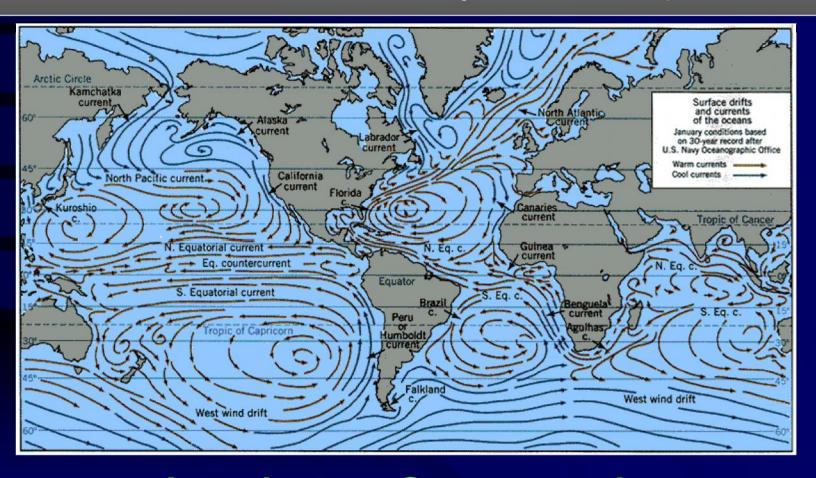
Ocean Circulation

Wind-Driven Surface and Density-Driven Deep Currents

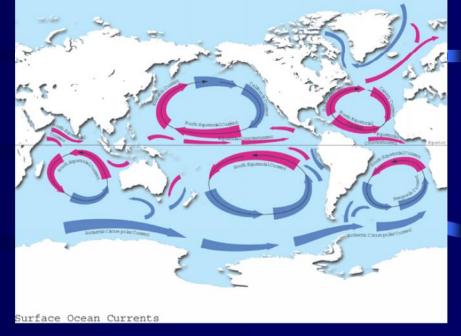


Introductory Oceanography
Ray Rector - Instructor

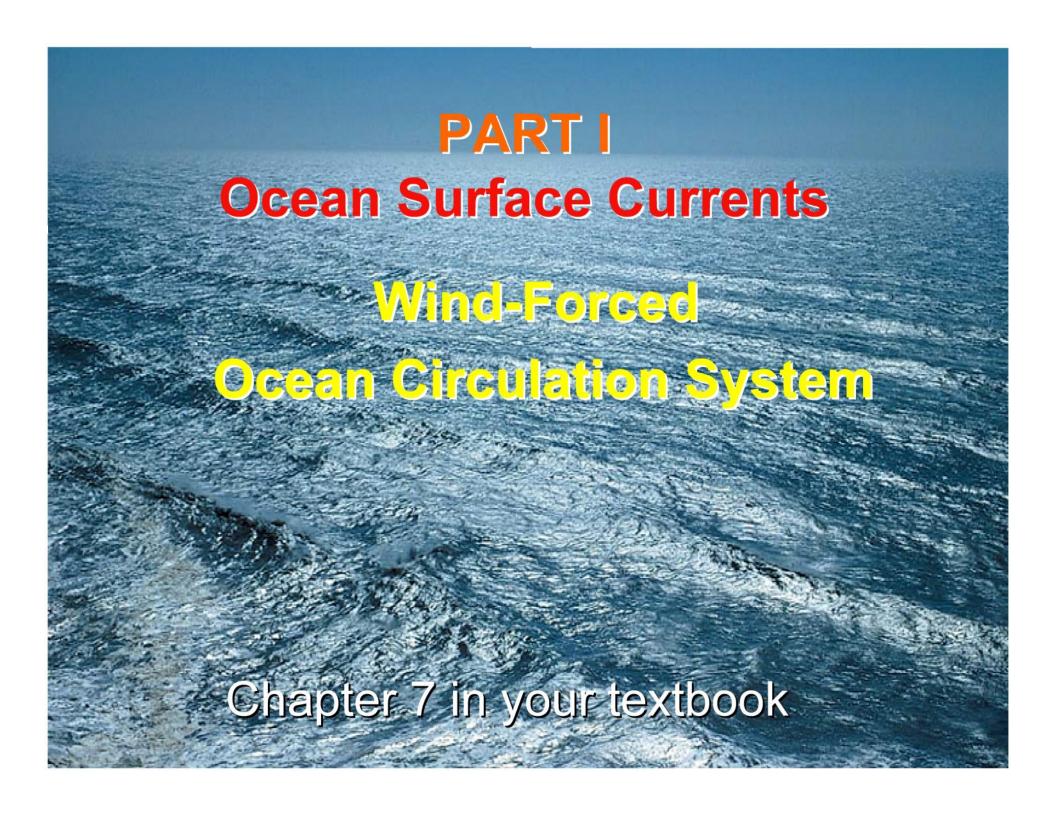
Ocean Circulation

Topics Covered

- ✓ Wind and Surface Currents
- ✓ Measuring Currents
- ✓ The Ekman Transport
- ✓ Geostrophic Gyres
- ✓ Boundary Currents
- ✓ Transverse Currents



- ✓ Countercurrents and Undercurrents
- ✓ Upwelling and Downwelling
- ✓ El Niño and the Southern Oscillation
- ✓ Thermohaline Circulation
- ✓ Global Ocean Heat Conveyor Belt

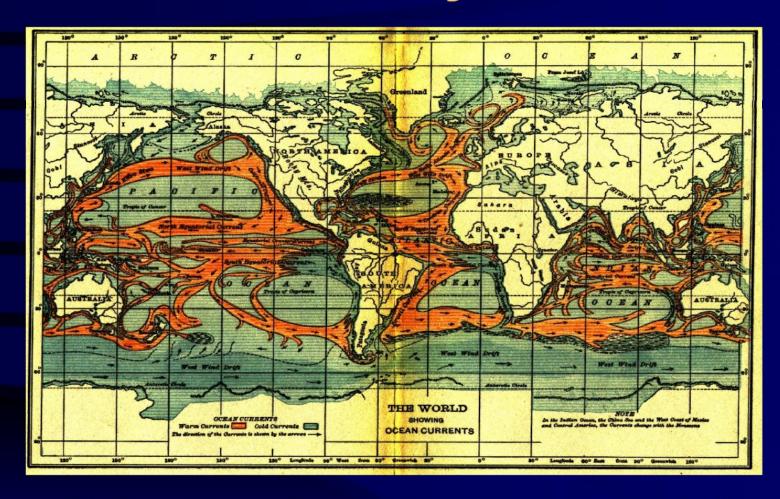


Surface Currents

Key Concepts

- 1) Ocean surface currents are generated by surface wind friction force applied to the ocean's surface mostly by the Westerlies and Trades
- 2) Surface currents affect the upper 10% of the ocean column
- 3) There are five major ocean basin circulation loops called gyres
- 4) Gyres form by five interacting factors: 1) Prevailing surface winds, 2) Coriolis effect, 3) Ocean "hill" pressure gradient, 4) Major landmass barriers, and 5) Westward intensification effect
- 5) Each gyre has four component currents: Western and Eastern boundary currents, and Equatorial and High-latitude transverse currents
- 6) Upwelling and downwelling currents form where surface currents divergence or convergence with each other or a land mass, respectively
- 7) An El Niño is caused by diminished trade winds and the reversal of the equatorial transverse current in the Pacific Ocean, which leads to a build-up of warm ocean waters in the Eastern Pacific La Niña is the opposite

Ocean Surface Layer Circulation



- Ocean Surface Currents have been known for centuries
- Who originally mapped out these currents? Oceanographers?
- What drives these currents?

Ocean Surface Currents

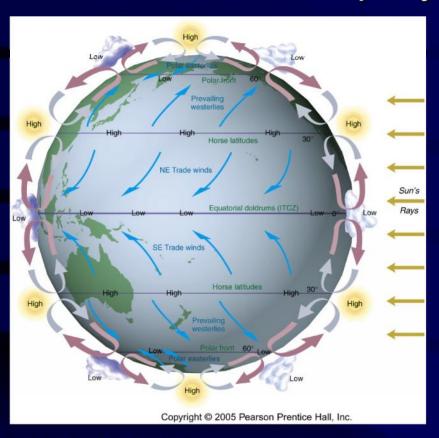
Major Controlling Factors:

- ✓ Prevailing Surface Winds
- ✓ Coriolis Effect
- Gravity
- Landmass Barriers

These factors work together to form a set of ocean basin-scale surface current loops termed geostrophic gyres

