# OCEANOGRAPHY

## 7. Ocean Circulation

notes from textbook, integrated with original contributions

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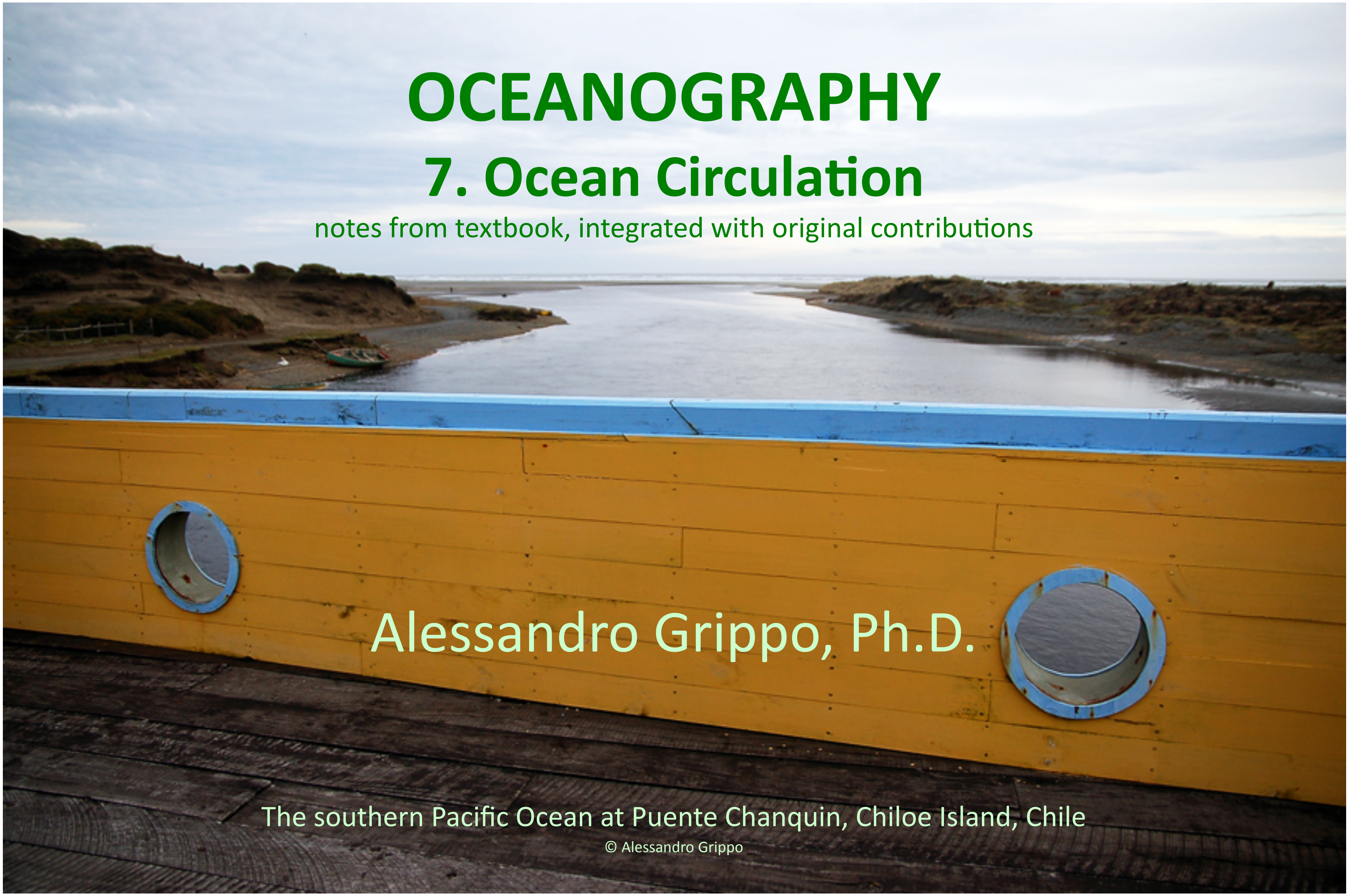


The southern Pacific Ocean at Puente Chanquin, Chiloe Island, Chile

# chapter overview

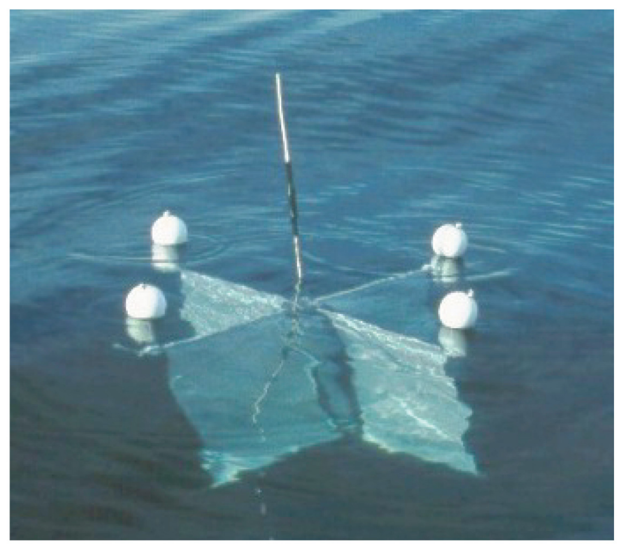
- Ocean currents are water masses in motion
- **Surface currents** are influenced by major wind belts
- Currents redistribute global heat
- Locally, surface currents affect coastal climates
- Thermohaline circulation affects **deep currents**
- Currents influence marine life by affecting the growth of microscopic algae (basis of most oceanic food webs)

# 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

# 7.1 – How Are Ocean Currents Measured?

- Measuring Surface Currents
  - Direct methods
    - Floating devices whose position is tracked through time
    - Fixed current meter
      (such as a propeller flow meter)
  - Indirect methods
    - Pressure gradients
      (water flows downhill)
    - Radar altimeters
      (dynamic topography maps)
    - Doppler flow meter
      (use of low-frequency sound signals)



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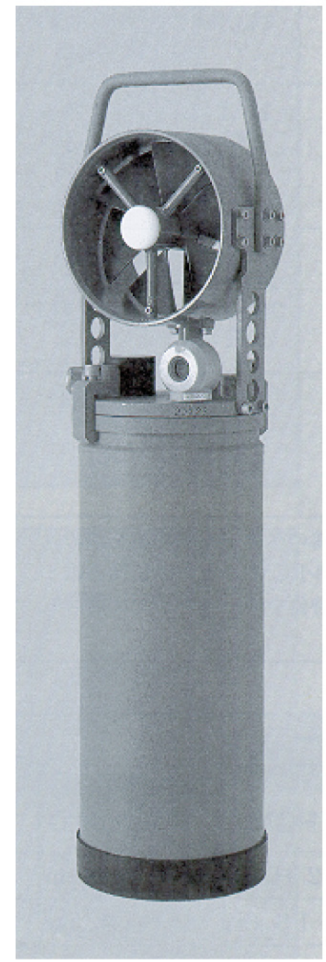

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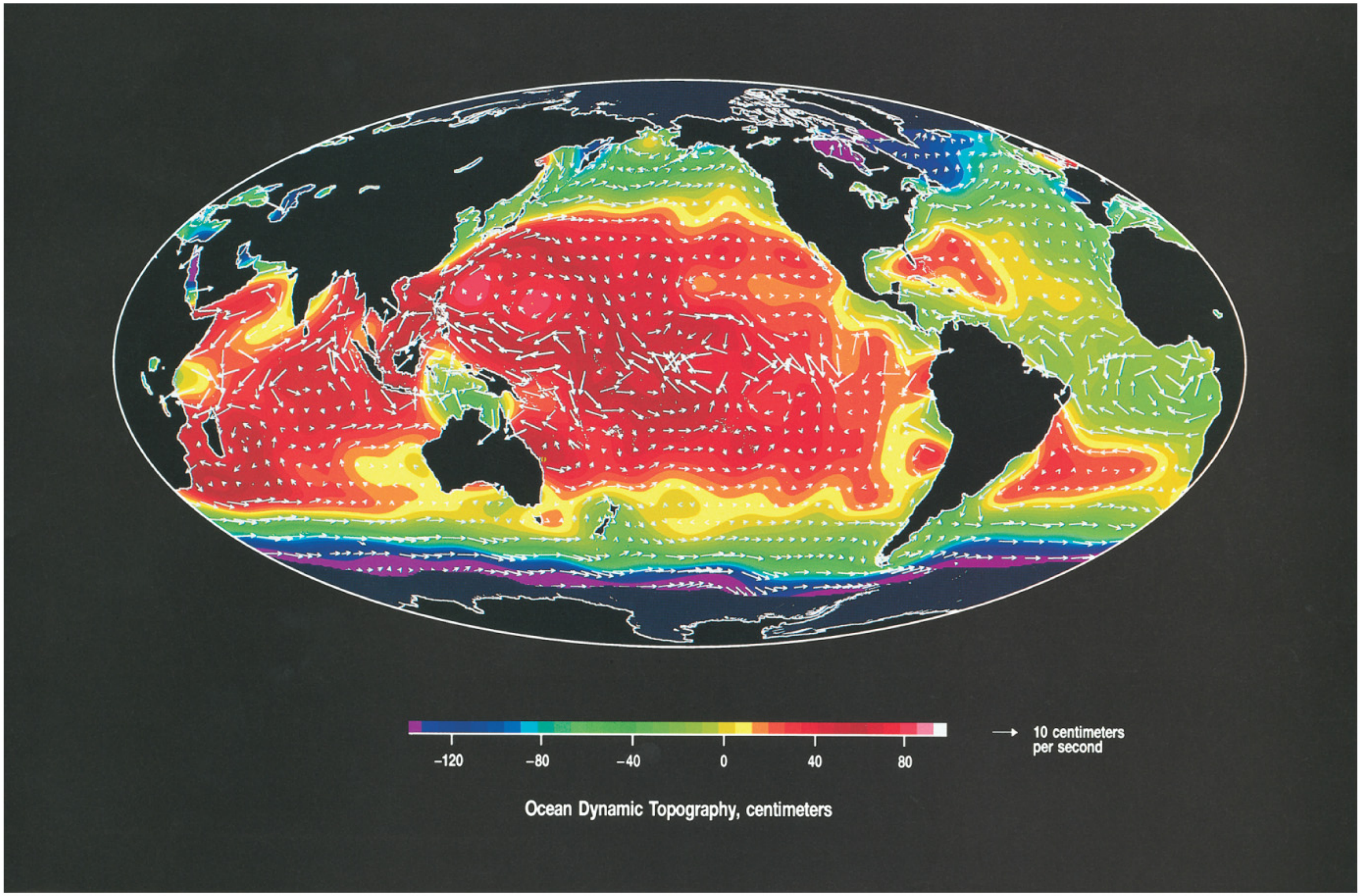
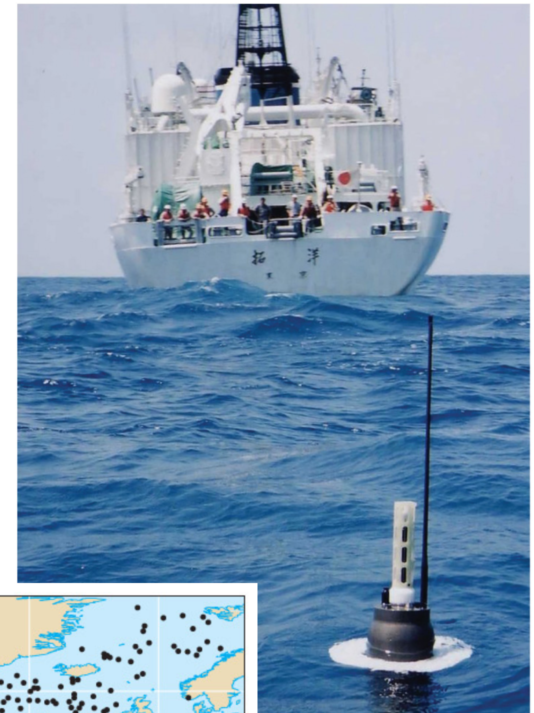
# Satellite View (from radar altimeter data) of Global Surface Current Flow, September 1992 to September 1993

