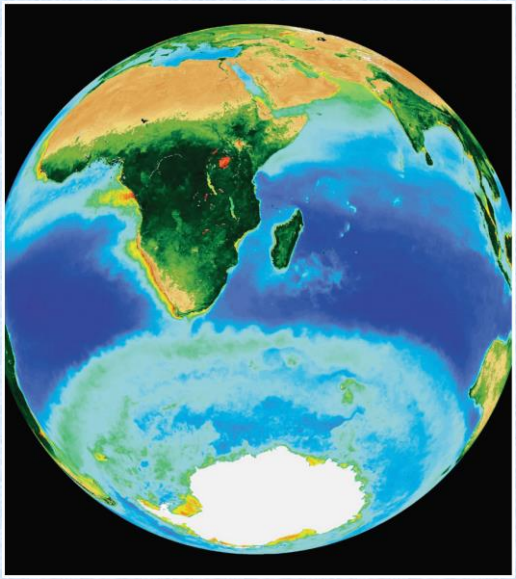
Chapter 7 - Chapter Overview

- Ocean currents are moving loops of water.
- Each ocean basin has its own circulation pattern.
- Currents redistribute global heat.
- Thermohaline circulation affects deep currents.
- Currents affect marine life.
- Currents as a source of energy

Types of Ocean Currents

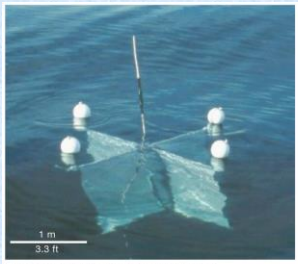
- **Surface currents**
  - Wind-driven
  - Primarily horizontal motion
- **Deep currents**
  - Driven by differences in density caused by differences in temperature and salinity
  - Vertical and horizontal motions

as seen from space



Measuring Surface Currents

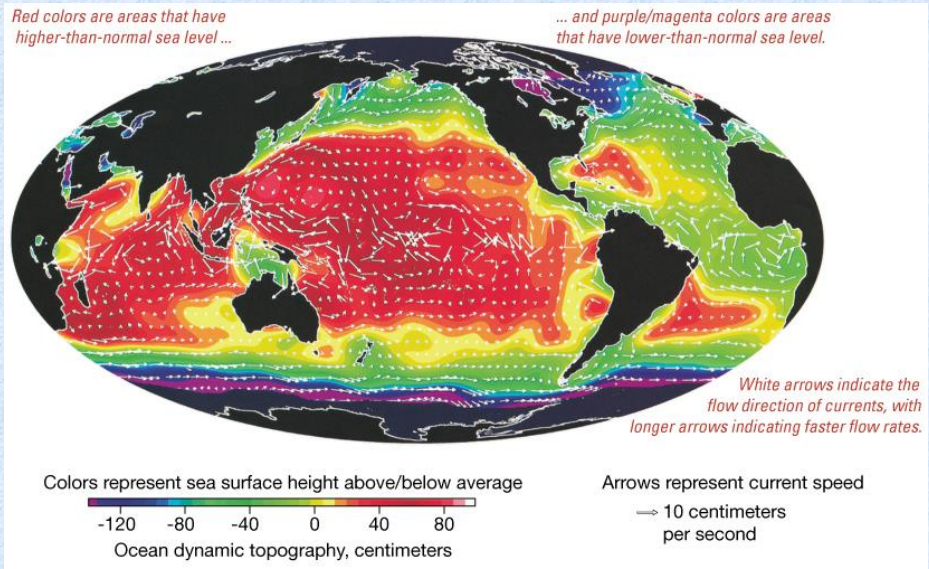
- **Direct methods**
  - Floating device tracked through time
  - Fixed current meter
- **Indirect methods**
  - Pressure gradients
  - Radar altimeters
  - Doppler flow meter



(a) A **drift current meter** afloat in the ocean.

(b) A **propellor-type flow meter** being brought back aboard a research vessel.

Ocean Dynamic Topography

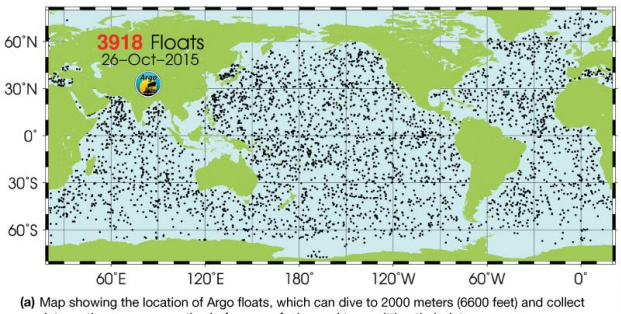


Measuring Deep Currents

- Chemical tracers
  - Tritium
  - Chlorofluorocarbons
- Characteristic temperature and salinity

Measuring Deep Currents

- **Argo**
  - Global array of free-drifting profiling floats
  - Floating device tracked through time



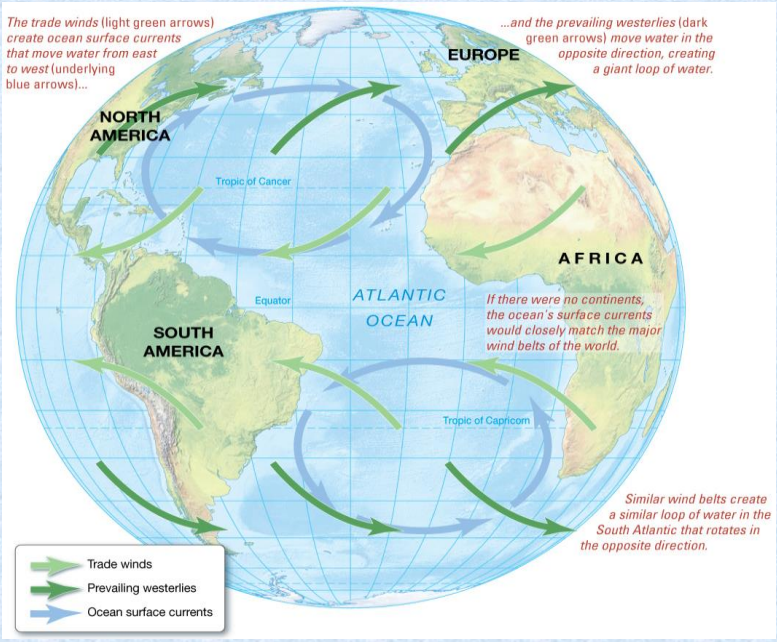
(a) Map showing the location of Argo floats, which can dive to 2000 meters (6600 feet) and collect data on the ocean properties before resurfacing and transmitting their data.