Wind - Current Connection

Ocean basins are swept by two prominent wind belts



Prevailing Westerlies

- > Strongest Winds
- Mid-Latitude

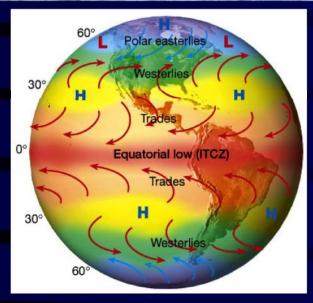
Easterly Trades

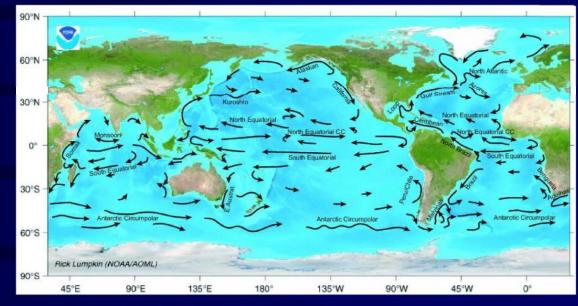
- Most Consistent Winds
- > Low-Latitude

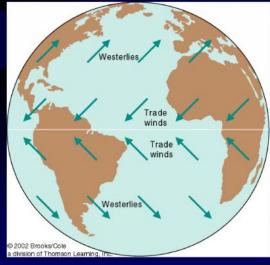
KEY POINTS

- 1) Ocean currents are direct result of ocean surface winds
- 2) The westerlies and trades are the primary forcing winds

Development of Ocean Currents







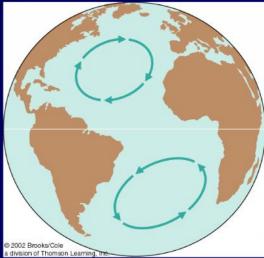
Trade winds

15 N B

Equator

Water moves
westward

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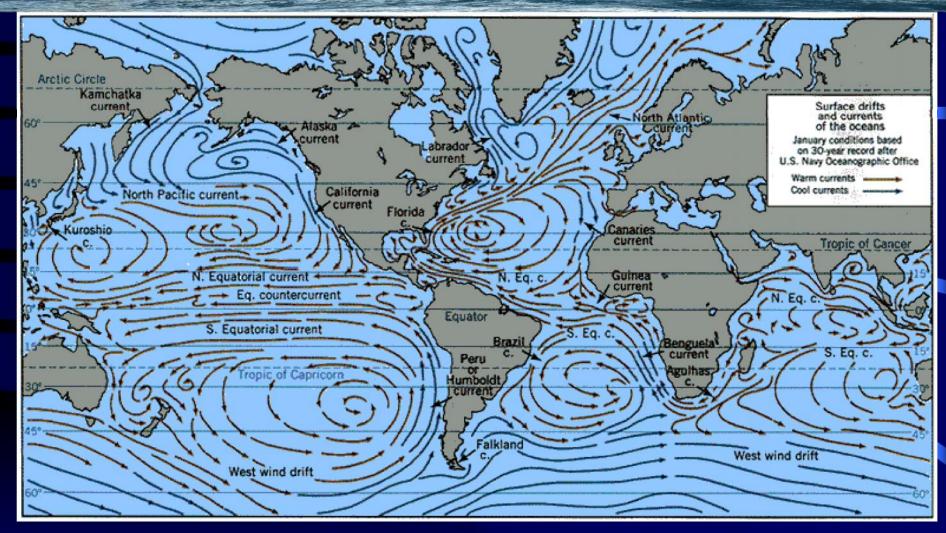


Prevailing Surface Winds

Wind-forced Ocean Currents

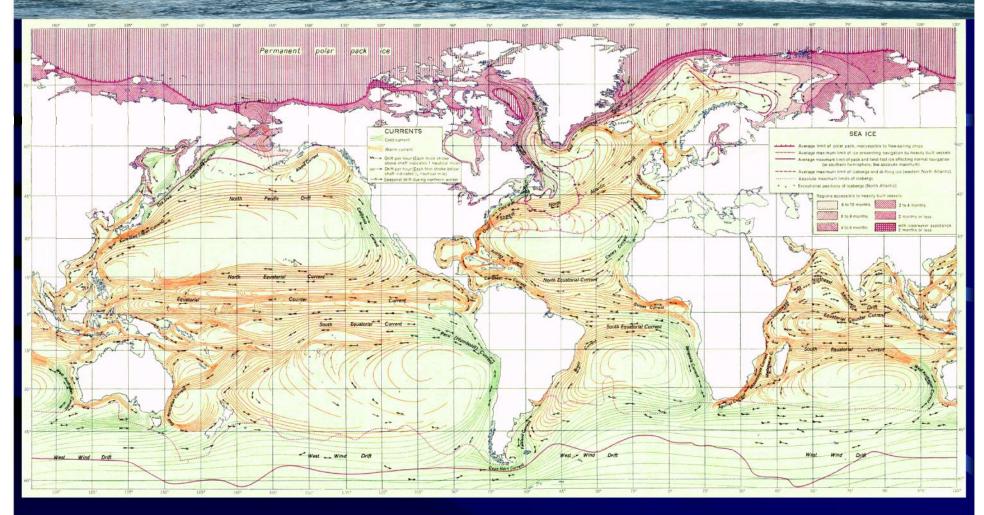
Resultant Ocean Gyres

Ocean Surface Currents



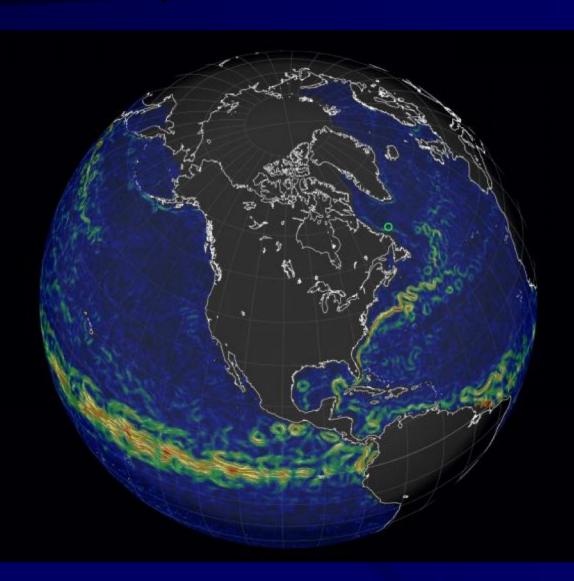
- 1) Five ocean-basin size circular rotating geostrophic gyres
- 2) West Wind Drift current. 3) Warm and Cold currents

Ocean Surface Currents



- 1) Five ocean-basin size circular rotating geostrophic gyres
- 2) West Wind Drift current. 3) Warm and Cold currents

Real-Time Global Ocean Currents



55.26° N, 53.93° W × 305° @ 0.21 m/s

© Cameron Beccario

Vertical Extent of Surface Currents

1) Ocean Divided into Three Layers

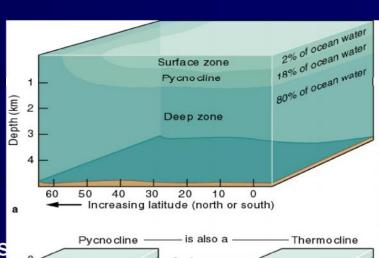
- Surface Zone Top 2%
- Pycnocline Middle 18%
- **Deep Zone** bottom 80%

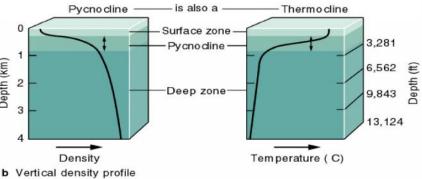
2) Surface Zone

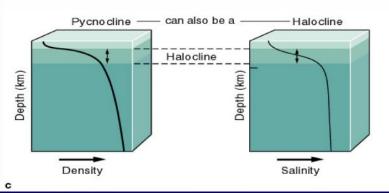
- Warmest, least dense
- Typically extends down to 150 meters
- Makes up only top 2% of ocean
- Zone coincides with surface currents

3) Surface Currents

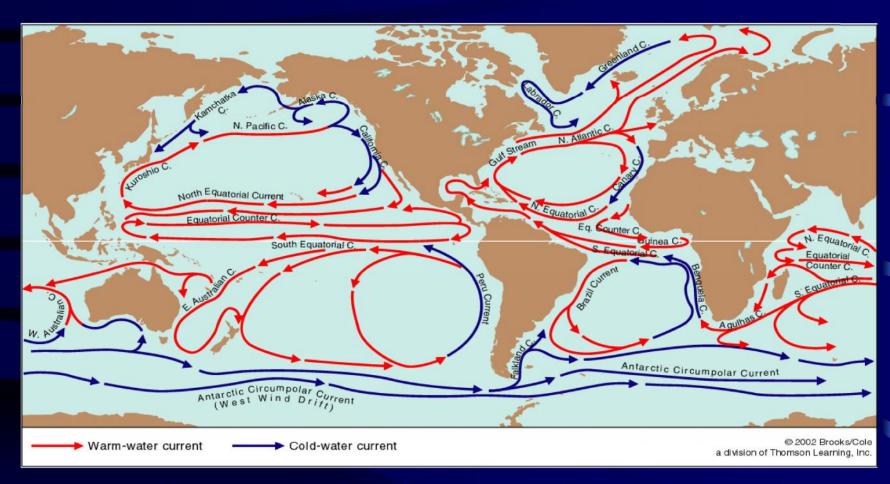
- Coincides with Surface Zone
- Extent down 100 to 200 meters
- Deeper on western side of basins
- Shallower on eastern side of basins