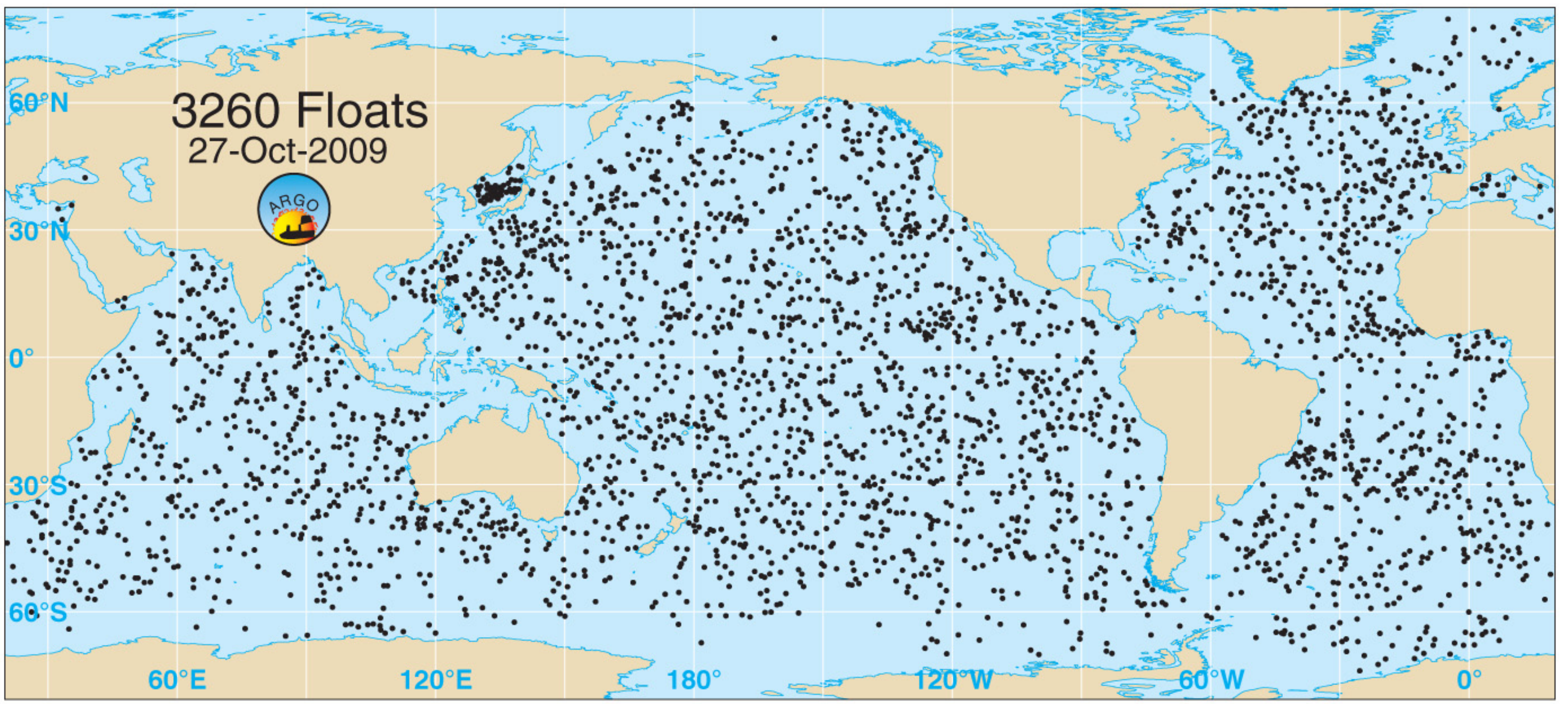


# Measuring Deep Currents

- It is very difficult to track deep currents
  - Argo program
    - release of thousands floating device that sink to depth, record data, come back to surface, transmit, sink again
  - Identification of distinctive temperature and salinity of deep water masses
  - Chemical tracers
    - Natural
    - Intentionally added
    - Unintentionally added

# Argo program






(a)

# 7.2 – What Creates Ocean Surface Currents and How Are They Organized?

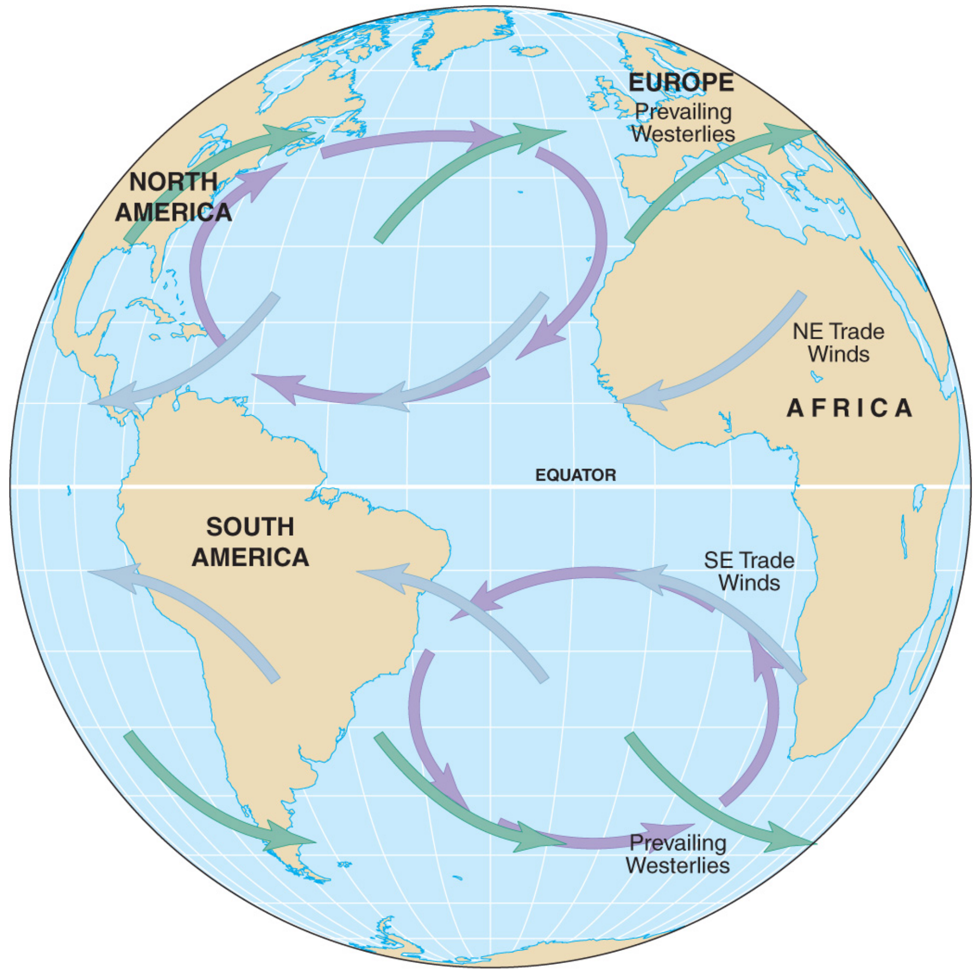
- Occur within and above pycnocline, because of frictional drag between wind and ocean
  - to a depth of about 1 km
  - affect only about 10% of world's ocean water

- Affected mostly by major wind belts of the world, so they generally follow wind belt patterns

- Other factors:
  - Distribution of continents and geometry of ocean basins
  - Gravity
  - Seasonal changes
  - Coriolis effect
  - Friction

# general surface currents patterns

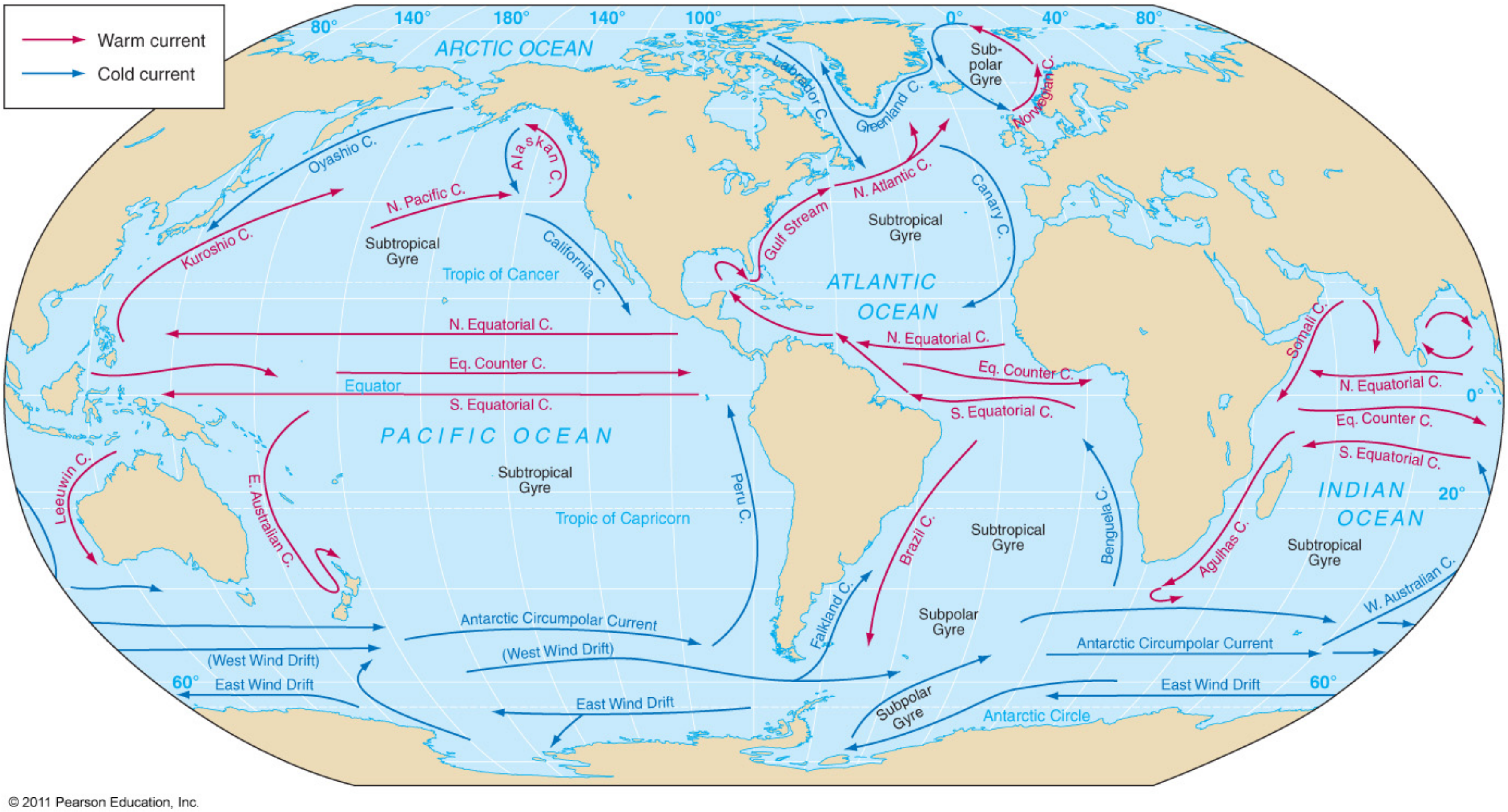
- Only 2% of wind energy is transmitted to ocean
- On a planet without land masses, ocean currents would follow wind belts, creating large, circular loops (**gyres**) of moving water
- On a planet with continents, currents are deflected by land
- Example from the Atlantic Ocean



# Subtropical Gyres

- There are five Subtropical Gyres
  - North and South Atlantic, North and South Pacific, Indian
  - rotate clockwise in Northern Hemisphere, counterclockwise in the Southern Hemisphere
  - average drift time is between 3 and 6 years
- Gyres are bounded by:
  - Equatorial current
  - Western Boundary currents
  - Northern or Southern Boundary currents
  - Eastern Boundary currents
- Centered around 30° latitude

# Subtropical Gyres and Currents



# the Four Currents that make up a Subtropical Gyre

All gyres have four main currents flowing into one another:

- Equatorial Currents
  - North or south of the Equator, traveling westward along it
- Western Boundary Currents – warm waters
- Northern or Southern Boundary Currents – easterly water flow across ocean basin
- Eastern Boundary Currents – cool waters

# Gyres and Boundary Currents

**TABLE 7.1 SUBTROPICAL GYRES AND SURFACE CURRENTS**

| | Pacific Ocean | Atlantic Ocean | Indian Ocean |
|---|---|---|---|
| | **North Pacific (Turtle) Gyre** | **North Atlantic (Columbus) Gyre** | **Indian Ocean (Majid) Gyre** |
| | North Pacific Current | North Atlantic Current | 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 (Heyerdahl) Gyre** | **South Atlantic (Navigator) 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).