(b) Argo floats are deployed from research or cargo vessels.

Surface Currents

- Occur above pycnocline
  - Affect only 10% of ocean water on Earth
- Friction between wind and ocean surface
  - 2% of wind energy transferred to ocean surface
  - Surface currents slower speed than corresponding winds
- Generally follow Earth's wind belt pattern

Wind Belts and Surface Current Movement



Surface Currents

- Distribution of continents
  - Influences flow in each ocean basin
- Other current influences
  - Gravity
  - Friction
  - Coriolis effect

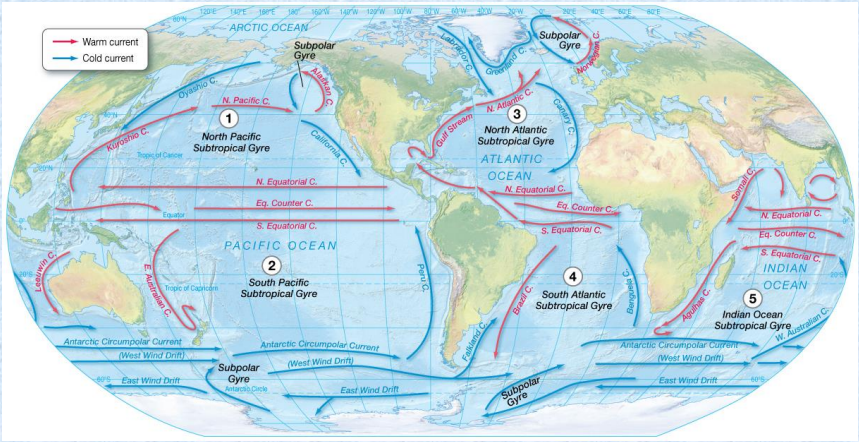
Subtropical Gyres

- **Gyres** – Large, circular loops of moving water
- **Subtropical gyres** centered around 30 degrees latitude
- Bounded by
  - Equatorial current
  - Western Boundary currents
  - Northern or Southern Boundary currents
  - Eastern Boundary currents

Five Subtropical Gyres

- North Atlantic – Columbus Gyre
- South Atlantic – Navigator Gyre
- North Pacific – Turtle Gyre
- South Pacific – Heyerdahl Gyre
- Indian Ocean – Majid Gyre

Subtropical Gyres and Currents



Subtropical Gyre Currents

- **Equatorial Currents**
  - North or south
  - Travel westward along equator
- **Western Boundary Currents**
  - Warm waters from equatorial regions
  - Western edge of ocean basins

Subtropical Gyre Currents

- **Northern** or **Southern Boundary Currents**
  - Easterly water flow across ocean basin
  - Northern boundary currents in Northern Hemisphere
  - Southern boundary currents in Southern Hemisphere
- **Eastern Boundary Currents**
  - Cool waters
  - Eastern edge of ocean basins

Other Surface Currents

- **Equatorial Countercurrents**
  - Eastward flow between North and South Equatorial Currents
  - Due to minimal Coriolis effect at equator
- **Subpolar Gyres**
  - Rotate opposite subtropical gyres
  - Smaller and fewer than subtropical gyres

Gyres and Boundary Currents

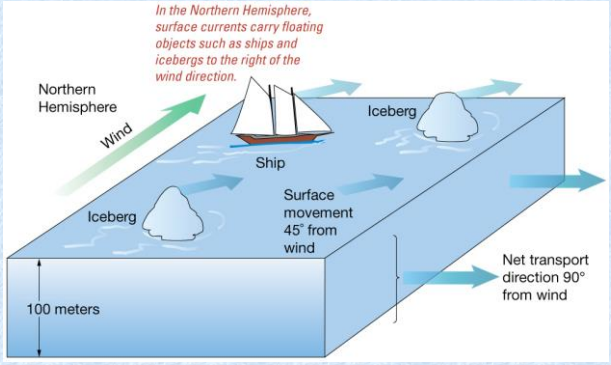
SMARTTABLE 7.1 SUBTROPICAL GYRES AND SURFACE CURRENTS

	North Pacific Gyre		North Atlantic Gyre		Indian Ocean Gyre
Pacific Ocean	North Pacific Current	Atlantic Ocean	North Atlantic Current	Indian Ocean	South Equatorial Current
	California Current[a]		Canary Current[a]		Agulhas Current[b]
	North Equatorial Current		North Equatorial Current		West Wind Drift
	Kuroshio (Japan) Current[b]		Gulf Stream[b]		West Australian Current[a]
	South Pacific Gyre		**South Atlantic Gyre**		**Other Major Currents**
	South Equatorial Current		South Equatorial Current		Equatorial Countercurrent
	East Australian Current[b]		Brazil Current[b]		North Equatorial Current
	West Wind Drift		West Wind Drift		Leeuwin Current
	Peru (Humboldt) Current[a]		Benguela Current[a]		Somali Current
	Other Major Currents		**Other Major Currents**		
	Equatorial Countercurrent		Equatorial Countercurrent		
	Alaskan Current		Florida Current		
	Oyashio Current		East Greenland Current		
			Labrador Current		
			Falkland Current		

[a]Denotes an eastern boundary current of a gyre, which is relatively *slow*, *wide*, and *shallow* (and is also a *cold-water* current).
[b]Denotes a western boundary current of a gyre, which is relatively *fast*, *narrow*, and *deep* (and is also a *warm-water* current).