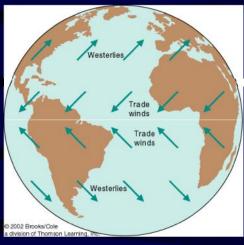
Major Ocean Surface Currents



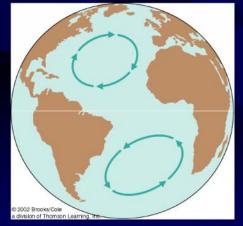
Gyre Current Directions and Temperatures

- > Red = Warm Currents
- > Blue = Cold Currents

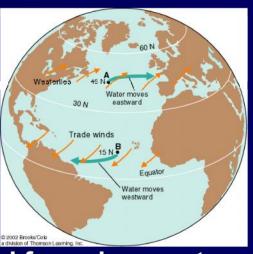
Development of Ocean Gyres



I. Prevailing surface winds provide a forcing agent



III. Surface currents deflected by landmasses to produce ocean gyres

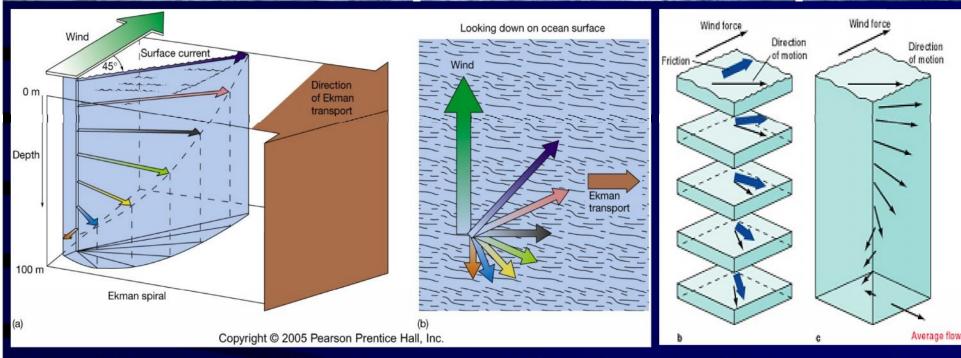


II. Wind forced currents modified by Coriolis effect and gravity



IV. Example: North Atlantic Gyre

The Ekman Spiral and Transport



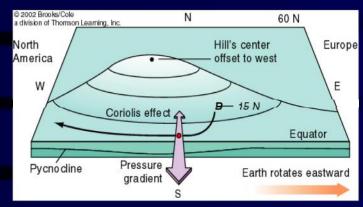
The Ekman *Spiral*

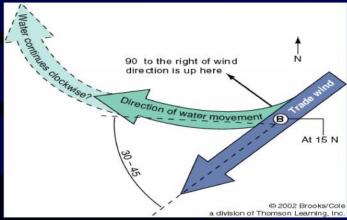
- Caused by wind and Coriolis effect
- ➤ Water motion does not "spiral" Instead current velocity progressively changes with depth
- ➤ Progressive change in velocity due to friction coupling between layers, layer isolation, and the Coriolis effect

The Ekman Transport

- ➤ Net motion of water down to 100 meters after allowance of Ekman spiral effect
- ➤ Direction of Ekman transport is 90° to the right of the wind in the N. Hemisphere and 90° to the left in the S. Hemisphere

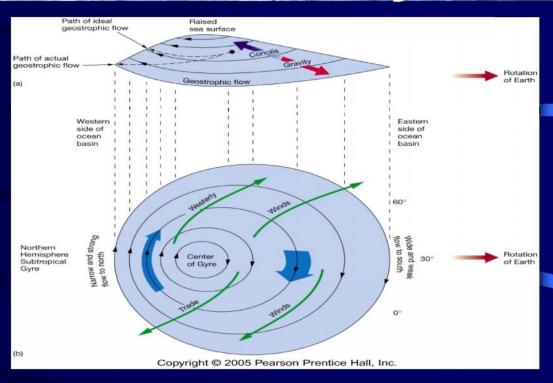
Development of Ocean Gyres





Geostrophic Factors

- 1) Wind Force/Friction
- 2) Coriolis Effect
- 3) "Hill" Pressure Gradient
- 4) Landmass Barriers
- 5) Westward Intensification



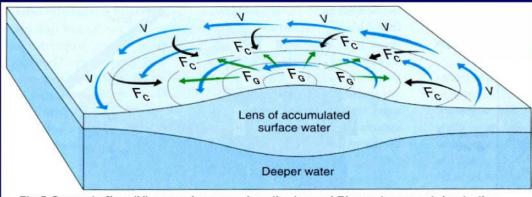
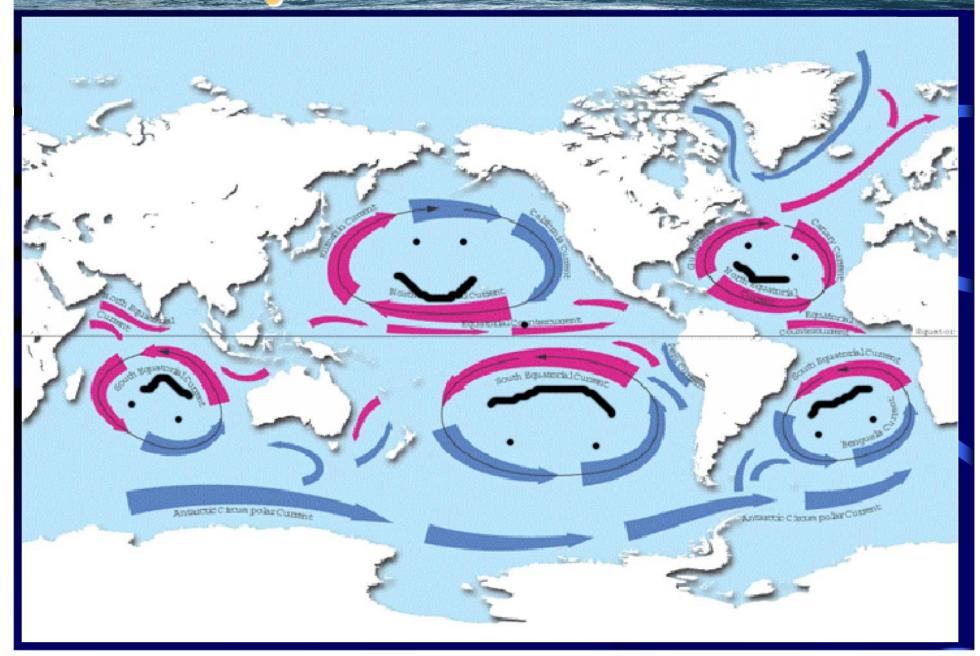
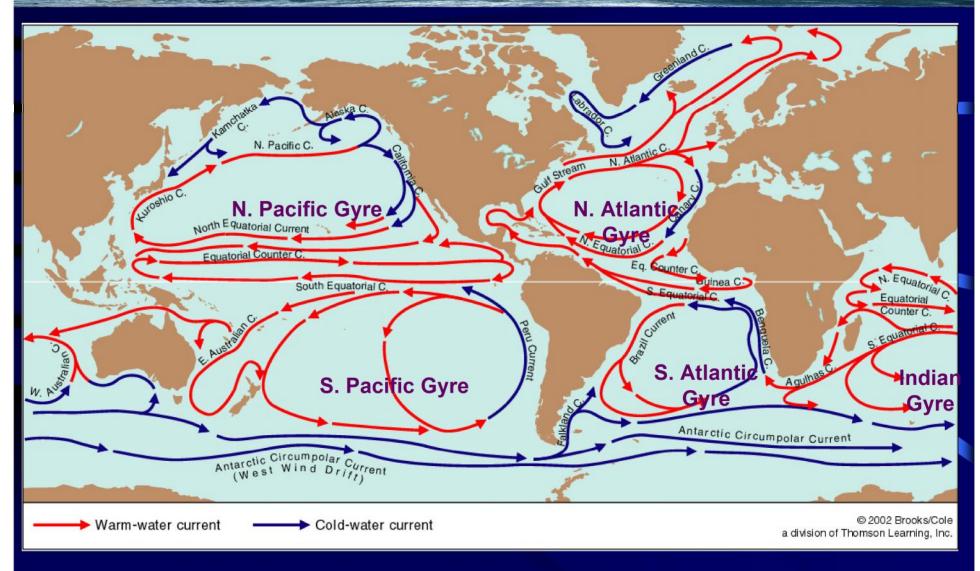


Fig.5 Currents flow (V) around a gyre when the inward Ekman transport due to the Coriolis effect (Fc) is balanced by Fg, the outward force due to gravity.

