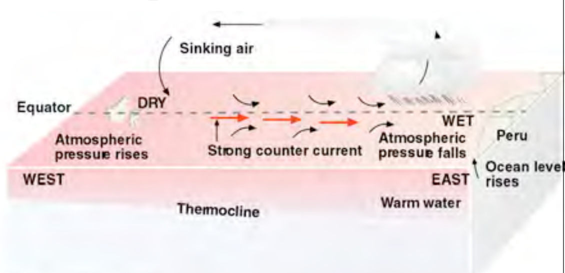


Normal (non-El Niño) Conditions



- Surface water flow from east toward west
- Deep thermocline and warm water in western Pacific (associated deep convection & rainfall)
- Shallow thermocline and cool SST's in east Pacific

El Niño Conditions



- Surface water flow toward east
- Warm SSTs, convection & rainfall shift to central Pacific
- Warmer SST's in eastern Pacific

Oscillating Atmospheric Mass

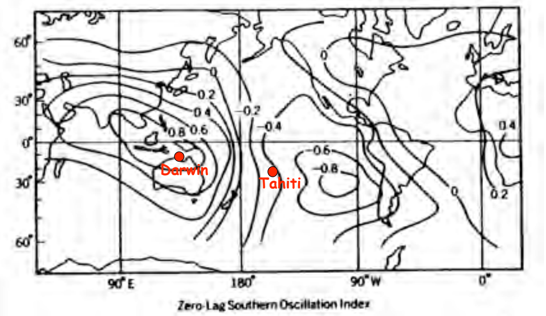
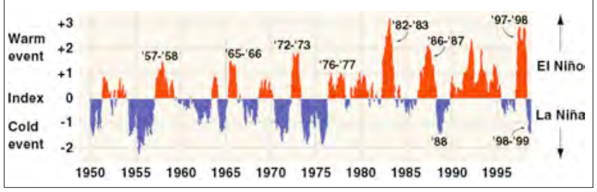


Figure 11.6. The correlation coefficient distribution of surface pressure variations relative to Darwin (from reference 8). Pattern indicates that when the pressure is anomalously high over Indonesia, it is low over the central and southeast Pacific Ocean, and vice versa. This seasaw of surface pressure defines the Southern Oscillation. It also shows why the Troup Index is a keen measure of the Southern Oscillation.

El Niño Southern Oscillation (ENSO)

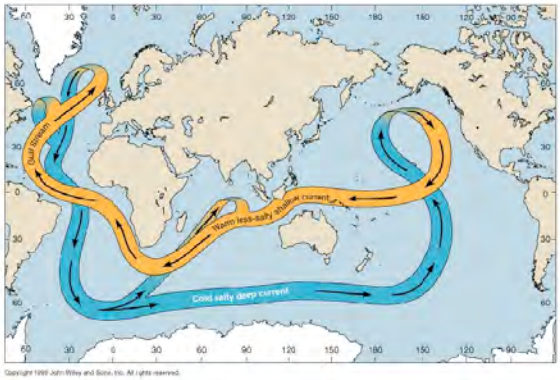
- Southern Osciallation Index (SOI) is the difference in normalized surface pressure (how many std deviations from the mean) between Darwin, Australia and Tahiti
- Positive SOI anomaly: “El Niño”
- Negative SOI anomaly: “La Niña”



Thermohaline Circulation

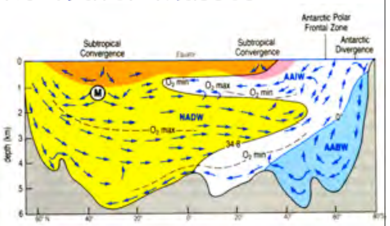
Read article by W. Broecker

Thermohaline Circulation



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.



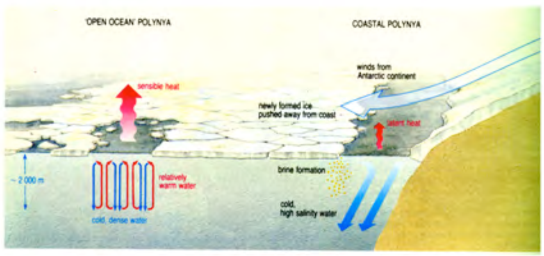
- Deep water formation in North Atlantic
- Bottom water formation in Antarctic
- Ekman convergence in subtropical gyres forces water down against buoyancy

Bottom Water Flow

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

Formation of Antarctic Bottom Water

Figure 6.19 The different roles played by coastal and 'open ocean' polynyas in the production of Antarctic Bottom Water.

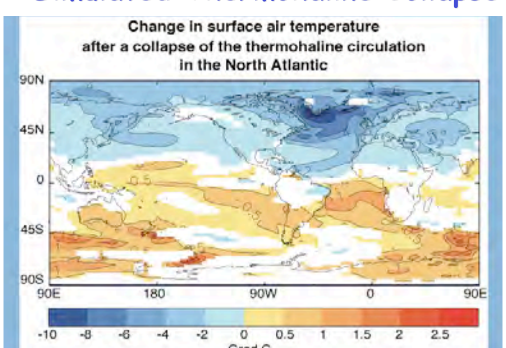


Continuous formation of ice along coast and in "leads" or "polynyas" forms extremely dense water

Thermohaline Heat Pump

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

Simulated Thermohaline Collapse



Average change of annual mean surface air temperature over the years 50-100 after a collapse of the THC in HadCM3. Areas with temperature differences that fall within the natural variability of the control run (at the 95% confidence level) appear as white. (courtesy of Michael Vellinga)