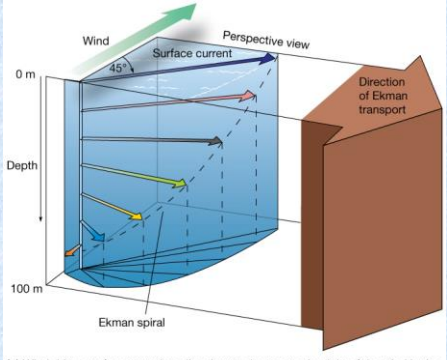
Ekman Spiral and Ekman Transport

- Observation that Arctic Ocean ice moved at a 20- to 40-degree angle to the right of the wind
- Southern Hemisphere movement to the left of the wind



Ekman Spiral

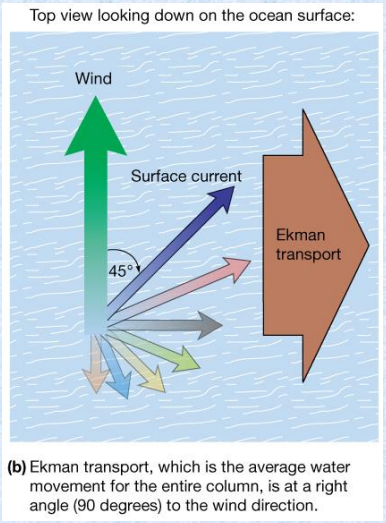
- **V. Walfrid Ekman**
  - Developed circulation model in 1905
- **Ekman spiral**
  - Explains balance between friction and Coriolis effect
  - Describes direction and flow of surface waters at different depths



(a) Wind drives surface water in a direction 45 degrees to the right of the wind in the Northern Hemisphere. Deeper water continues to deflect to the right and moves at a slower speed with increased depth, causing the Ekman spiral.

Ekman Transport

- **Ekman transport**
  - Average movement of surface waters
  - 90 degrees to right in Northern Hemisphere
  - 90 degrees to left in Southern Hemisphere



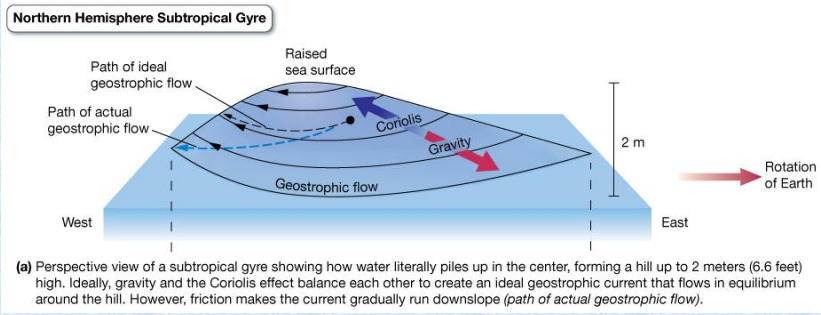
(b) Ekman transport, which is the average water movement for the entire column, is at a right angle (90 degrees) to the wind direction.

Geostrophic Currents

- Ekman transport generates rotational flow in ocean basin.
- **Subtropical Convergence** – piling up of water in middle of gyre

Geostrophic Currents

- Surface water flows downhill and is deflected
  - Right in Northern Hemisphere
  - Left in Southern Hemisphere



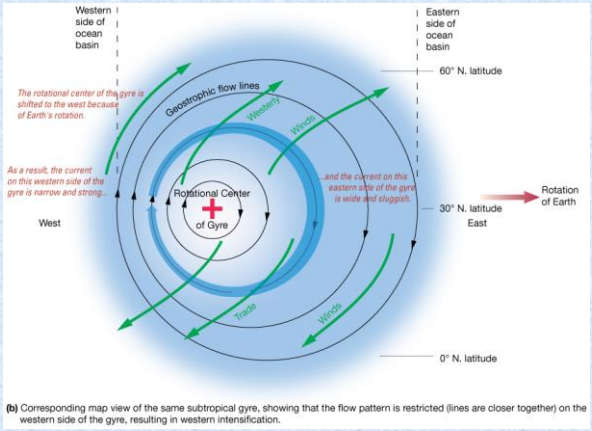
(a) Perspective view of a subtropical gyre showing how water literally piles up in the center, forming a hill up to 2 meters (6.6 feet) high. Ideally, gravity and the Coriolis effect balance each other to create an ideal geostrophic current that flows in equilibrium around the hill. However, friction makes the current gradually run downslope *(path of actual geostrophic flow)*.

Geostrophic Currents

- **Geostrophic current**
  - Balance of Coriolis effect and gravitational forces
  - Moves in circular path downhill

Geostrophic Currents

- Ideal geostrophic flow
- Friction generates actual geostrophic flow.



(b) Corresponding map view of the same subtropical gyre, showing that the flow pattern is restricted (lines are closer together) on the western side of the gyre, resulting in western intensification.

Western Intensification

- Top of hill of water displaced toward west due to Earth's rotation.
- Western boundary currents intensified in both hemispheres.
  - Faster
  - Narrower
  - Deeper
  - Warmer
- Coriolis effect contributes to **western intensification.**

Eastern Boundary Currents

- Eastern side of ocean basins
- Tend to have the opposite properties of Western Boundary Currents
  - Cold
  - Slow
  - Shallow
  - Wide

Eastern and Western Boundary Currents

SMARTTABLE 7.2 CHARACTERISTICS OF WESTERN AND EASTERN BOUNDARY CURRENTS OF SUBTROPICAL GYRES

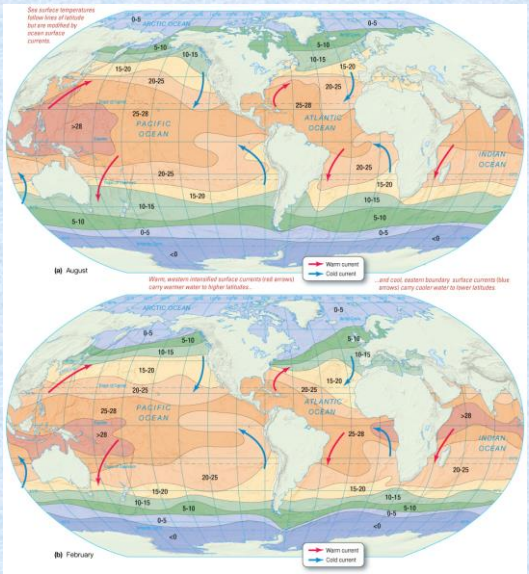
Current type	Examples	Width	Depth	Speed	Transport volume (millions of cubic meters per second[a])	Comments
Western boundary current	Gulf Stream, Brazil Current, Kuroshio Current	*Narrow:* usually less than 100 kilometers (60 miles)	*Deep:* to depths of 2 kilometers (1.2 miles)	*Fast:* hundreds of kilometers per day	*Large:* as much as 100 Sv[a]	Waters derived from low latitudes and are warm; little or no upwelling
Eastern boundary current	Canary Current, Benguela Current, California Current	*Wide:* up to 1000 kilometers (600 miles)	*Shallow:* to depths of 0.5 kilometer (0.3 mile)	*Slow:* tens of kilometers per day	*Small:* typically 10 to 15 Sv[a]	Waters derived from middle latitudes and are cool; coastal upwelling common

[a]One million cubic meters (35.3 million cubic feet) per second is a flow rate equal to one Sverdrup (Sv).