Major Ocean Currents

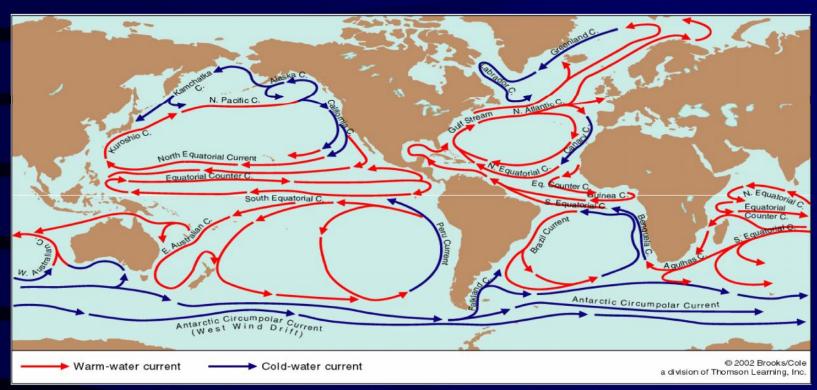


Five Ocean Basin Gyres



The Antarctic Circumpolar Current is not one of the gyres

The Boundary Currents



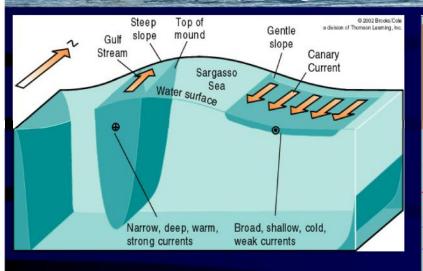
Five Western Boundary Currents

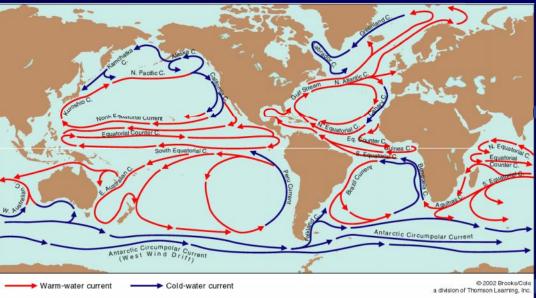
- 1) Gulf Stream
- 2) Brazil
- 3) Japan
- 4) East Australian
- 5) Agulhas

Five Eastern Boundary Currents

- 1) Canary
- 2) Benguela
- 3) California
- 4) West Australian
- 5) Peru

Boundary Current Characteristics





Western versus **Eastern** Boundary Currents

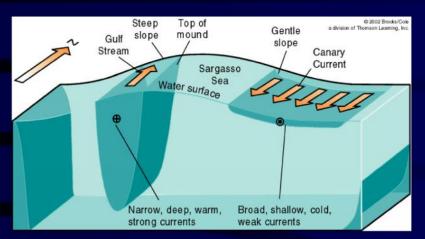
Type of Current (example)	General Features	Speed	Transport (millions of cubic meters per second	Special Features
Western Boundary Currents	Warm			
Gulf Stream, Kuroshio (Japan) Current	Narrow, , 100 km. Deep—substantial transport to depths of 2 km	Swift, hundreds of kilometers per day.	Large, usually 50 sv or greater.	Sharp boundary with coastal circulation system; little or no coastal upwelling; waters tend to be depleted in nutrients, unproductive; waters derived from trade wind belts.
Eastern Boundary Currents	Cold			
California Current. Canary Current	Broad, ~1,000 km. Shallow, , 500 m.	Slow, tens of kilometers per day.	Small, typically 10–15 sv.	Diffuse boundaries separating from coastal currents; coastal upwelling common; waters derived from mid-latitudes.

Source: From M. Grant Gross, *Oceanography: A View of the Earth,* 5/e, © 1990, p. 173. Prentice-Hall. Reprinted by permission.

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Boundary Current Flow Rates

Western versus Eastern Boundary Currents



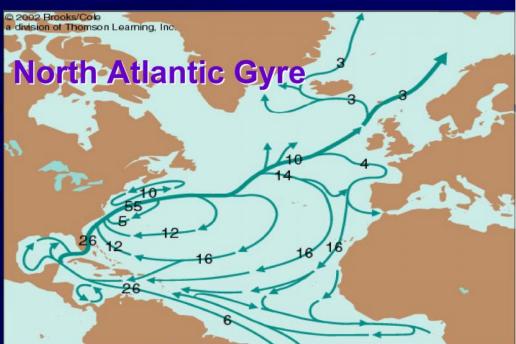


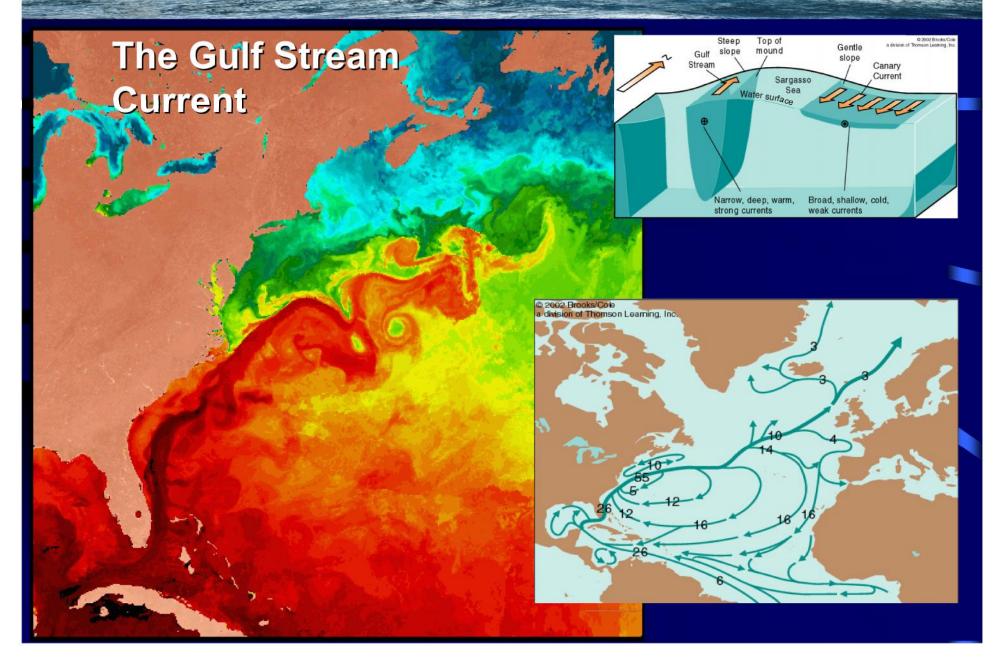
Table 9.1 Boundary Currents in the Northern Hemisphere

Type of Current (example)	General Features	Speed	Transport (millions of cubic meters per second	Special Features
Western Boundary Currents	Warm			
Gulf Stream, Kuroshio (Japan) Current	Narrow, , 100 km. Deep—substantial transport to depths of 2 km	Swift, hundreds of kilometers per day.	Large, usually 50 sv or greater.	Sharp boundary with coastal circulation system; little or no coastal upwelling; waters tend to be depleted in nutrients, unproductive; waters derived from trade wind belts.
Eastern Boundary Currents	Cold			
California Current. Canary Current	Broad, ~1,000 km. Shallow, , 500 m.	Slow, tens of kilometers per day.	Small, typically 10–15 sv.	Diffuse boundaries separating from coastal currents; coastal upwelling common; waters derived from mid-latitudes.

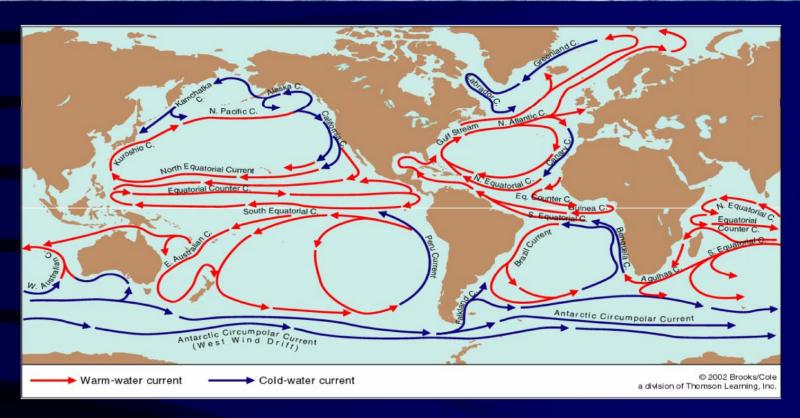
Source: From M. Grant Gross, *Oceanography: A View of the Earth,* 5/e, © 1990, p. 173. Prentice-Hall. Reprinted by permission.