# Other Surface Currents

- Equatorial Countercurrents
  - equatorial currents push water westward
  - an eastward flow (between North and South Equatorial Currents) develops because of a higher sea level to the west
  - different in the three oceans
- Subpolar Gyres
  - Rotate opposite subtropical gyres
  - Smaller and fewer than subtropical gyres

# Other factors affecting ocean surface circulation

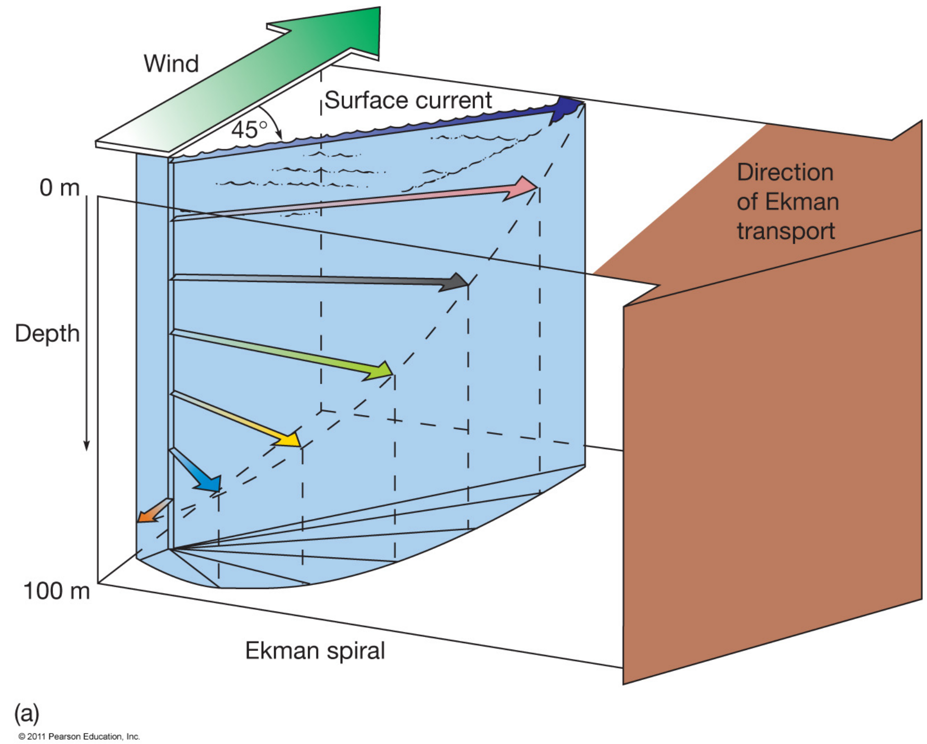
- Ekman Spiral
- Ekman transport

- Geostrophic currents

- Western intensification of subtropical gyres

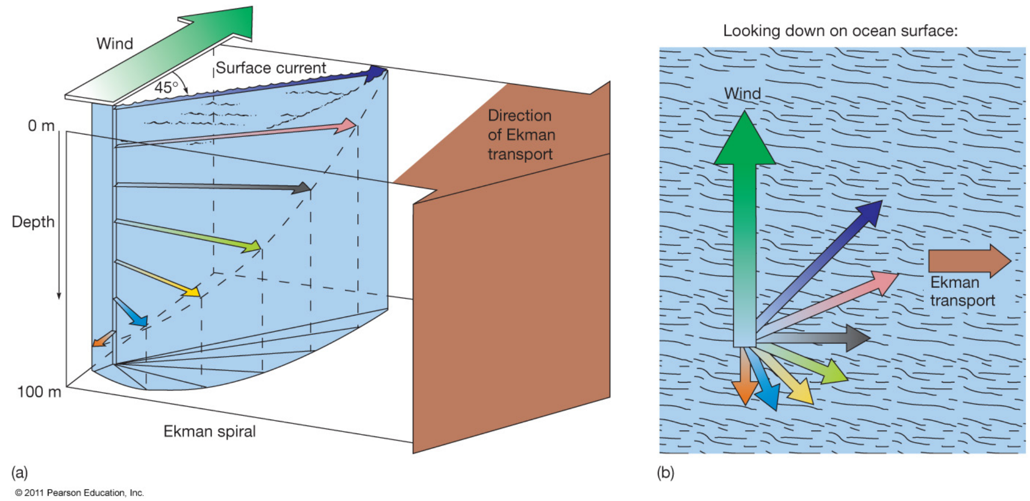
# Ekman Spiral

- Surface currents move at an angle to the wind
- To the right in the NH, to the left in the SH
- Upper layer drags lower layer, but with less energy
- Each successive layer moves increasingly to the right  in the Northern Hemisphere
  - Coriolis effect
- Movement stops at about 100 m of depth
- The Ekman spiral describes speed and direction of seawater flow at different depths.



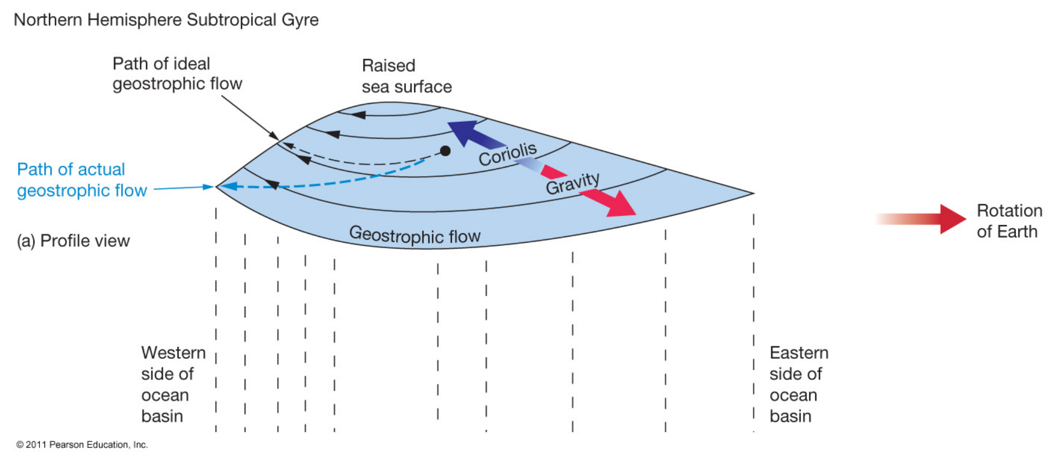
# Ekman Transport

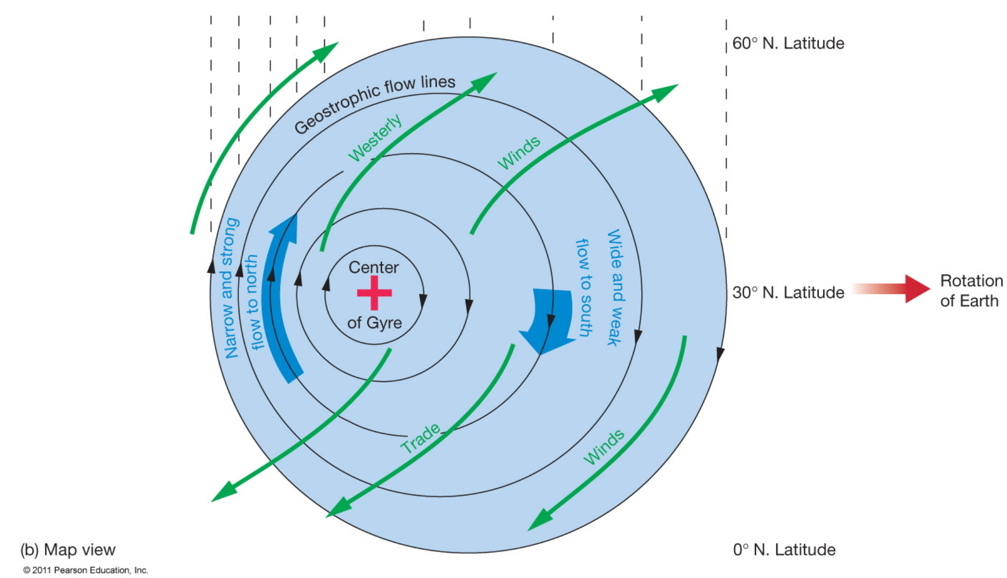
- Average movement of seawater under influence of wind
- 90° to right of wind in NH
- 90° to left of wind in SH
- “Ideal conditions” rarely exist, so on average Ekman transport is 70°
- In coastal waters, might be 0°



# Geostrophic Currents

- Ekman transport piles up water within subtropical gyres.
- Surface water flows downhill and to the right.
- Geostrophic flow: balance of Coriolis Effect and gravitational forces
- Ideal geostrophic flow
- Friction generates actual geostrophic flow



# Western Intensification

- The top of the hill of water is displaced toward the west due to Earth's rotation
- Western boundary currents are intensified in both hemispheres
  - Faster, Narrower, Deeper, Warm
- Coriolis Effect contributes to western intensification
- Eastern boundary currents tend to have the opposite properties of Western Boundary Currents
  - Cold, Slow, Shallow, Wide

# Eastern and Western Boundary Currents

TABLE 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 |

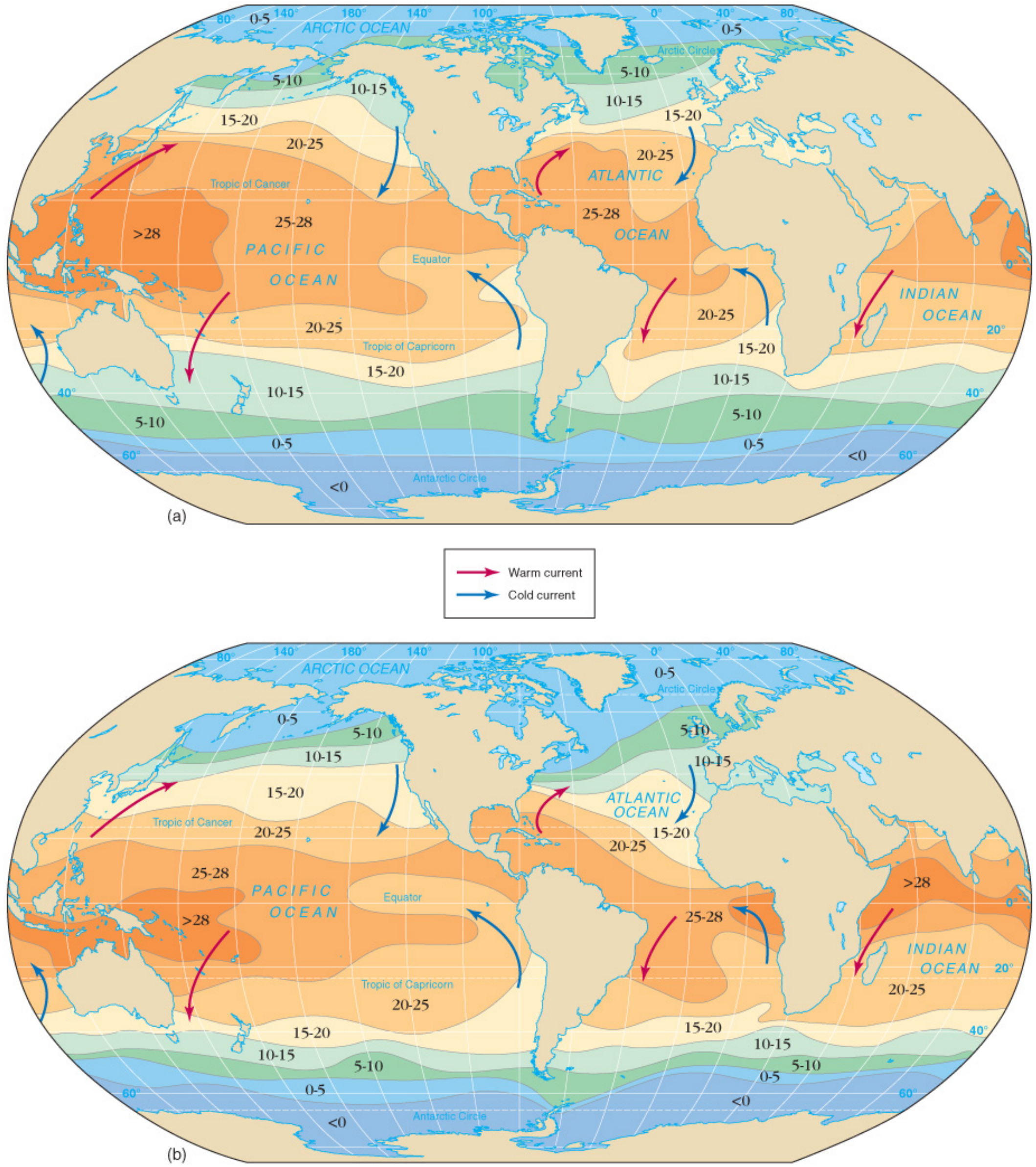
[a] One million cubic meters per second is a flow rate equal to one Sverdrup (Sv).