Ocean Currents and Climate

- Warm ocean currents warm the air at the coast.
  - Warm, humid air
  - Humid climate on adjoining landmass
- Cool ocean currents cool the air at the coast.
  - Cool, dry air
  - Dry climate on adjoining landmass

World Ocean Sea Surface Temperatures

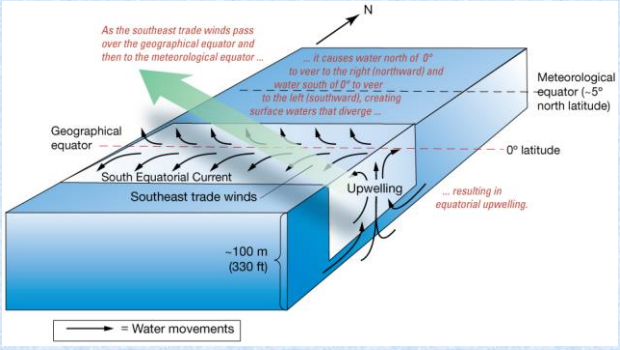


Upwelling and Downwelling

- **Upwelling** – Vertical movement of cold, nutrient-rich water to surface
  - High biological **productivity** – an abundance of algae at the base of the food web
- **Downwelling** – Vertical movement of surface water downward in water column

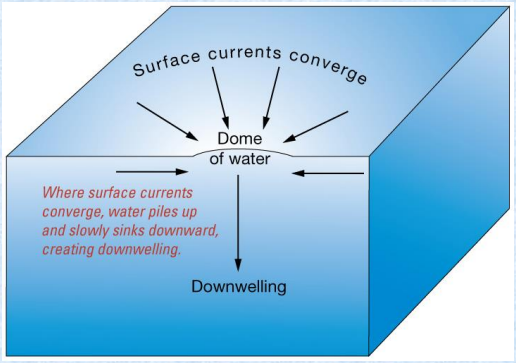
Diverging Surface Water

- Surface waters move away from area.
- **Equatorial upwelling**
  - Divergence of currents at equator generates upwelling and high productivity.



Converging Surface Water

- Surface waters move toward each other.
- Water piles up.
- Low biological productivity



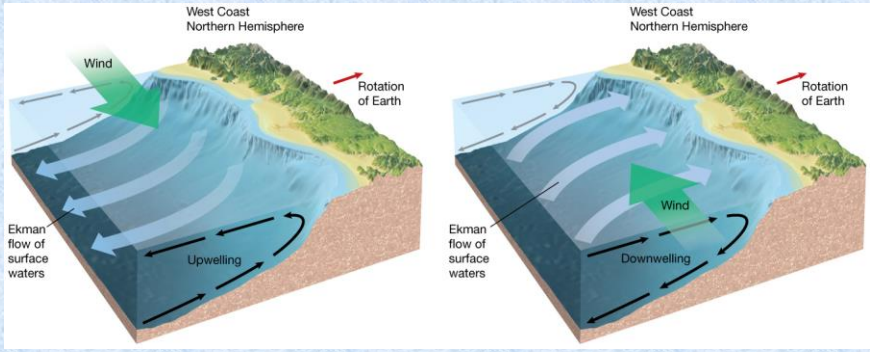
Coastal Upwelling

- Ekman transport moves surface seawater away from shore.
- Cool, nutrient-rich deep water comes up to replace displaced surface waters.
- Western U.S. and cool San Francisco temperatures

Coastal Downwelling

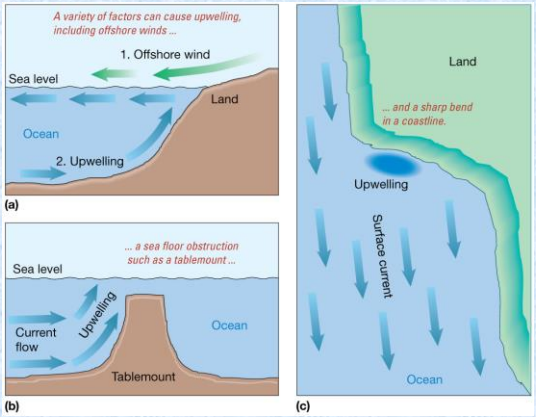
- Ekman transport moves surface seawater toward shore.
- Water piles up, moves downward in water column
- Lack of marine life

Coastal Upwelling and Downwelling



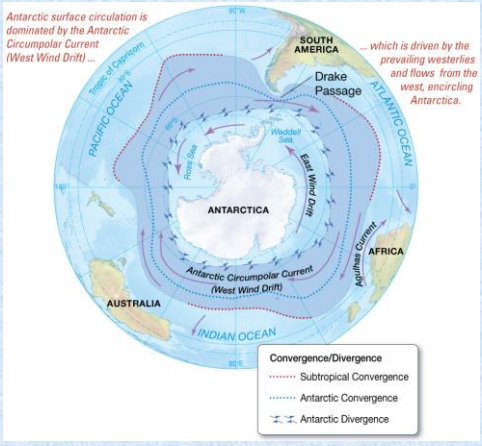
Other Causes of Upwelling

- Offshore winds
- Seafloor obstruction
- Coastal geometry change
- Lack of pycnocline
  - High latitude oceans



Antarctic Circulation

- **Antarctic Circumpolar Current**
  - Also called **West Wind Drift** and Penguin Gyre
  - Only current to completely encircle Earth
  - Moves more water than any other current