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Western Boundary Currents



The Transverse Currents



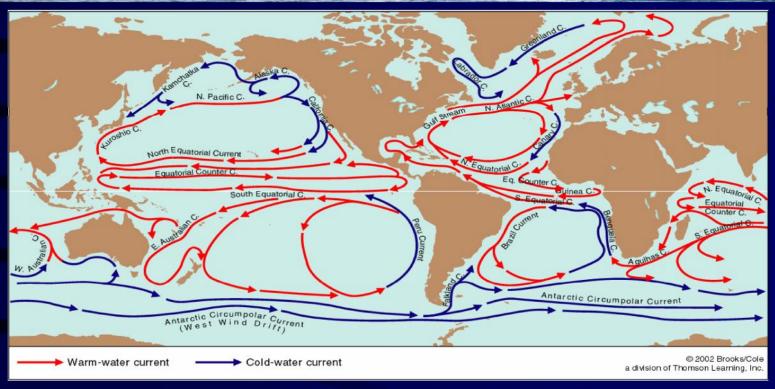
Nine Transverse Currents

- 1) North and South Atlantic Equatorial
- 2) North and South Pacific Equatorial
- 3) North and South Indian Equatorial
- 4) North Atlantic and Pacific Currents
- 5) Antarctic Circumpolar (West Wind Drift)

Characteristics

- 1) Travels east to west
- 2) Moderate current speed
- 3) Moderate volume (except West Wind Drift)
- 4) Equatorial currents are warm
- 5) High latitude currents are cold

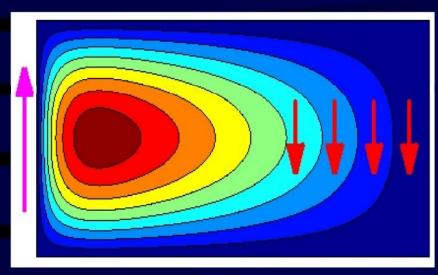
Antarctic Circumpolar Current



A Super-sized Transverse Current

- ✓ Called the "West Wind Drift"
- ✓ The Ocean's largest surface current
- ✓ Powered by very strong Southern Hemi Westerlies
- ✓ Isolates Antarctica from warmer currents
- ✓ Stormiest weather on the planet

Westward Intensification

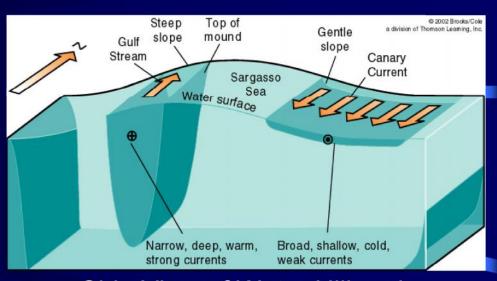


Overhead View of Water Hill in an Ocean Basin

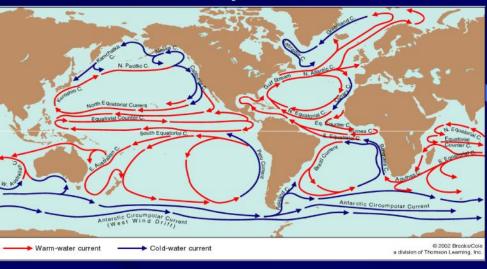
Westward Intensification

Factors

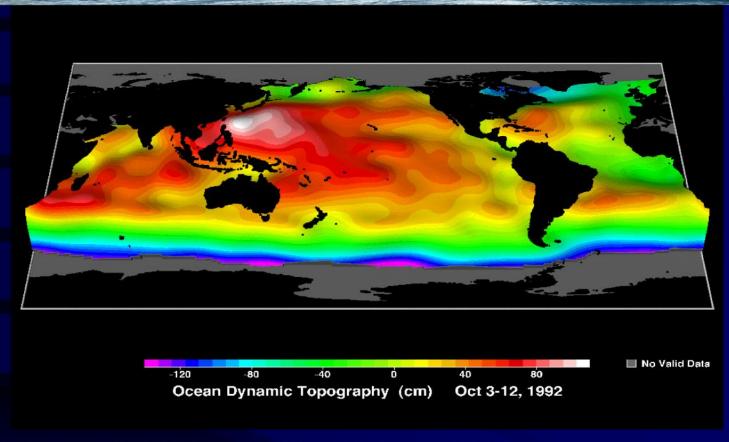
- 1) Converging Flow of Trade Winds
- 2) Eastward Rotation of Earth
- 3) Continent Landmass Barriers



Side View of Water Hill and Boundary Currents



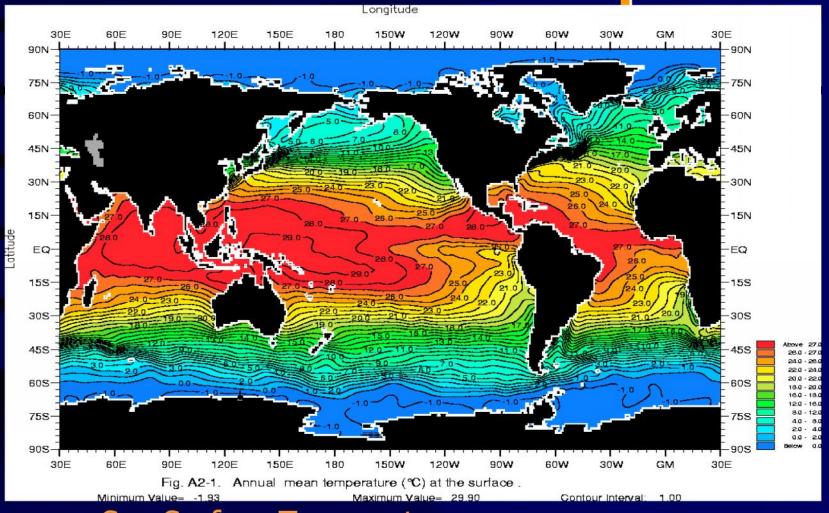
Ocean Surface Topography



Ocean Surface Height Anomalies (centimeters)

- > Heights compared to averaged global sea level
- ➤ Highest = Western sides of ocean basins
- Lowest = Eastern sides of ocean basins

Ocean Surface Temperature



Sea Surface Temperature (Annual mean temperature (°C) at the surface)

- Warmest in low-latitudes
- Coldest in high latitudes

Ocean Upwelling and Downwelling

Six Principle Factors

- ✓ Wind
- ✓ Ekman transport
- ✓ Basin edge effect
- ✓ Bottom topography
- ✓ Converging currents
- ✓ Diverging currents

Three Principle Regions

- ✓ Continental margins
- √ Equatorial belt
- √ Circum-Polar

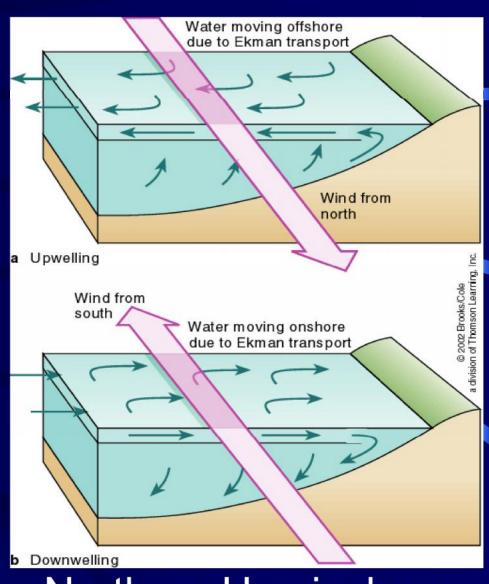


Coastal Upwelling

Coastal Upwelling and Downwelling

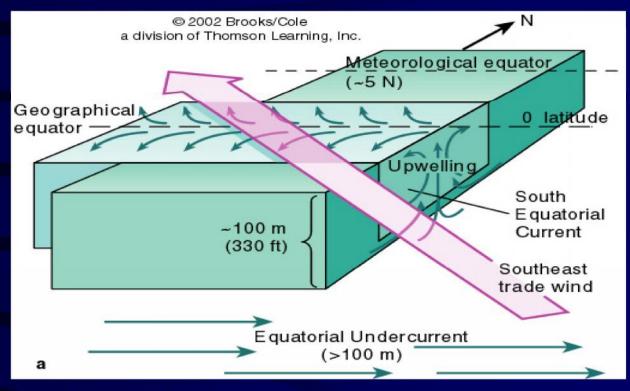
Principle Factors

- ✓ Prevailing Longshore Winds
- ✓ Coriolis Effect on Current
- √ Ekman Transport
- ✓ Resultant Current Either Diverges or Converges in Respect to Coastline
- ✓ Divergence = Upwelling
- ✓ Convergence = Downwelling



Northern Hemisphere

Equatorial Upwelling

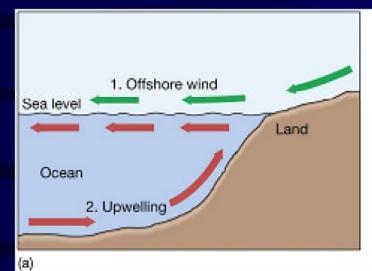


Three Principle Factors

- ✓ Southeast Trade Winds
- ✓ Bifurcating Coriolis Effect at Equator
- ✓ Resulting Diverging Current at Equator = Upwelling

Other Types of Upwelling

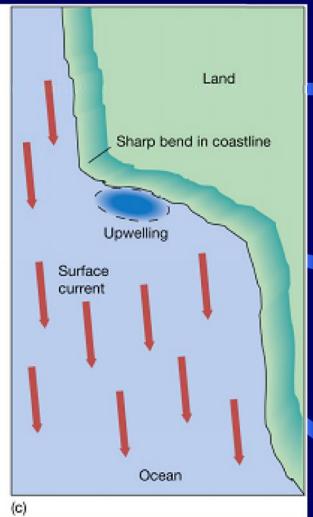
Offshore Wind-Induced Upwelling



Sea level

Current flow
Tablemount

(b)