# Ocean Currents and Climate

- Warm coastal ocean currents warm the air above. Air absorbs more moisture
  - Warm, humid air
  - Humid climate on adjoining landmass
    - Florida

- Cool coastal ocean currents cool the air above. Air cannot acquire moisture
  - Cool, dry air
  - Dry climate on adjoining landmass
    - California

# Ocean Currents and Climate



# 7.3 – What Causes Upwelling and Downwelling?

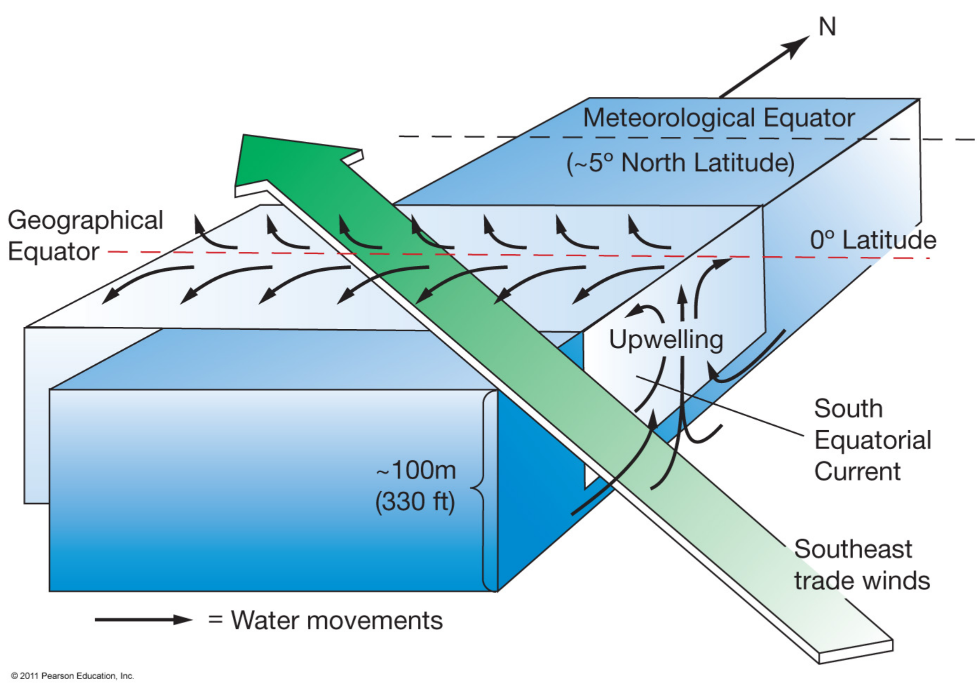
- Upwelling – Vertical movement of cold, nutrient-rich water to surface
  - High biological productivity
- Downwelling – Vertical movement of surface water downward in water column
  - Low productivity, but downwelling carries oxygen to deep waters

- Upwelling and downwelling provide important mixing mechanisms between surface and deep waters

## How do upwelling and downwelling occur?

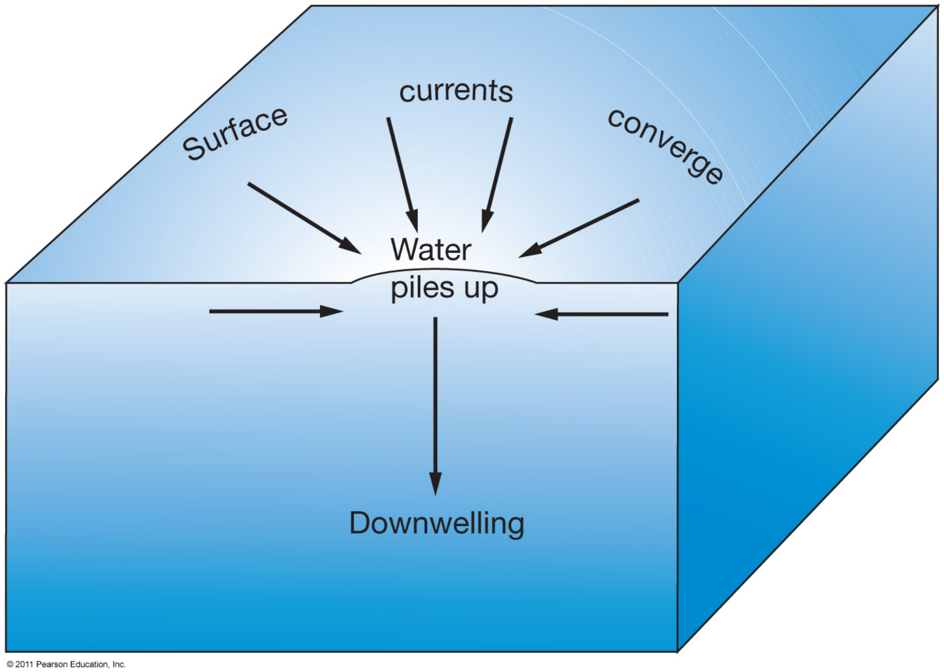
- Diverging surface water
- Converging surface water
- Coastal upwelling and downwelling
- Offshore winds
- Seafloor obstructions
- Sharp bends in coastline
- Absence of pycnocline in high-latitude regions

# Diverging Surface Water




- Surface waters move away from an area on the ocean's surface
- Example: Trade Winds along the equator
  - Ekman transport to the right in NH
  - Ekman transport to the left in SH
- Equatorial upwelling

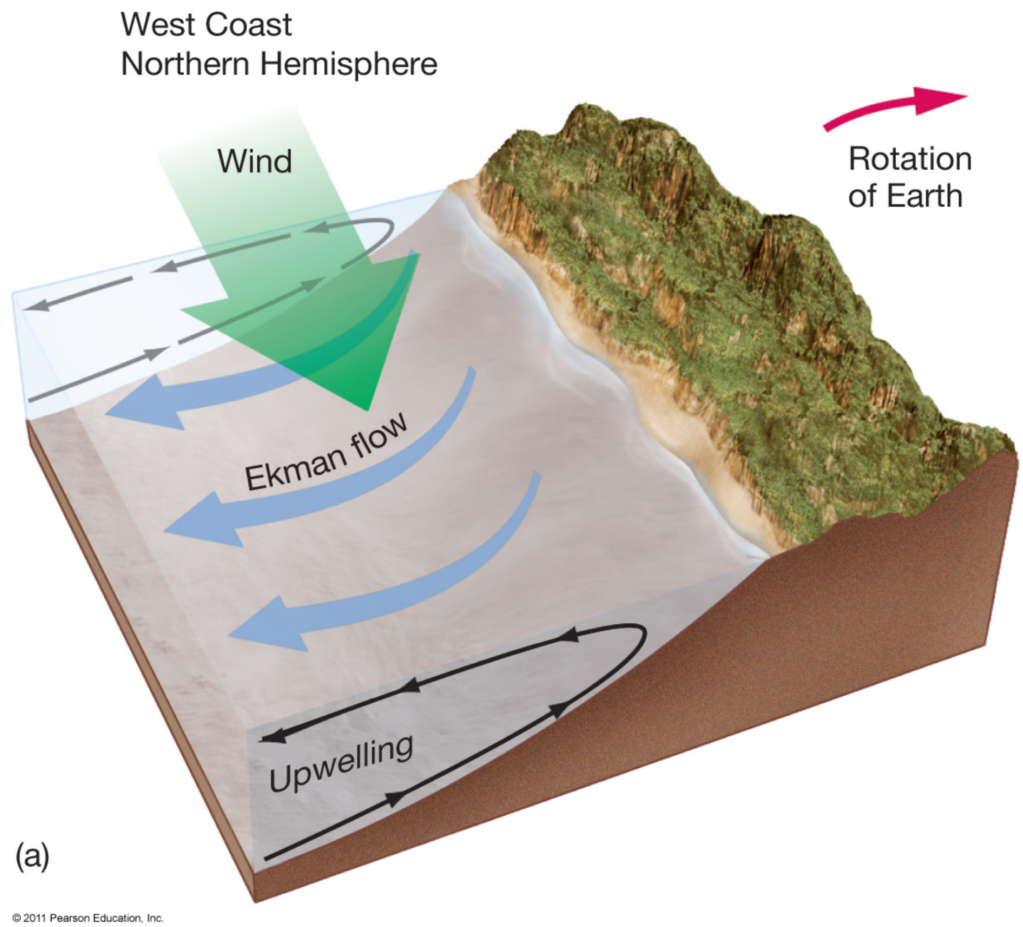
# Converging Surface Water




- Occurs when surface waters move toward each other
- Water piles up and has no place to go but downward (downwelling)
- Low biological productivity

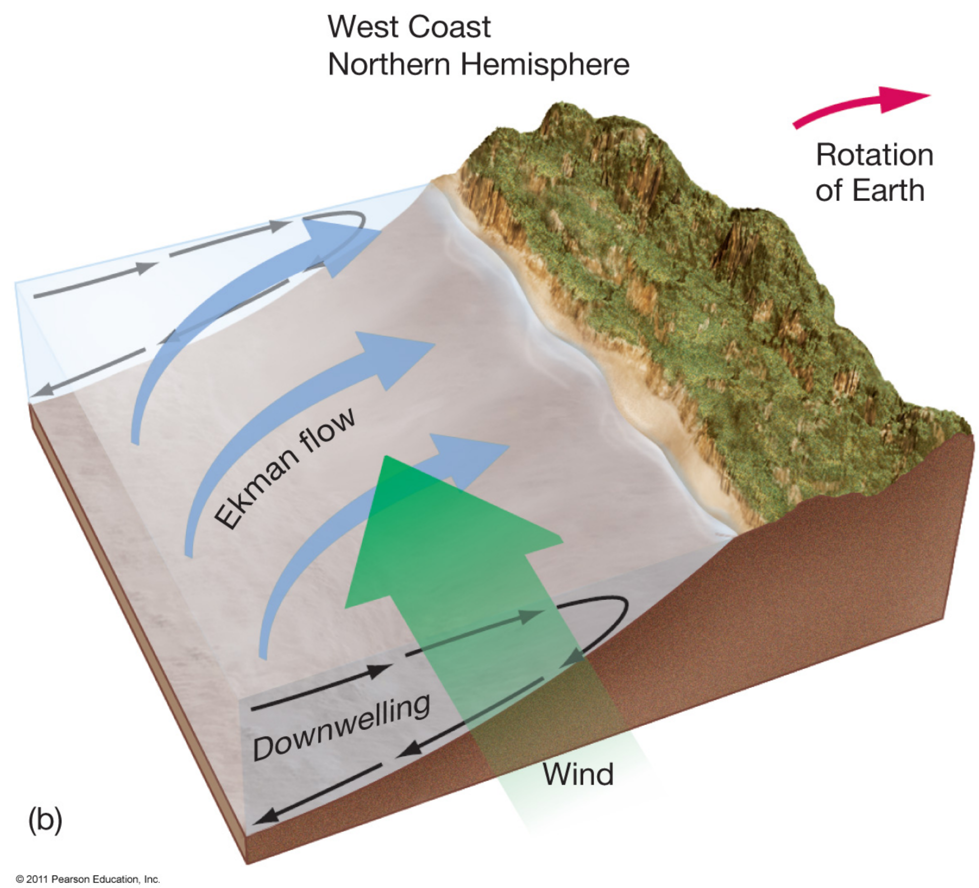
# Coastal Upwelling

- Ekman transport moves surface seawater offshore.
- Cool, nutrient-rich deep water comes up to replace displaced surface waters.
- Example: U.S. West Coast