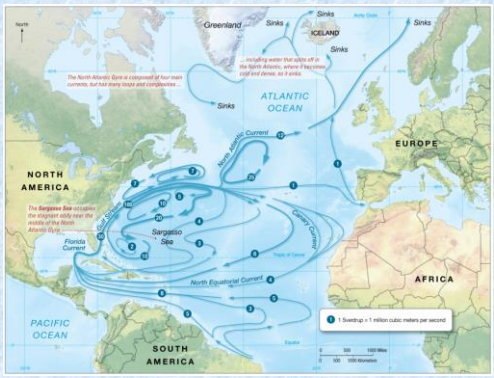


Antarctic Circulation

- **Antarctic Convergence**
  - Cold, dense Antarctic waters converge with warmer, less dense sub-Antarctic waters.
  - Northernmost boundary of Antarctic Ocean
- **East Wind Drift**
  - Polar Easterlies
  - Creates surface divergence with opposite flowing Antarctic Circumpolar Current
- **Antarctic Divergence**
  - Abundant marine life

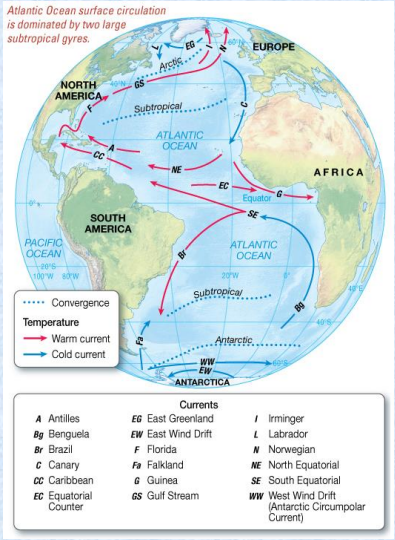
Atlantic Ocean Circulation

- North Atlantic Subtropical Gyre
  - **North Equatorial Current**
  - **Gulf Stream**
  - **North Atlantic Current**
  - **Canary Current**
  - **South Equatorial Current**
  - **Atlantic Equatorial Counter Current**



Atlantic Ocean Circulation

- South Atlantic Subtropical Gyre
  - **Brazil Current**
  - **Antarctic Circumpolar Current**
  - **Benguela Current**
  - **South Equatorial Current**



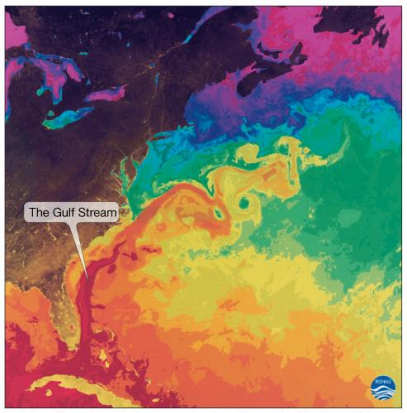
Gulf Stream

- Best studied of all ocean currents
- Moves northward along U.S. East Coast
- Meanders and loops
- Merges with **Sargasso Sea**
  - Circulates around center of North Atlantic Gyre
  - Unique biology – *Sargassum*

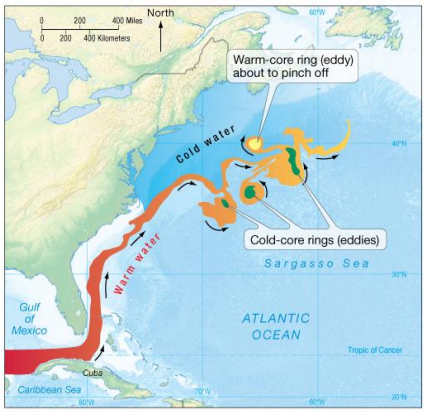
Gulf Stream

- Meanders or loops may cause loss of water volume and generate:
  - **Warm-core rings** – warmer Sargasso Sea water trapped in loop surrounded by cool water
  - **Cold-core rings** – cold water trapped in loop surrounded by warmer water
- Unique biological populations

Gulf Stream and Sea Surface Temperatures



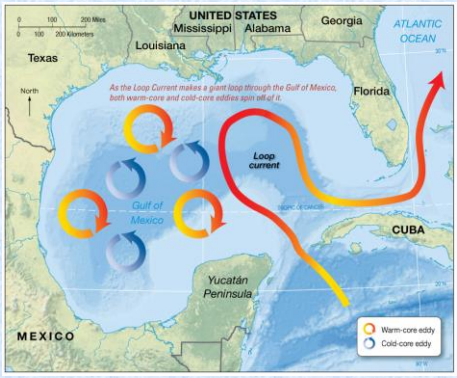
(a) The Gulf Stream is shown flowing along the U.S. East Coast in this NOAA satellite false-color image of sea surface temperature (warm waters = red and orange; cool waters = green, blue, purple, pink).



(b) Matching map of the same area as part a. As the Gulf Stream flows northward, some of its meanders pinch off and form either warm-core or cold-core rings.

Loop Current

- Warm ocean surface current in Gulf of Mexico
- Generates warm loop current eddies
- Hurricanes intensify when passing over warm cores.



Other North Atlantic Currents

- **Labrador Current**
- **Irminger Current**
- **Norwegian Current**
- **North Atlantic Current**

Climate Effects of North Atlantic Currents

- North-moving currents – warm
  - Gulf Stream warms east coast of United States and northern Europe
  - North Atlantic and Norwegian Currents warm northwestern Europe

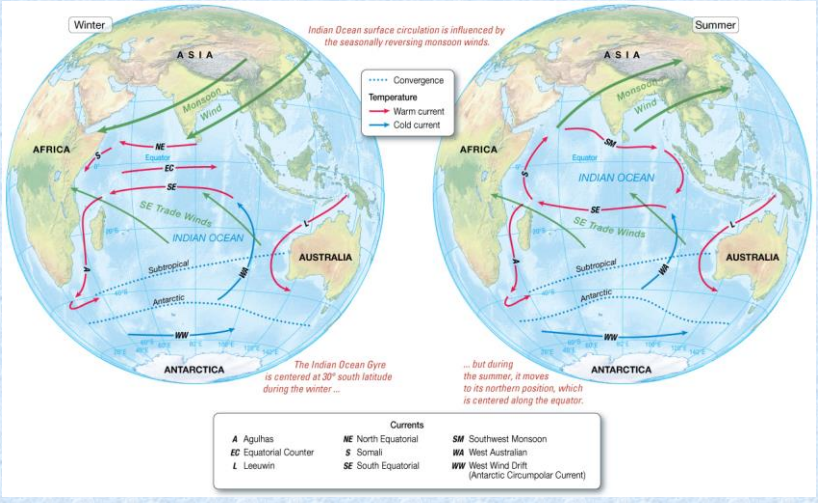
Climate Effects of North Atlantic Currents