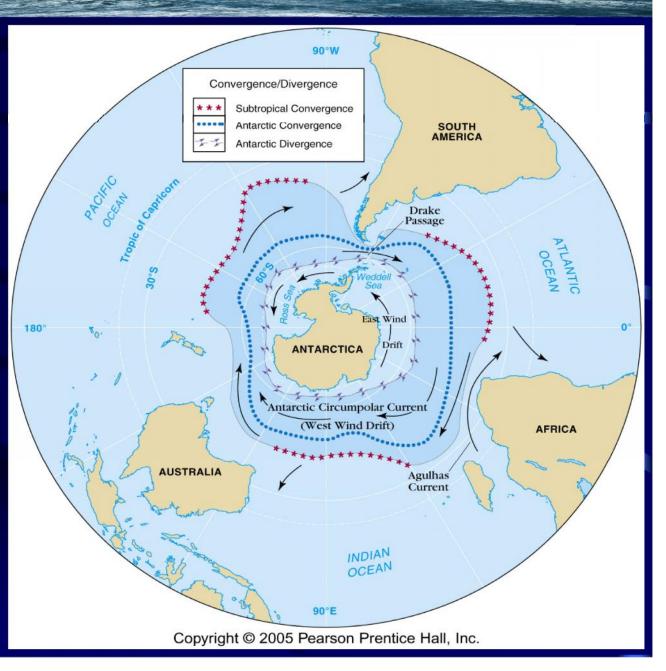
Bottom Topography-Induced Upwelling

Irregular Coastline-Induced Upwelling

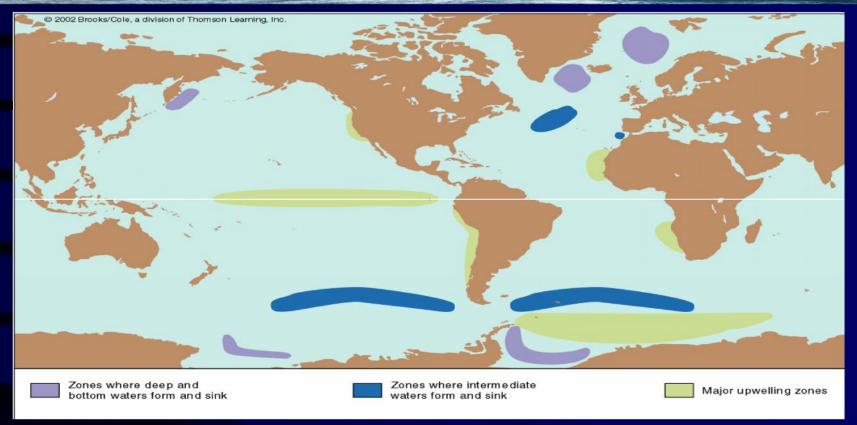
Circum-Antarctic Upwelling and Downwelling

Convergence = Downwelling

Divergence = Upwelling



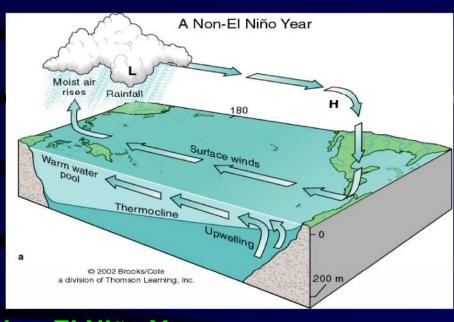
Regions of Ocean Upwelling and Downwelling



Three Principle Regions

- ✓ Continental margins
- ✓ Equatorial belt
- √ Circum-Polar

El Niño and the Southern Oscillation - ENSO



Indonesia Drought conditions Rainfall Water is 0.5 - 1.0 C Water warmer is 1 C warmer thermocline Deeper thermocline Deeper thermocline Deeper thermocline Dear Downwelling warmer warme

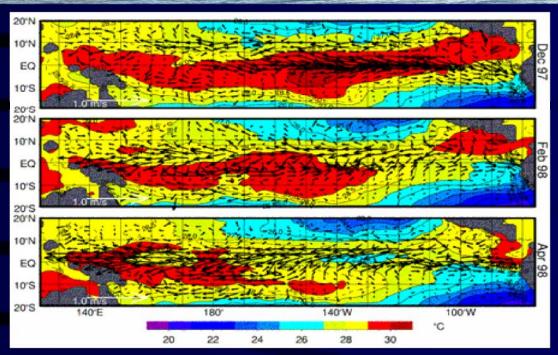
Non-El Niño Year

- 1) Normal easterly trade wind activity
- 2) Normal east-to-west N. and S. Pacific Equatorial Current
- 3) Warmest water in equatorial West Pacific
- 4) Low pressure, wet equatorial W. Pacific
- 5) Dry, high-pressure equatorial E. Pacific

El Niño Year

- 1) Little to no easterly trade wind activity
- 2) Reversal of east-to-west N. and S. Pacific Equatorial Current (now west to east)
- 3) Warmest water in equatorial East-Central Pacific
- 4) Droughts in equatorial Western Pacific
- 5) Wet, low pressure equatorial Central Pacific

El Niño and the Southern Oscillation - ENSO



El Niño Year

Non-El Niño Year

Non-El Niño Year

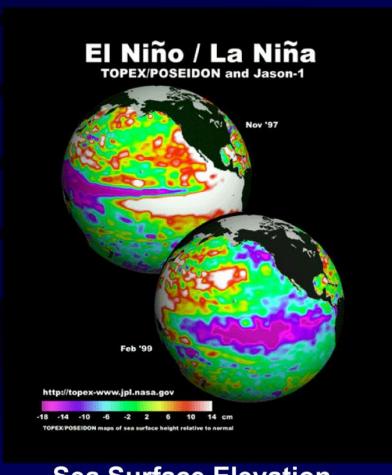
- 1) Normal easterly trade wind activity
- 2) Normal east-to-west N. and S. Pacific Equatorial Current
- 3) Warmest water in equatorial West Pacific
- 4) Stormy, wet equatorial Western Pacific
- 5) Dry equatorial Eastern Pacific

El Niño Year

- 1) Little to no easterly trade wind activity
- 2) Reversal of east-to-west N. and S. Pacific Equatorial Current (now west to east)
- 3) Warmest water in equatorial East-Central Pacific
- 4) Droughts in equatorial Western Pacific
- 5) Stormy, wet equatorial Central Pacific

El Niño and El Niña — Mirror Patterns

El Niño versus La Niña Events



Sea Surface Elevation

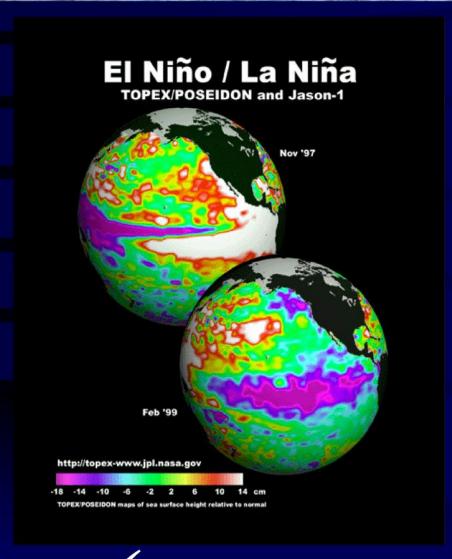
El Niño Year

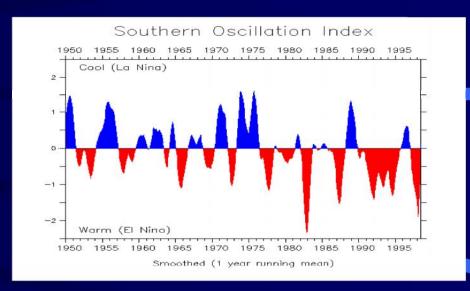
- 1) Little to no easterly trade wind activity
- 2) Reversal of east-to-west N. and S. Pacific **Equatorial Current (now west to east)**
- 3) Warmest water in equatorial East-Central **Pacific**
 - 4) Droughts in equatorial Western Pacific
 - 5) Stormy, wet equatorial Central Pacific

La Niña Year

- 1) Strong easterly trade wind activity
- 2) Strong east-to-west N. and S. Pacific **Equatorial Current**
- 3) Abnormally cool water in equatorial East-**Pacific**
 - 4) Droughts in equatorial Eastern Pacific
 - 5) Very wet equatorial Central Pacific