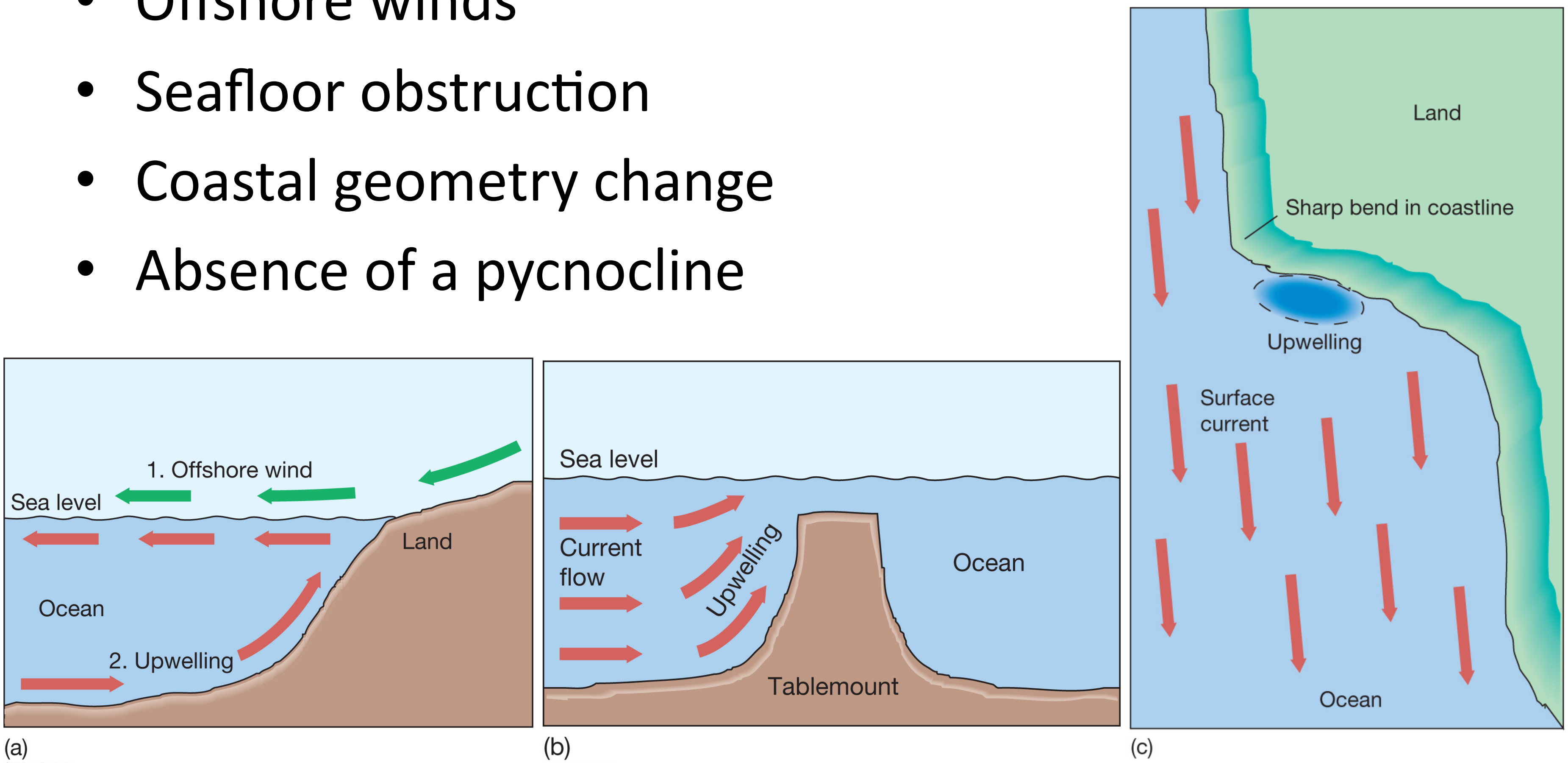
# Coastal Downwelling

- Ekman transport moves surface seawater toward shore.
- Water piles up, has no place to go, and moves downward in water column
- Lack of marine life



# Other Causes of Upwelling

- Offshore winds
- Seafloor obstruction
- Coastal geometry change
- Absence of a pycnocline



# 7.4 – What Are the Main Surface Circulation Patterns in Each Ocean Basin?

- The specific pattern of surface currents varies from ocean to ocean, depending on:
  - the geometry of the ocean basin
  - the pattern of major wind belts
  - seasonal factors, and other periodic changes

- We are going to look at the surface ocean water circulation of:
  - the Antarctic Ocean
  - the Atlantic Ocean
  - The Indian Ocean
  - the Pacific Ocean

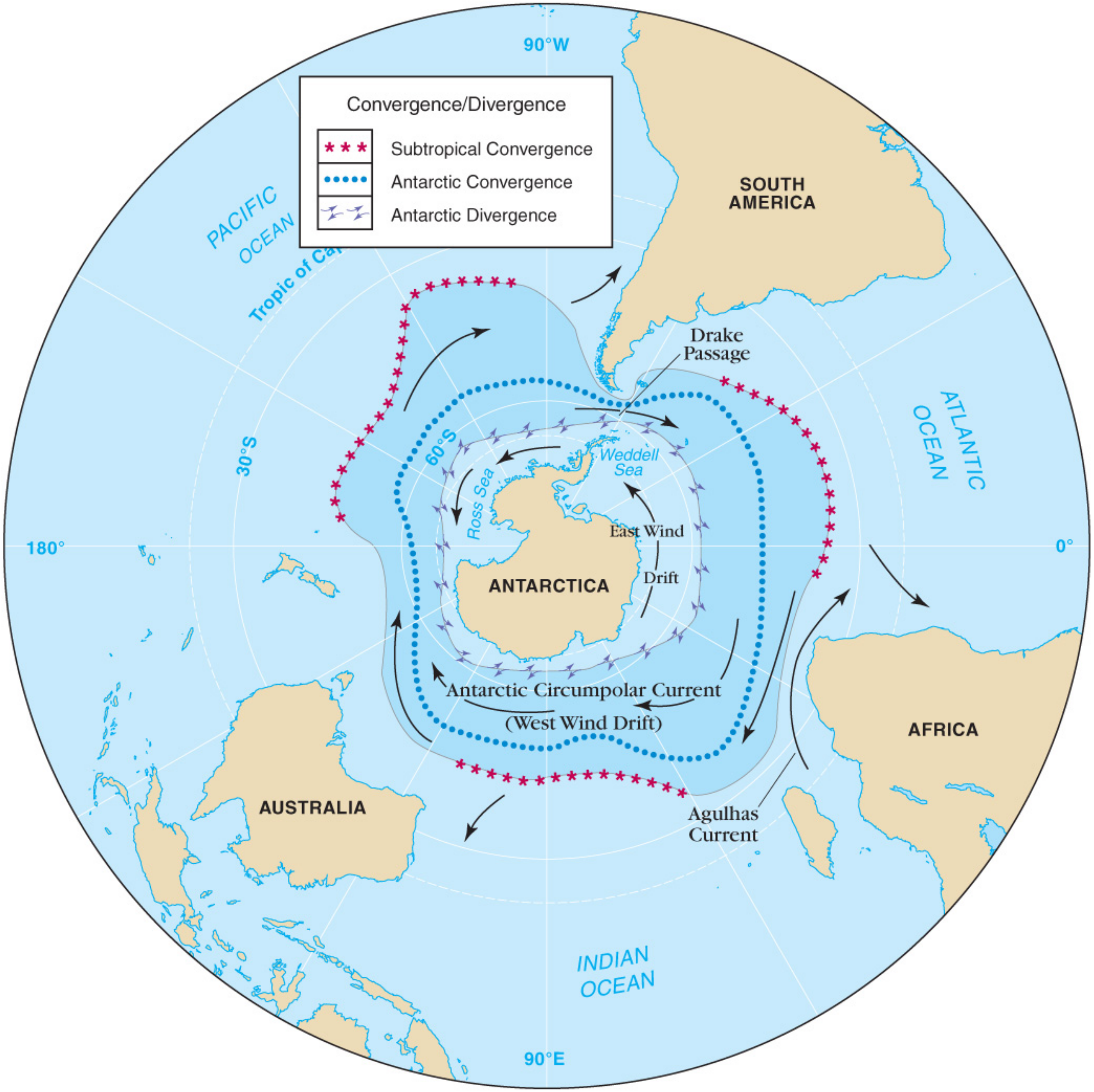
# Antarctic Circulation

- Antarctic circulation is dominated by movement of water masses in the southern Atlantic, Indian, and Pacific Oceans, at latitudes south of 50°S

- There are two main currents:
  - Antarctic Circumpolar Current (West Wind Drift)
  - East Wind Drift

- Antarctic Circumpolar Current (West Wind Drift)
  - Only current to completely encircle Earth
  - Powered by the prevailing westerly wind belt
  - Moves more water than any other current
  - Subtropical convergence located at 40°S

- East Wind Drift
  - propelled by Polar Easterlies
  - Creates surface divergence with opposite flowing West Wind Drift



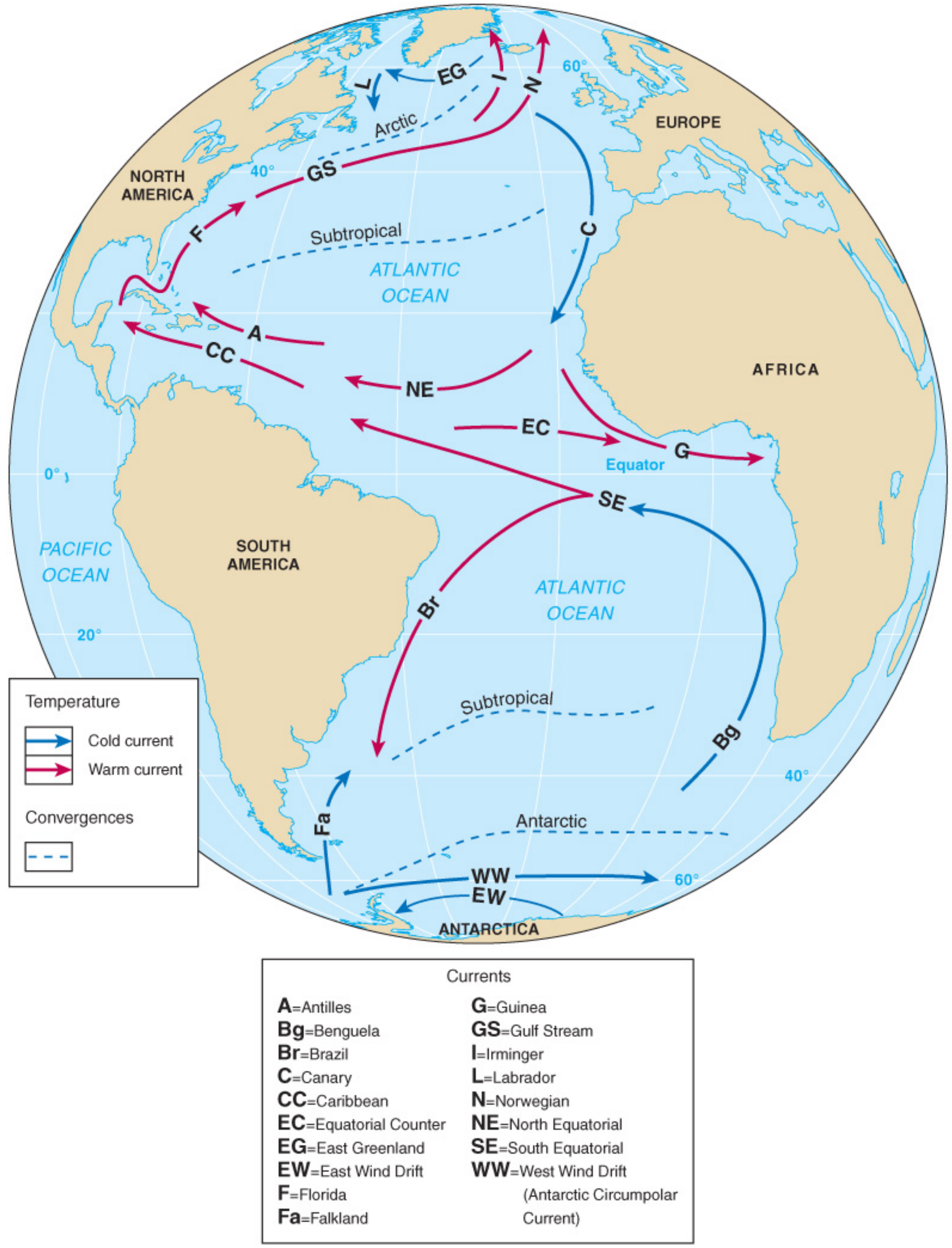
Convergence/Divergence
Subtropical Convergence
Antarctic Convergence
Antarctic Divergence
90°W
PACIFIC OCEAN
Tropic of Ca
SOUTH AMERICA
Drake Passage
ATLANTIC OCEAN
30°S
60°S
Weddell Sea
Ross Sea
East Wind
Drift
ANTARCTICA
180°
0°
Antarctic Circumpolar Current
(West Wind Drift)
AFRICA
AUSTRALIA
Agulhas Current
INDIAN OCEAN
90°E