- South-moving currents – cool
  - Labrador Current cools eastern Canada
  - Canary Current cools north African coast

Indian Ocean Circulation

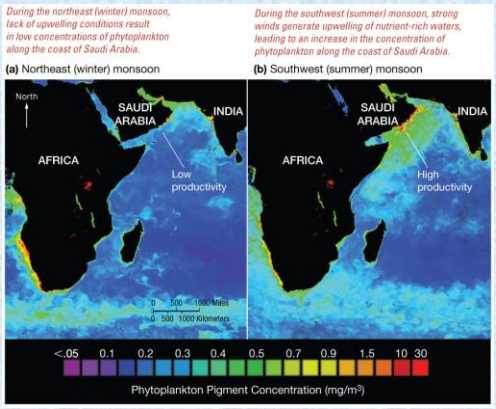
- **Monsoons** – seasonal reversal of winds over northern Indian Ocean
- Heat Capacity Differential
- Northeast monsoon – winter
- Southwest monsoon – summer

Indian Ocean Circulation



Indian Ocean Monsoon

- Affects seasonal land weather
- Affects seasonal Indian Ocean current circulation
- Affects phytoplankton productivity



Indian Ocean Circulation

- Indian Ocean Subtropical Gyre
  - **Agulhas Current**
  - **Australian Current**
  - **Leeuwin Current**

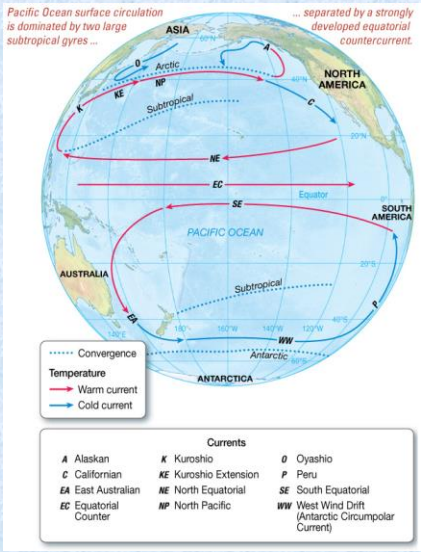
Pacific Ocean Circulation

- North Pacific Subtropical Gyre
  - **Kuroshio Current**
  - **North Pacific Current**
  - **California Current**
  - **North Equatorial Current**
  - **Alaskan Current**

Pacific Ocean Circulation

- South Pacific Subtropical Gyre
  - **East Australian Current**
  - **Antarctic Circumpolar Current**
  - **Peru Current**
  - **South Equatorial Current**
  - **Equatorial Counter Current**

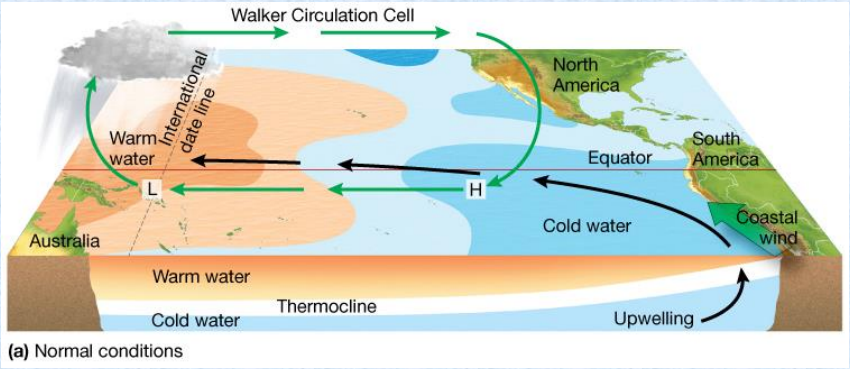
Pacific Ocean Circulation



Atmospheric-Ocean Connections in the Pacific Ocean

- **Walker Circulation Cell** – normal conditions
  - Air pressure across equatorial Pacific is higher in eastern Pacific.
  - Strong southeast trade winds
  - **Pacific warm pool** on western side of ocean
  - Thermocline deeper on western side
  - Upwelling off the coast of Peru

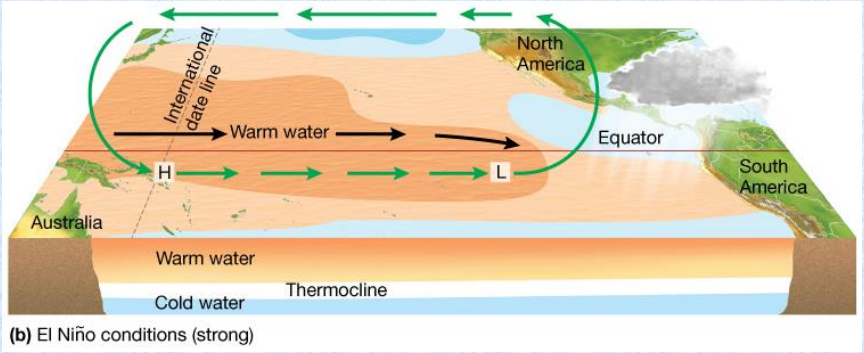
Normal Conditions, Walker Circulation



El Niño – Southern Oscillation (ENSO)