El Niño and El Niña - Mirror Patterns







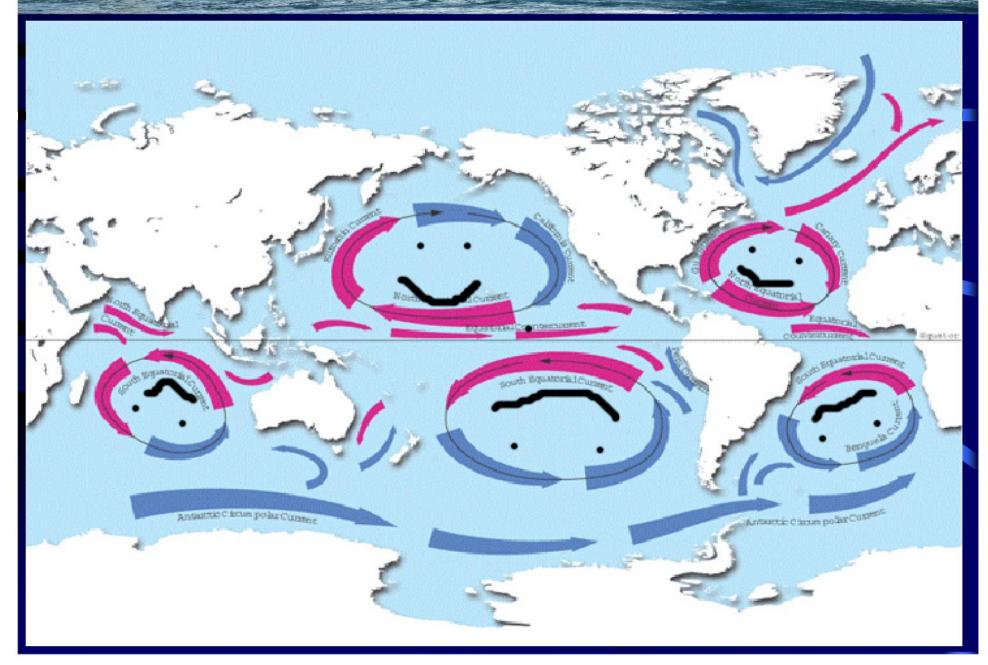
✓ El Nino's run in 2 to 10 year cycles

Surface Currents

Key Concepts

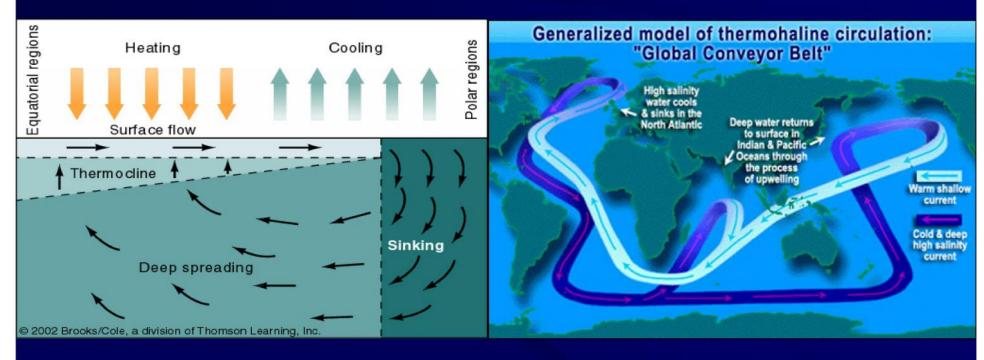
- 1) Ocean surface currents are generated by surface wind friction force applied to the ocean's surface mostly by Westerlies and Trades
- 2) Surface currents affect the upper 10% of the ocean column
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- 4) Gyres form by five interacting factors: 1) Prevailing surface winds, 2) Coriolis effect, 3) Ocean "hill" pressure gradient, 4) Major landmass barriers, and 5) Westward intensification effect
- 5) Each gyre has four unique component currents: Western and Eastern boundary currents, and Equatorial and High-latitude transverse currents
- 6) Upwelling and downwelling currents form where surface currents divergence or convergence with each other or a land mass, respectively
- 7) An El Niño is caused by diminished trade winds and the reversal of the equatorial transverse current in the Pacific Ocean, which leads to a build-up of warm ocean waters in the Eastern Pacific La Niña is the opposite

Current Discussion



PART II Deep Ocean Density Currents

Temperature/Salinity-Controlled Ocean Circulation System



Chapter 7 in your textbook

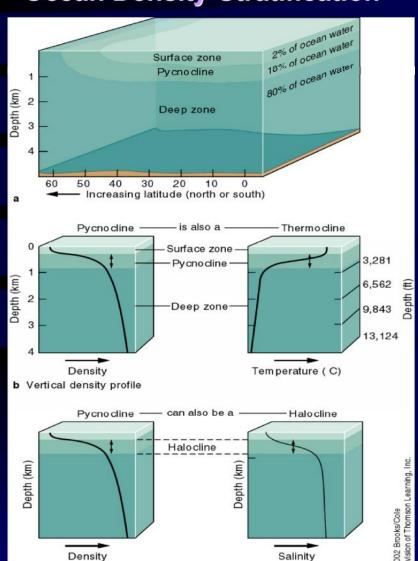
Deep Ocean Circulation

Key Concepts

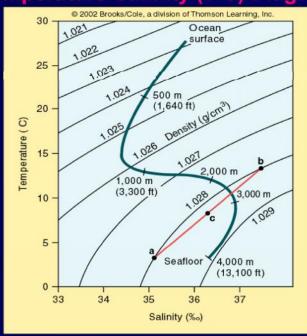
- 1) Ocean is density-stratified = controlled by temperature and salinity
- 2) Ocean water masses are identified by their Temp-Salinity profile
- 3) Seawater masses are named surface, intermediate, deep, or bottom
- 4) Gravity drives the deep ocean currents ---- determined by the difference in density between adjacent ocean water masses
- 5) Deep ocean currents occur in the lower 90% of the ocean
- 6) Most deep water masses form at the surface in polar regions and subsequently sink and move toward the equator
- 7) Formation of deep waters involves: 1) decrease in temperature, 2) increase in salinity, and/or 3) mixing of water masses
- 8) Deep ocean currents are very slow; residence time is 100's of years
- 9) Deep ocean currents connect with surface currents to form a global-scale conveyor belt for the mass transfer of heat

Thermohaline Circulation

Ocean Density-Stratification



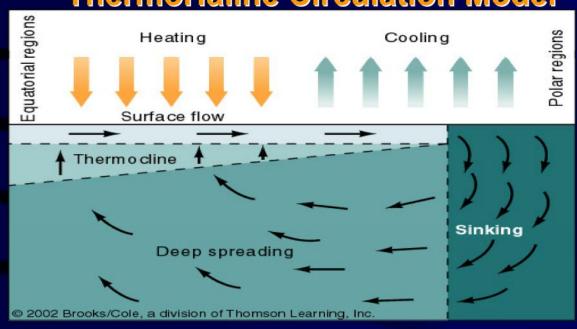
Temperature-Salinity (T-S) Diagram

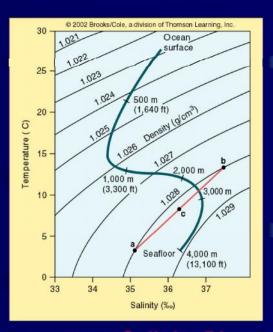


- ✓ Ocean column is density-stratified
- ✓ Ocean water masses are defined by their temperature and salinity
- ✓ Two water masses of different T and S can have identical densities
- ✓ Mixing two water masses of same density can produce a hybrid mass of lower density termed "caballing"