- These two currents create zones of convergence and divergence

- Antarctic Convergence (or Antarctic Polar Front)
  - Cold, dense Antarctic waters converge with warmer, less dense sub-Antarctic waters, at about 50°S
  - Downwelling
  - Northernmost boundary of Antarctic Ocean
- Antarctic Divergence
  - Upwelling
  - Nutrients from the bottom, and as a consequence, Abundant marine life

# Atlantic Ocean Circulation

- Consists of two large subtropical gyres:
  - North Atlantic Subtropical Gyre
  - South Atlantic Subtropical Gyre

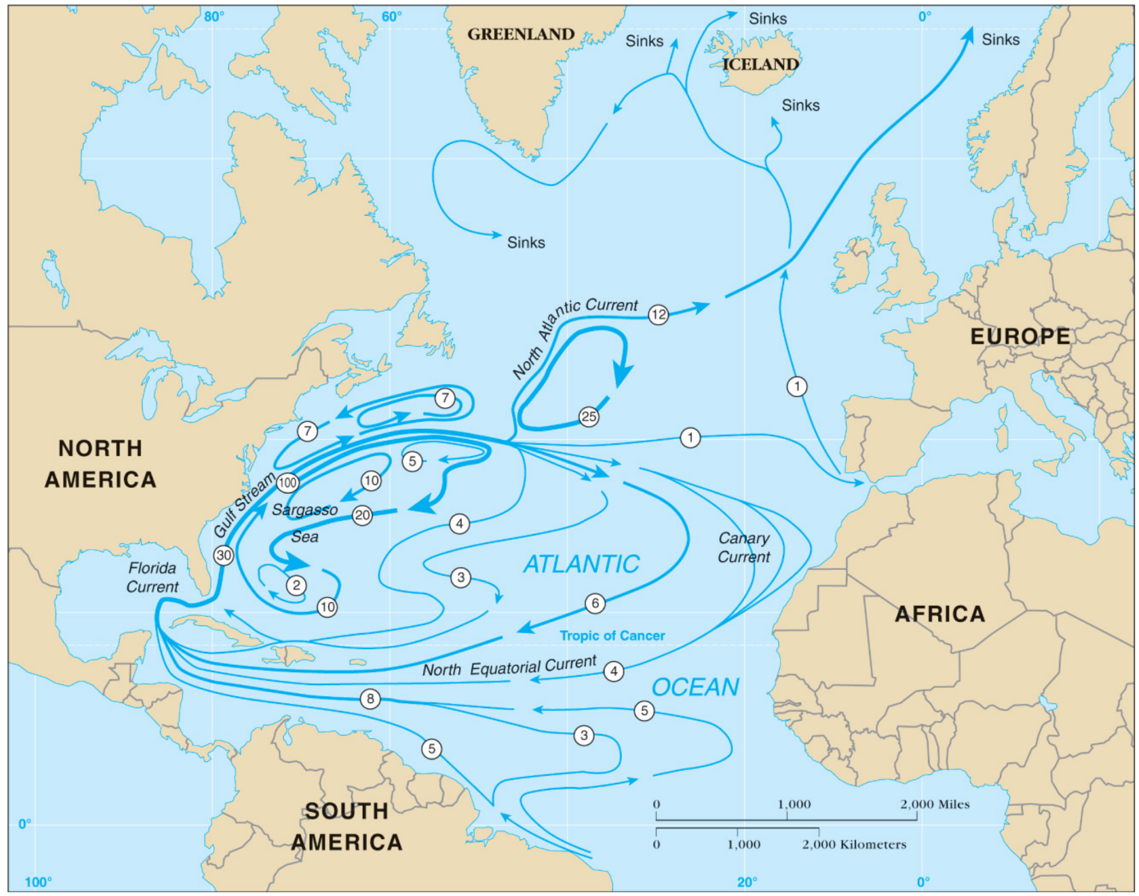


# North and South Atlantic Subtropical Gyres

- North Atlantic Subtropical Gyre
  - North Equatorial Current
  - Gulf Stream
  - North Atlantic Current
  - Canary Current
  - South Equatorial Current
  - Atlantic Equatorial Counter Current
- South Atlantic Subtropical Gyre
  - Brazil Current
  - Antarctic Circumpolar Current
  - Benguela Current
  - South Equatorial Current
  - Falkland Current

# Gulf Stream

- moves northward along the east coast of North America
- warms coastal states
- warms northern Europe





Numbers indicate average flow rates in Sverdrups
One Sverdrup is equivalent to 1,000,000 $m^3$/sec

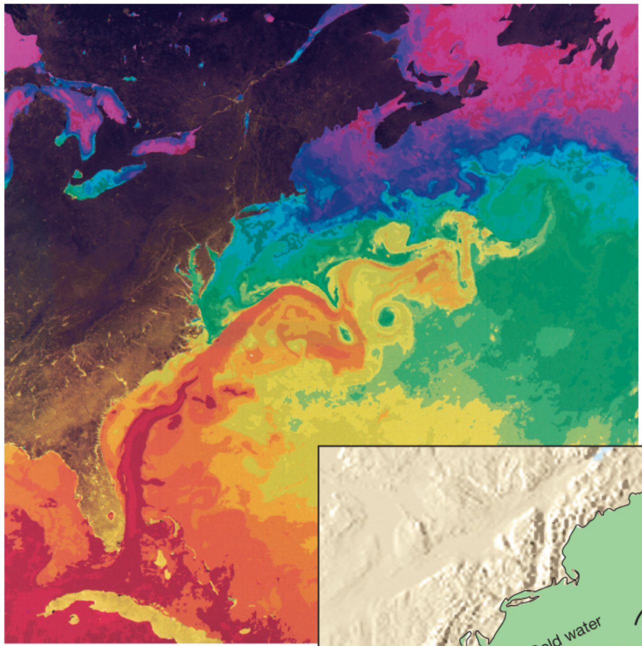

- originates from North Equatorial Current
- receives water from South Equatorial Current
  - (because of the geography of South America)
- splits into Antilles and Caribbean currents
- these join again between Florida and Cuba
- as it moves off from Cape Hatteras it is properly called “Gulf Stream”

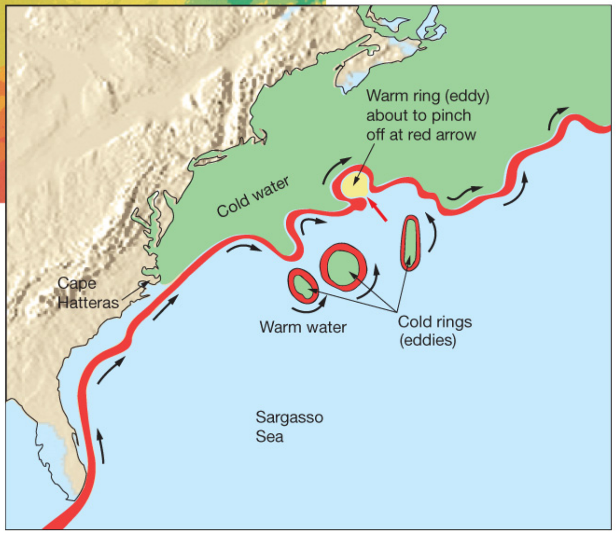
# Gulf Stream and Sargasso Sea

- as a western boundary current, the Gulf Stream is narrow, deep, and fast
- its western margin is abrupt, while its eastern margin is less defined
- it gradually merges eastward with the Sargasso Sea
- the Sargasso Sea is a body of water that circulates around the center of the North Atlantic Gyre
  - *Sargassum* is a floating marine algae that is particularly abundant in this area

# Rings of the Gulf Stream

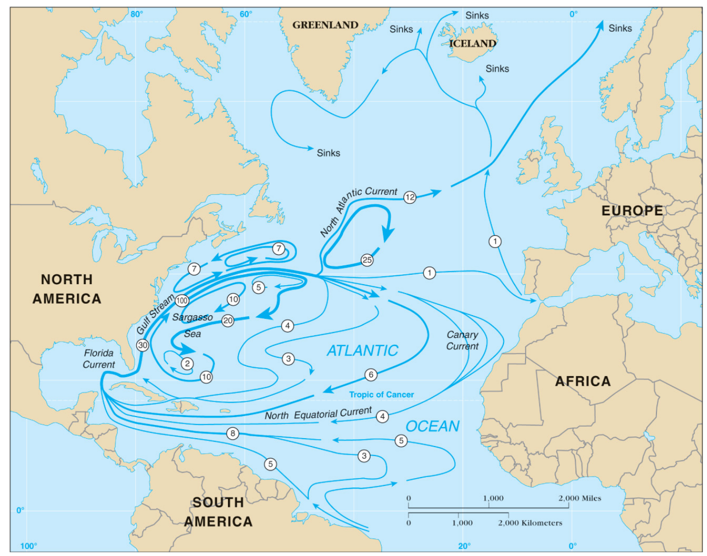
- Meanders or loops may cause loss of water volume and generate:
  - Warm-core rings: warmer Sargasso Sea water trapped in loop surrounded by cool water. Narrow and shallow
  - Cold-core rings: cold water trapped in loop surrounded by warmer water. Wide and deep. Vertical mixing, with consequent upwelling and abundance of life
- Unique biological populations





# Other North Atlantic Currents

- Labrador Current
  - comes from between Newfoundland and Greenland. Mixes with Gulf Stream to create fogbanks in the North Atlantic
- Irminger Current
  - west of Iceland
- Norwegian Current
  - west of Norway
- North Atlantic Current
  - crosses the Atlantic





- Canary Current
  - cold current that closes the gyre by rejoining the North Equatorial Current

# Climate effects of North Atlantic Currents

## North-moving currents – warm

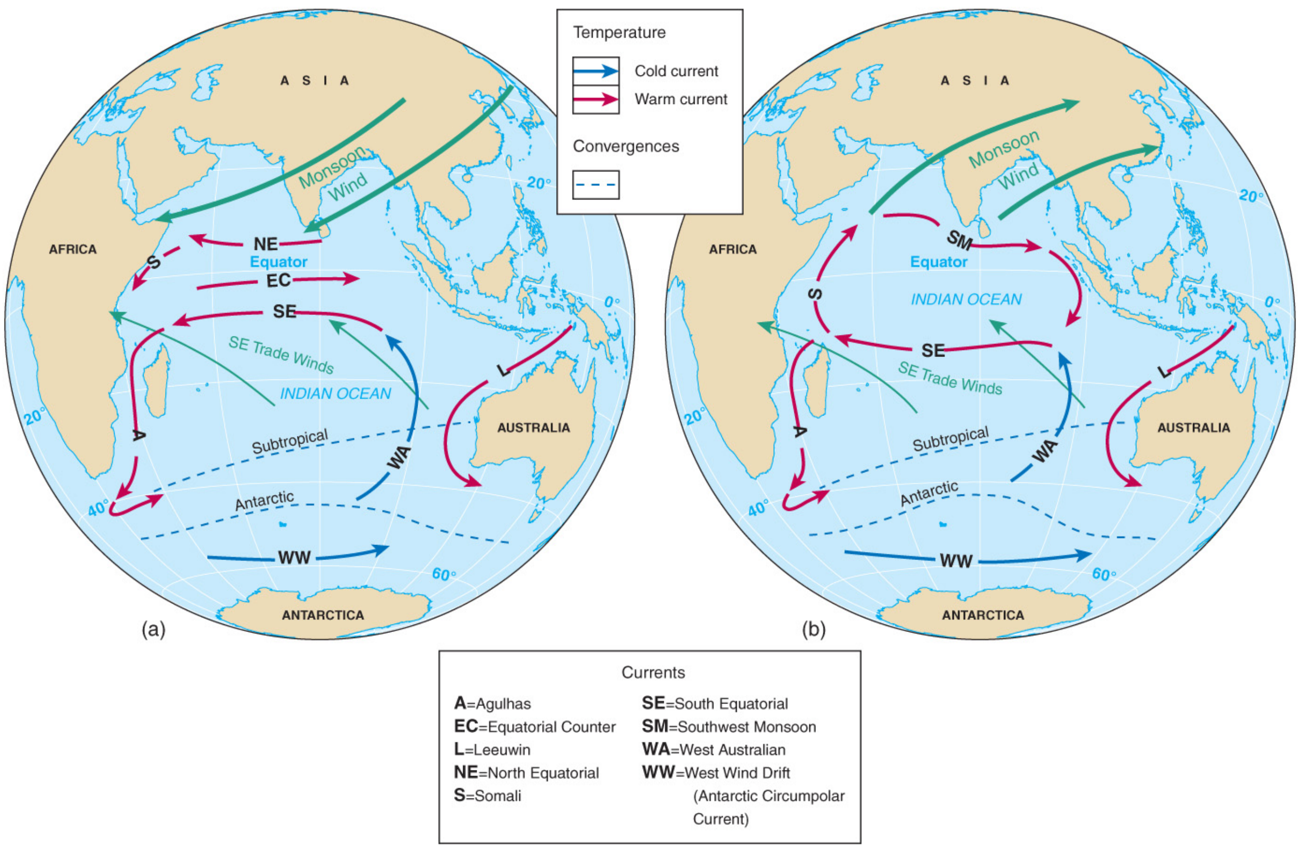
- the Gulf Stream warms the East coast of the United States and northern Europe
- North Atlantic and Norwegian Currents warm northwestern Europe