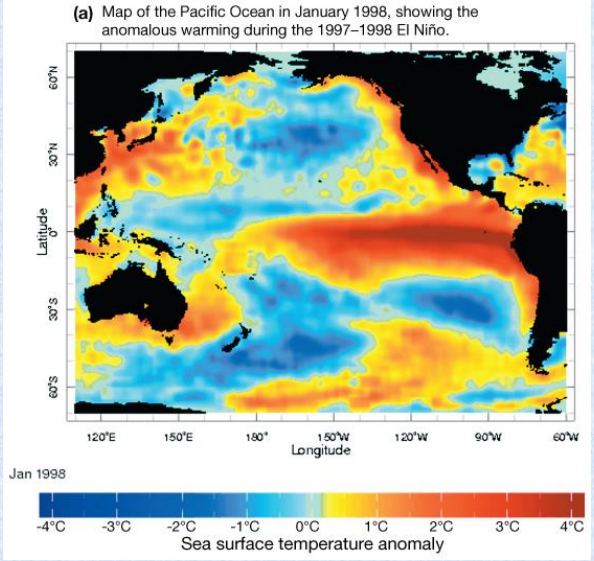
- Walker Cell Circulation disrupted
  - High pressure in eastern Pacific weakens.
  - Weaker trade winds
  - Warm pool migrates eastward
  - Thermocline deeper in eastern Pacific
  - Downwelling
  - Lower biological productivity
    - Peruvian fishing suffers

ENSO Conditions in the Pacific Ocean



(b) El Niño conditions (strong)

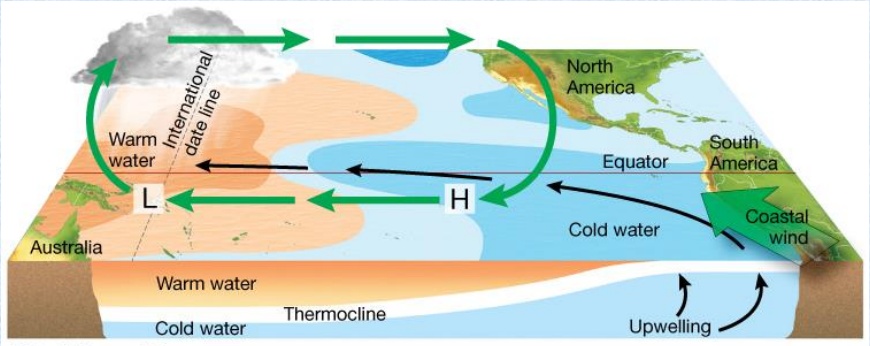
ENSO Conditions in the Pacific Ocean



La Niña – ENSO Cool Phase

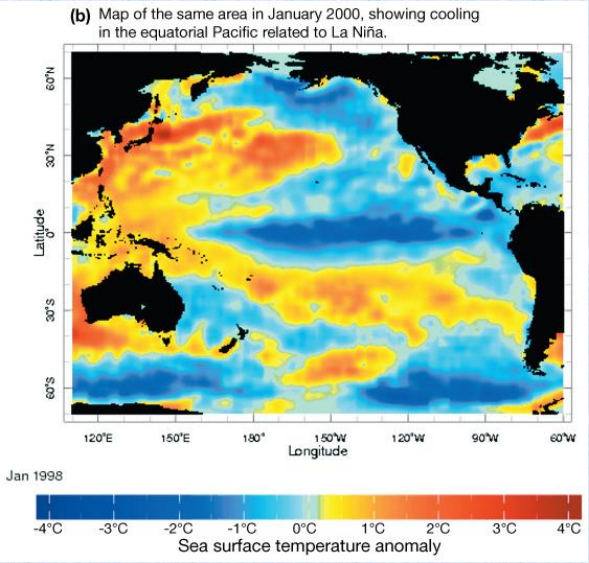
- Increased pressure difference across equatorial Pacific
- Stronger trade winds
- Stronger upwelling in eastern Pacific
- Shallower thermocline
- Cooler than normal seawater
- Higher biological productivity

La Niña Conditions



(c) La Niña conditions

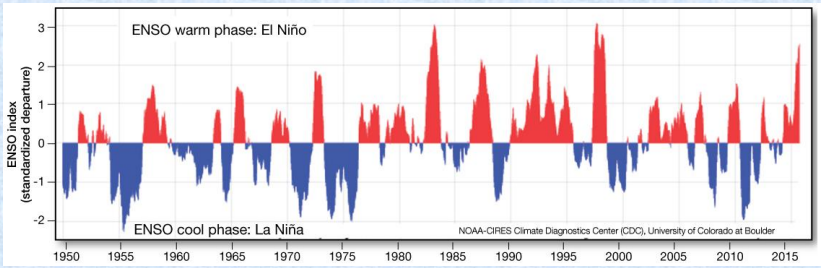
La Niña Conditions



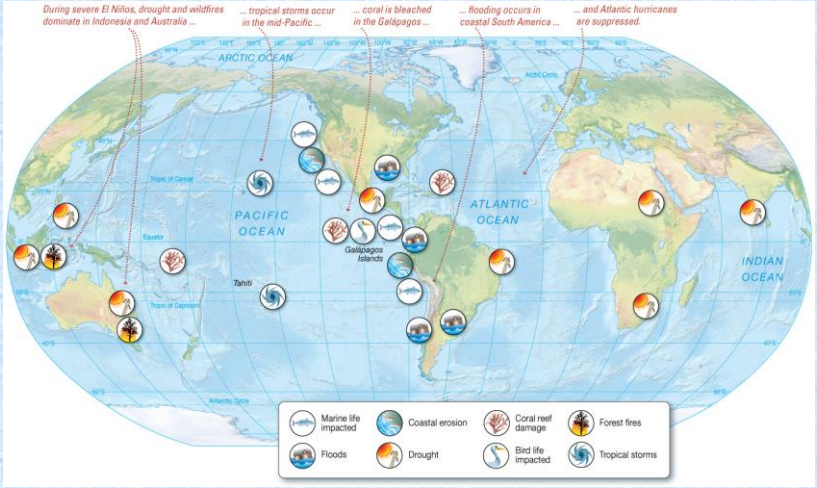
Occurrence of ENSO Events

- El Niño warm phase about every 2–10 years
- Highly irregular
- Phases usually last 12–18 months
- 10,000-year sediment record of events
- ENSO may be part of **Pacific Decadal Oscillation (PDO)**
  - Long-term natural climate cycle
  - Lasts 20–30 years