Formation and Movement of Deep Waters

ThermoHaline Circulation Model



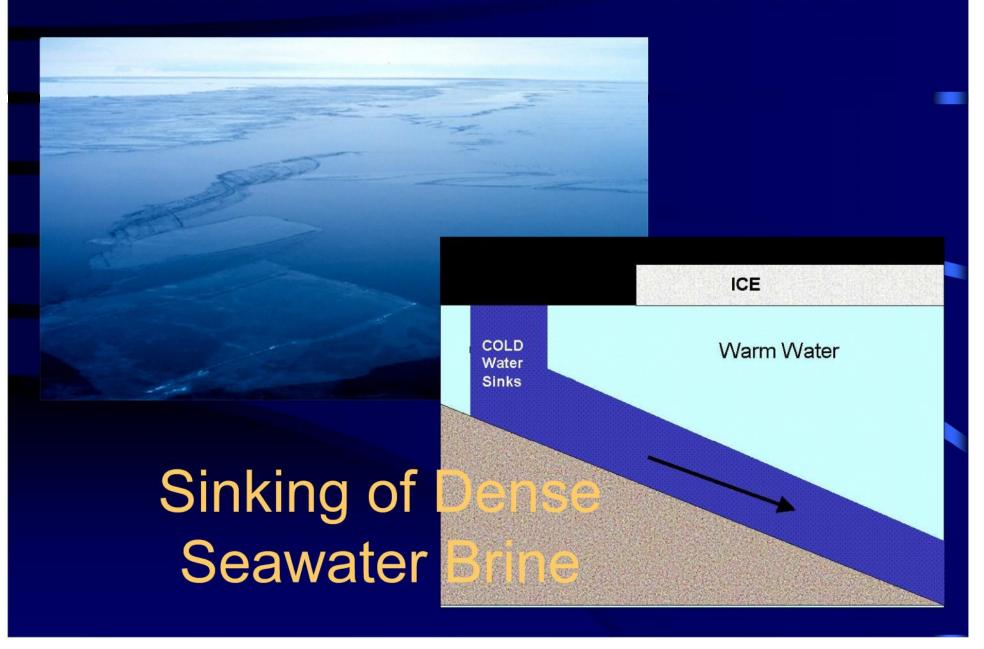


Temperature-Salinity Diagram

Density-driven Deep Ocean Currents

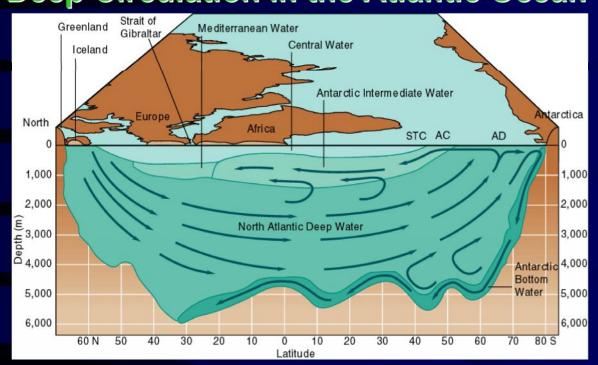
- ✓ Sinking of super-cooled, salty polar surface waters
- ✓ Very slow lateral deep water current flow
- ✓ Rising of mixed intermediate and deep waters
- ✓ Incorporation into mid- and low-latitude surface currents

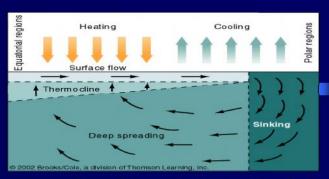
Formation of Polar Sea Ice & Brine



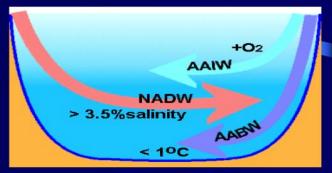
Deep Ocean Water Masses

Deep Circulation in the Atlantic Ocean





Density Circulation Model



Deep Ocean Water Masses

- ✓ Formation and sinking of polar Antarctic Bottom Water (AABW) and North Atlantic Deep Water (NADW) due to super-cooling of surface waters
- ✓ Formation and sinking of Antarctic (due to current convergence) and Mediterranean (due to hyper-evaporation) Intermediate Waters (AAIW and MIW)
- ✓ Very slow lateral deep water current flow and overlapping of water masses

Thermohaline Circulation

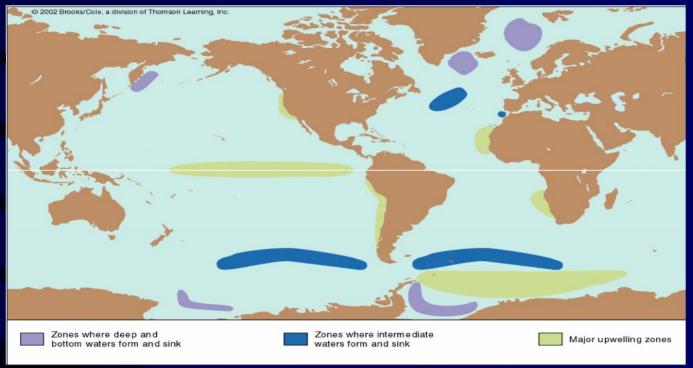


Ocean Current Convergence Zones

- ✓ Zones of Convergence where distinct surface current water masses
- ✓ The five major surface water masses are 1) Central Water, 2) Subarctic Surface Water, 3) Arctic Surface Water, 4) Subantarctic Surface Water, and the Antarctic Surface Water
- ✓ Convergence zones are the site where ocean water masses mix and sink

Thermohaline Circulation

Zones of Sinking and Rising of Ocean Water Masses



- ✓ Formation and sinking of polar Antarctic Bottom Water (AABW) and North Atlantic Deep Water (NADW) due to zones of super-cooling of surface waters
- ✓ Formation and sinking of Antarctic (due to current convergence) and Mediterranean (due to hyper-evaporation) Intermediate Waters (AAIW and MIW)
- ✓ Rising and mixing of deep and intermediate water masses along zones of divergence and upwelling at equator, Antarctic circumpolar, and coastlines

Measuring Ocean Currents

1) Surface Buoys





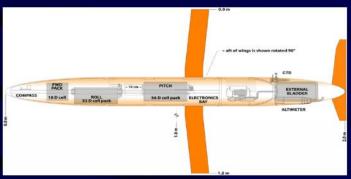


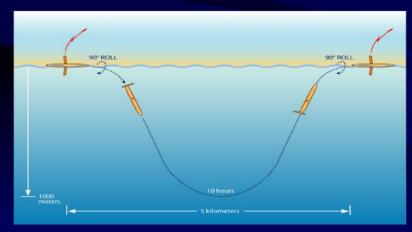


Measuring Ocean Currents

and



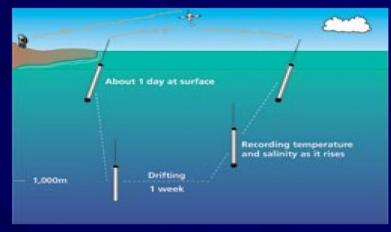




2) Drift Gliders



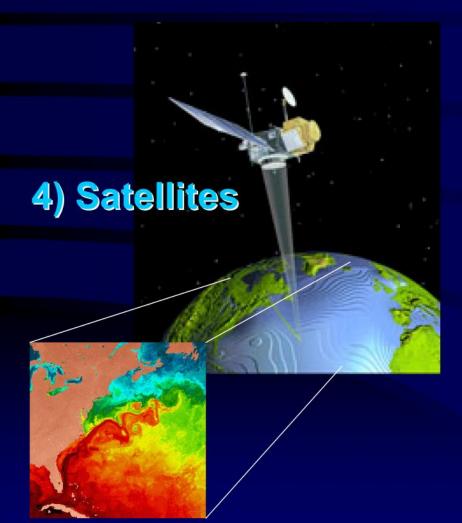




3) Drift Bobbers

Measuring Ocean Gurrents

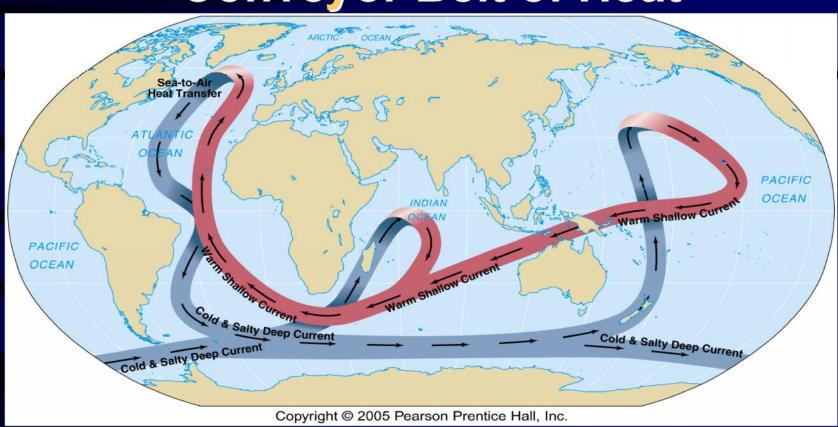
Real-Time Remote Sensing – 24/7





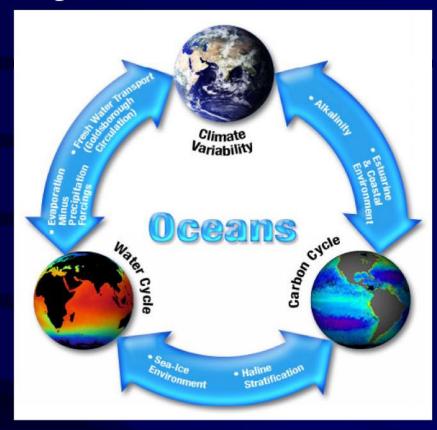
5) Shipboard

Global-Scale Ocean Mass Transfer Conveyor Belt of Heat



- √ Super-warmed equatorial surface waters move poleward
- ✓ Super-cooled polar surface waters become dense and sink to become the bottom and deep waters (AABW, NADW)
- ✓ Bottom and deep waters (e.g. AABW, NADW) move equatorial and eventual mix and rise to become mid- and low-latitude surface waters

The Ocean's Role in Water Cycle, Carbon Cycle and Global Climate



The Ocean Plays a Central Role in Controlling Earth's

- ✓ Hydrologic Cycle (Heat absorbing, releasing, and transferring)
- √ Carbon Cycles (Heat absorbing)
- ✓ Climate Moderation (Limiting Variation)

Deep Ocean Circulation

Key Concepts

- 1) Ocean is density-stratified = controlled by temperature and salinity
- 2) Ocean water masses are identified by their Temp-Salinity profile
- 3) Seawater masses are named surface, intermediate, deep, or bottom
- 4) Gravity drives the deep ocean currents ---- determined by the difference in density between adjacent ocean water masses
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Deep Current Discussion