## South-moving currents – cool

- Labrador Current cools eastern Canada
- Canary Current cools north African coast

# Indian Ocean Circulation

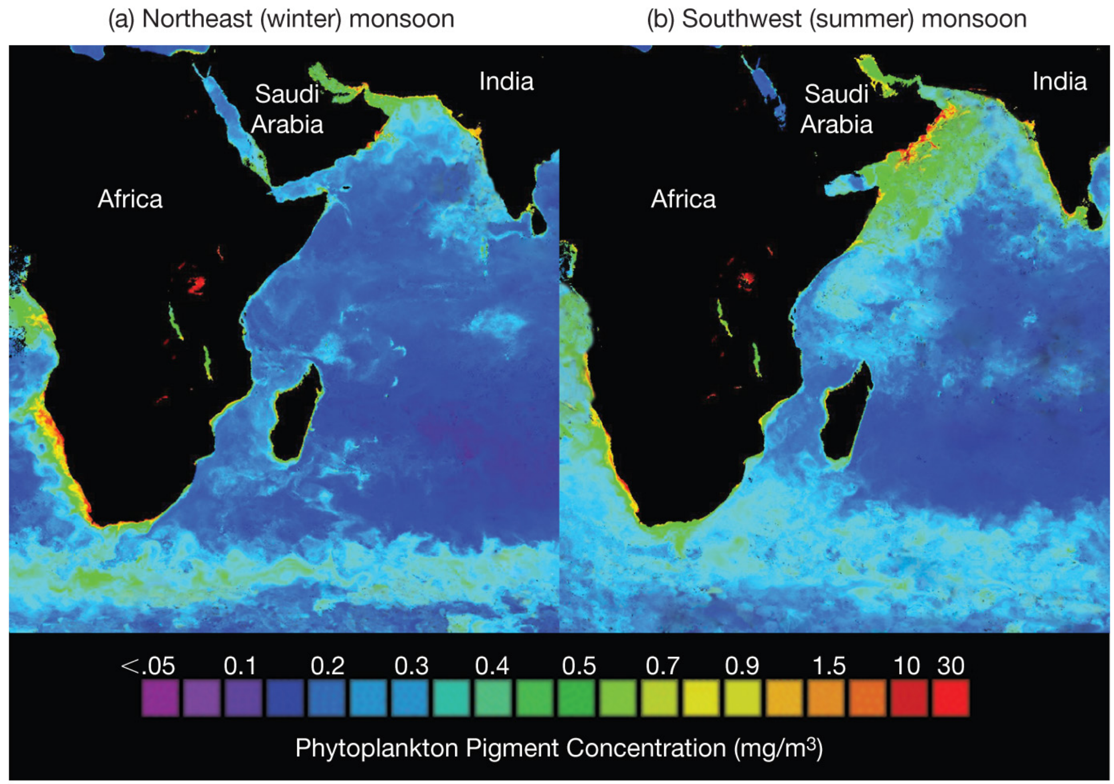
- Because of local geography, the Indian Ocean exists mostly in the southern hemisphere
- In winter, equatorial circulation is similar to Atlantic
- proximity to Himalayas and shape of coastline and ocean basin cause it to experience strong seasonal changes



# Monsoons

- Seasonal reversals of winds over northern Indian Ocean
- Northeast monsoon (winter)
  - winds blowing from land: dry weather
- Southwest monsoon (summer)
  - winds blowing from ocean: heavy precipitation