Multivariate ENSO Index 1950–2015



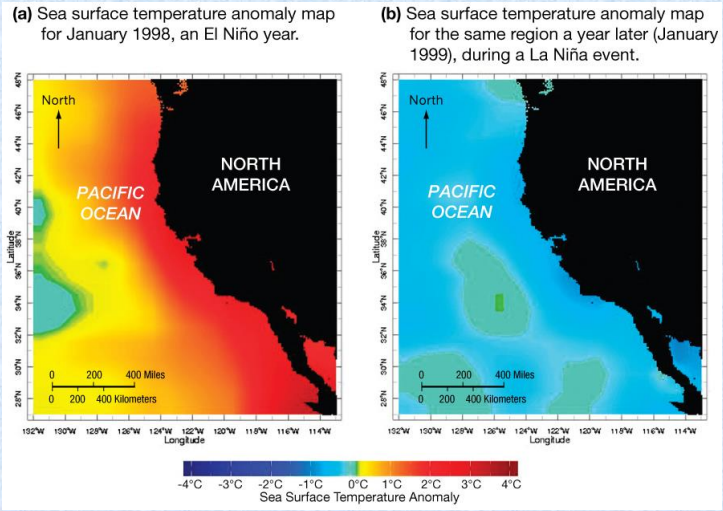
ENSO Has Global Impacts



Notable ENSO Events

- 1982–1983
- 1997–1998
- Flooding, drought, erosion, fires, tropical storms, harmful effects on marine life
- Unpredictable

Sea Surface Temperatures During El Niño and La Niña



Predicting El Niño Events

- **Tropical Ocean−Global Atmosphere (TOGA)** program
  - 1985
  - Monitors equatorial South Pacific
  - System of buoys
- **Tropical Atmosphere and Ocean (TOA)** project
  - Continues monitoring
- ENSO still not fully understood

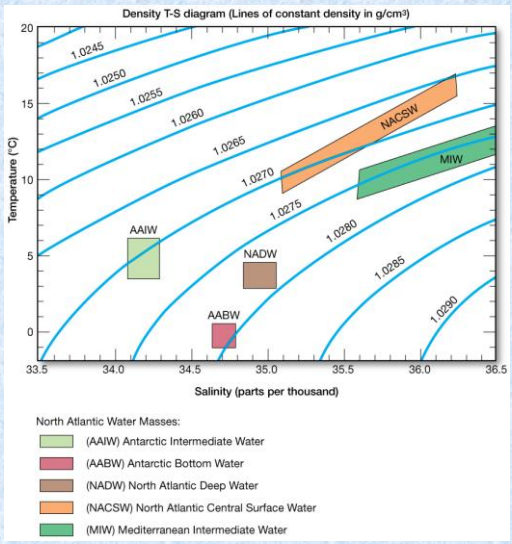
Deep-Ocean Currents

- **Thermohaline Circulation** – deep ocean circulation driven by temperature and density differences in water
- Below the pycnocline
- 90% of all ocean water
- Slow velocity

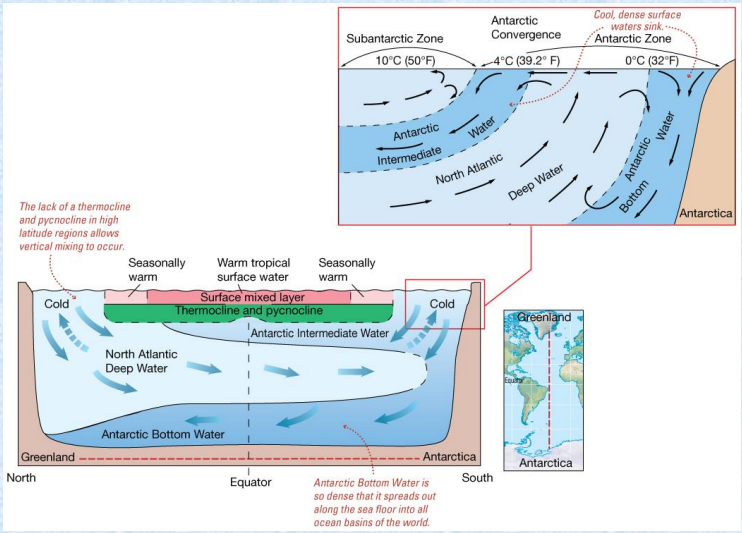
Thermohaline Circulation

- Originates in high latitude surface ocean
- Cooled, now dense surface water sinks and changes little.
- Deep-water masses identified on **temperature–salinity (T–S) diagram**
  - Identifies deep water masses based on temperature, salinity, and resulting density

T–S Diagram



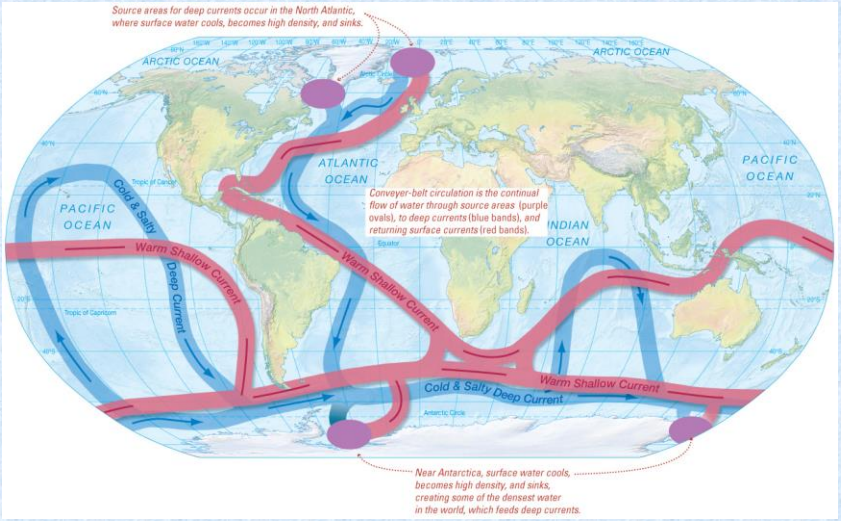
Thermohaline Circulation



Thermohaline Circulation

- Some deep-water masses
  - **Antarctic Bottom Water**
  - **North Atlantic Deep Water**
  - **Antarctic Intermediate Water**
  - **Oceanic Common Water**
- Cold surface seawater sinks at polar regions and moves equatorward.

Conveyor Belt Circulation



Power from Currents

- Currents carry more energy than winds.
- Florida–Gulf Stream Current System
- Underwater turbines
  - Expensive
  - Difficult to maintain
  - Hazard to boating