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






Indian Ocean Subtropical Gyre

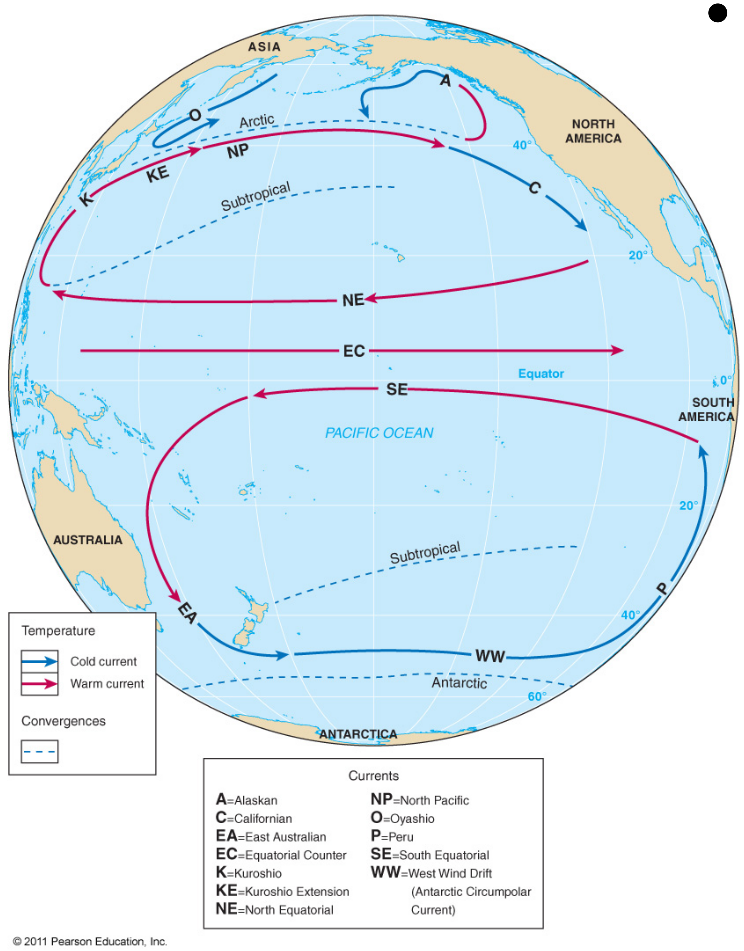
Agulhas Current

Australian Current

Leeuwin Current

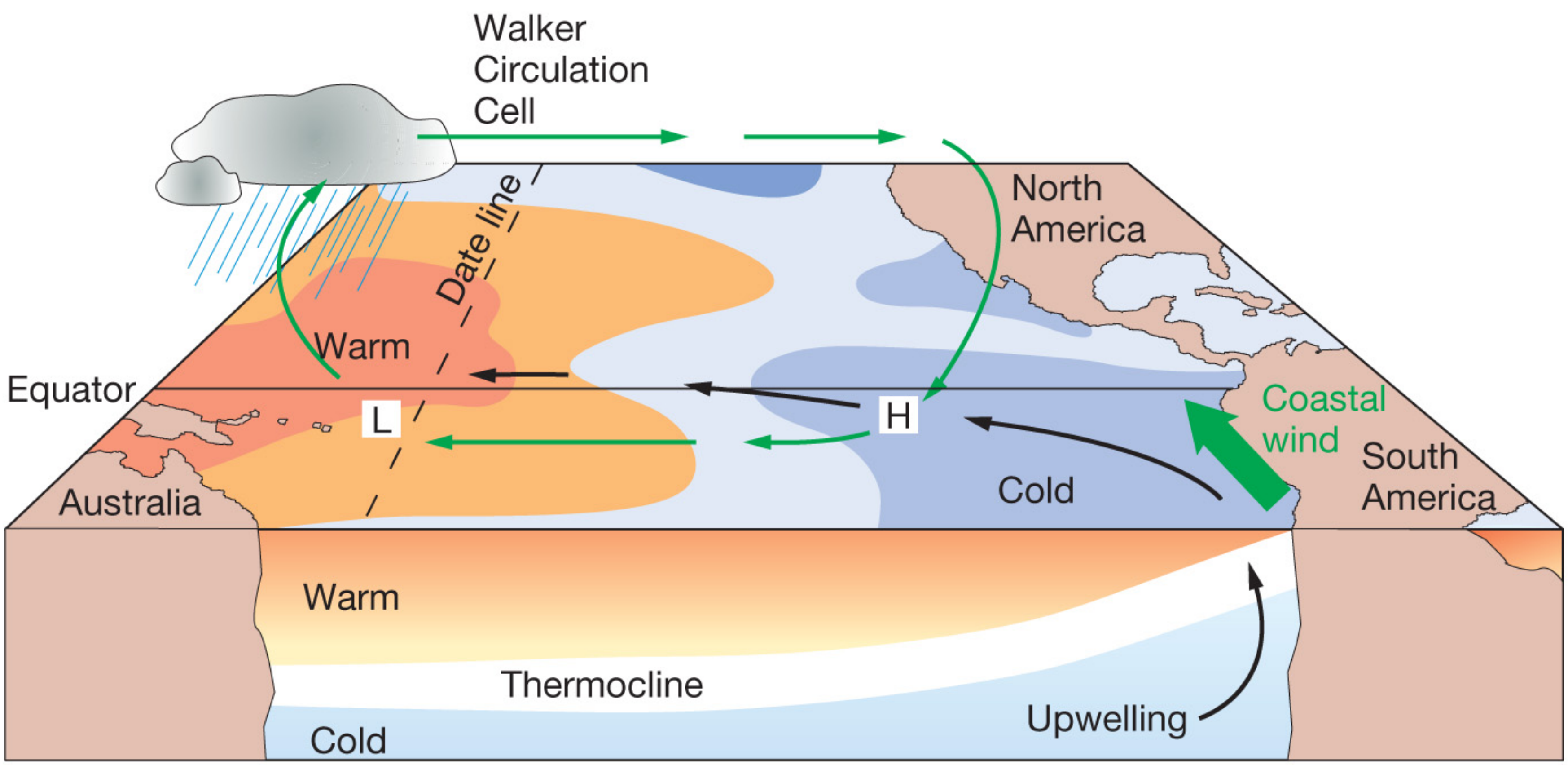
# Pacific Ocean Circulation

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




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

# Normal Conditions in the Pacific Ocean (Walker Circulation)

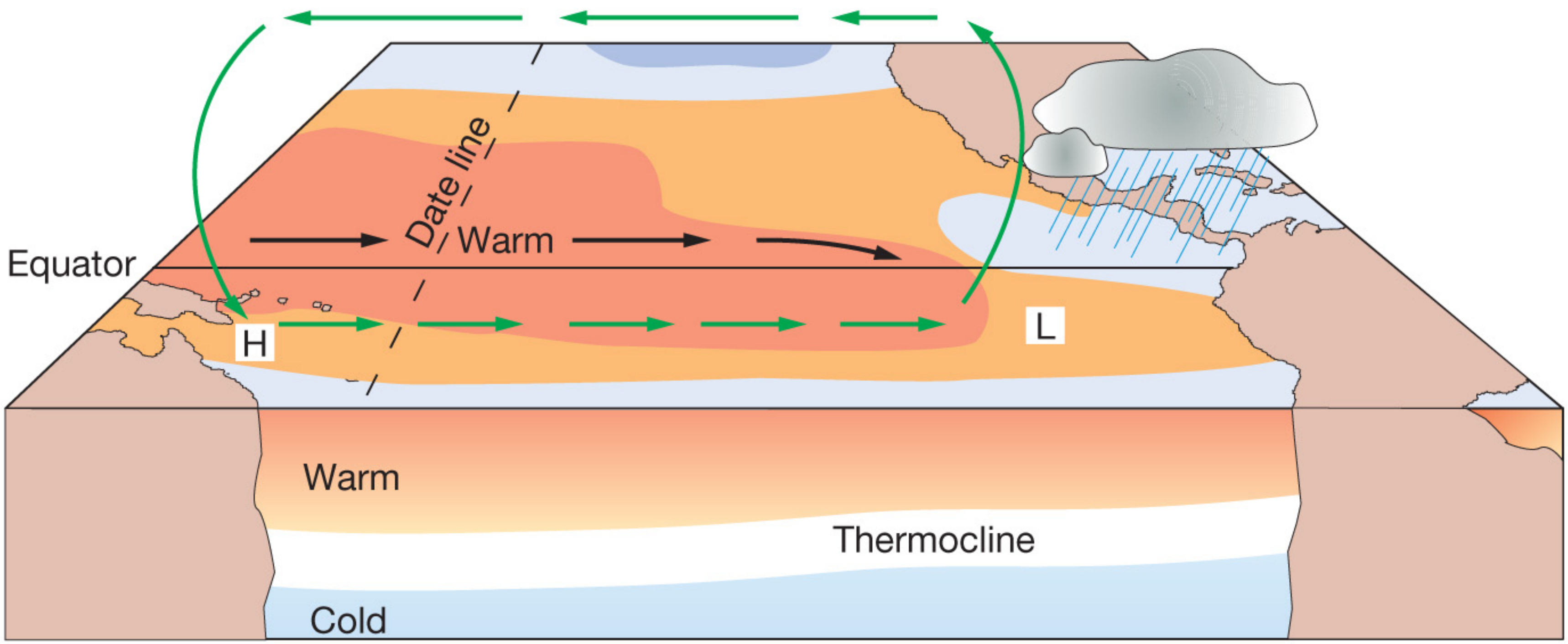



(a) Normal conditions

# 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

# ENSO (El Niño – Southern Oscillation) Conditions in the Pacific Ocean

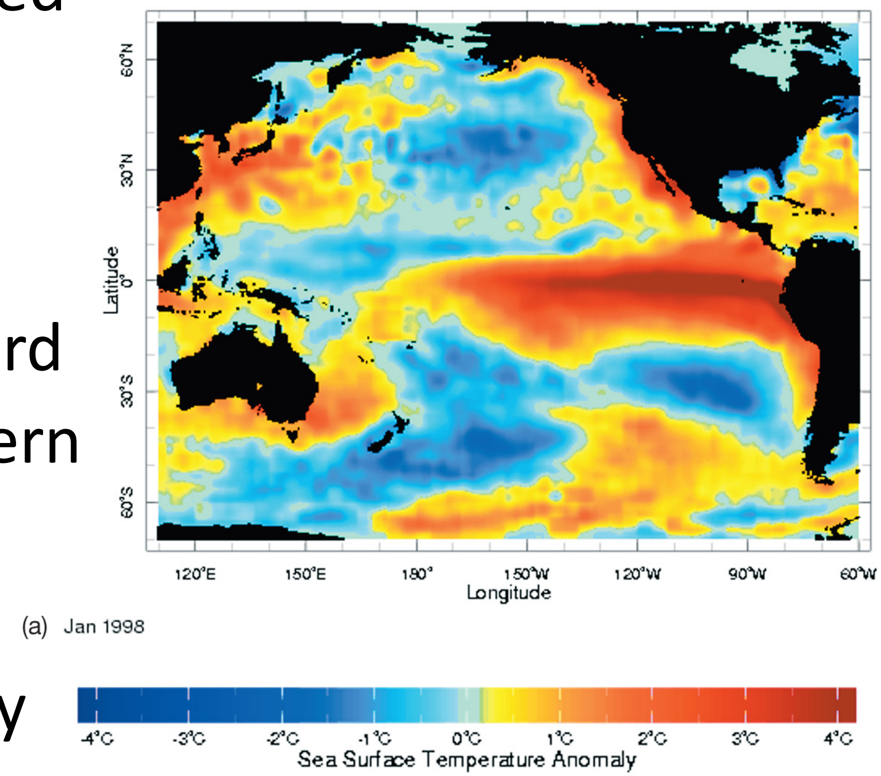



(b) El Niño conditions (strong)

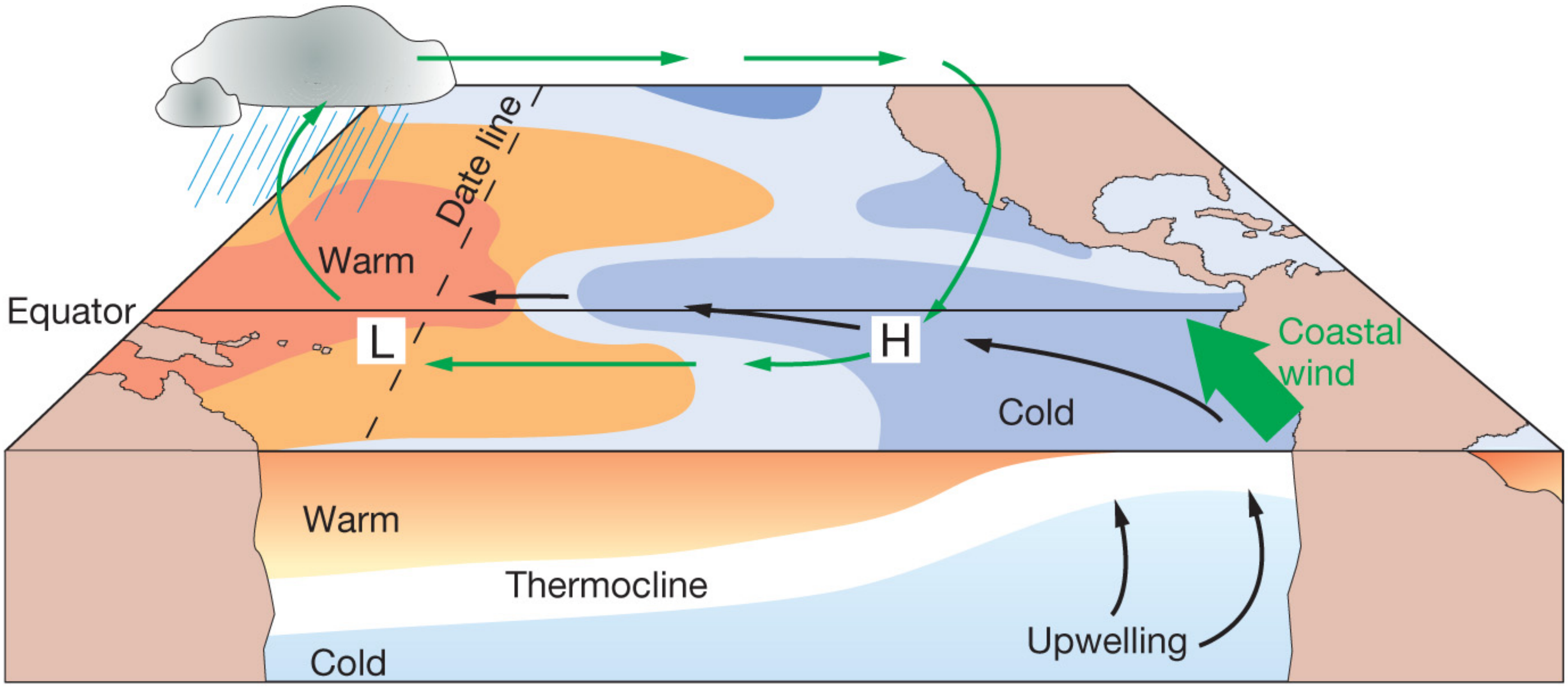
# El Niño – Southern Oscillation (ENSO)

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



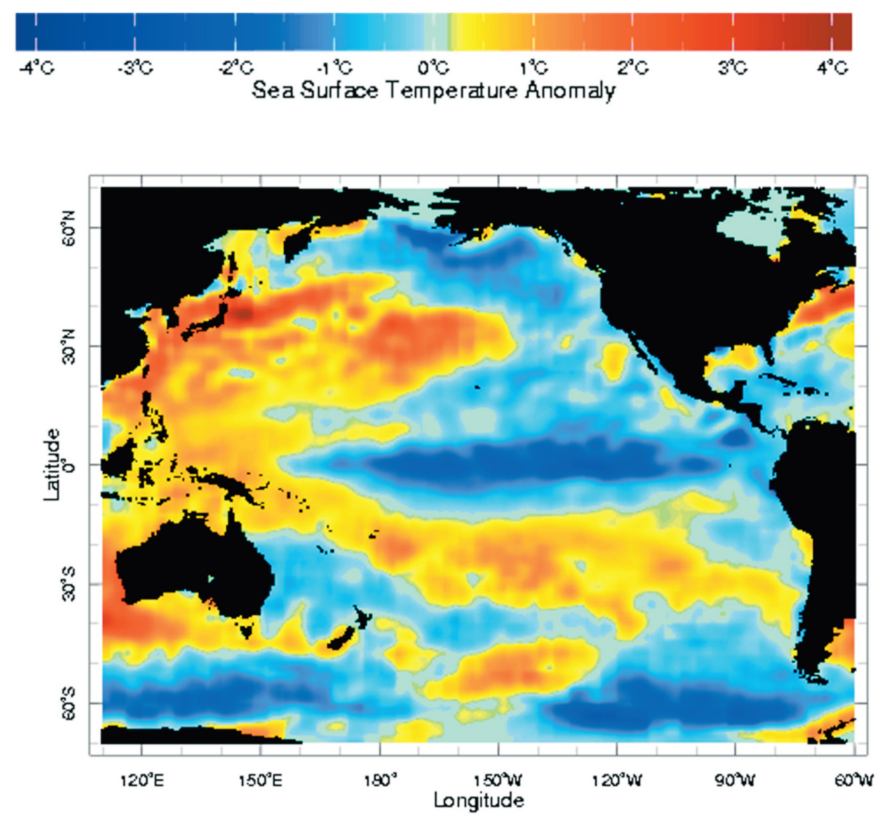
# La Niña Conditions




(c) La Niña conditions

# La Niña – ENSO Cool Phase

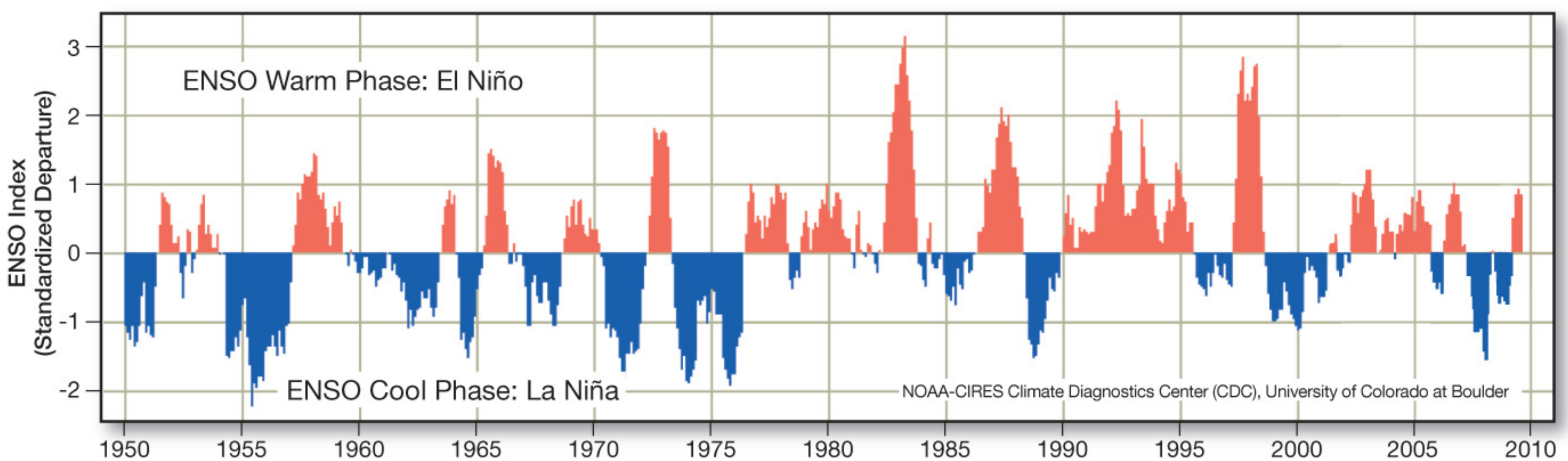
- Increased pressure difference across equatorial Pacific
- Stronger trade winds
- Stronger upwelling in eastern Pacific
- Shallower thermocline
- Cooler than normal seawater
- Higher biological productivity



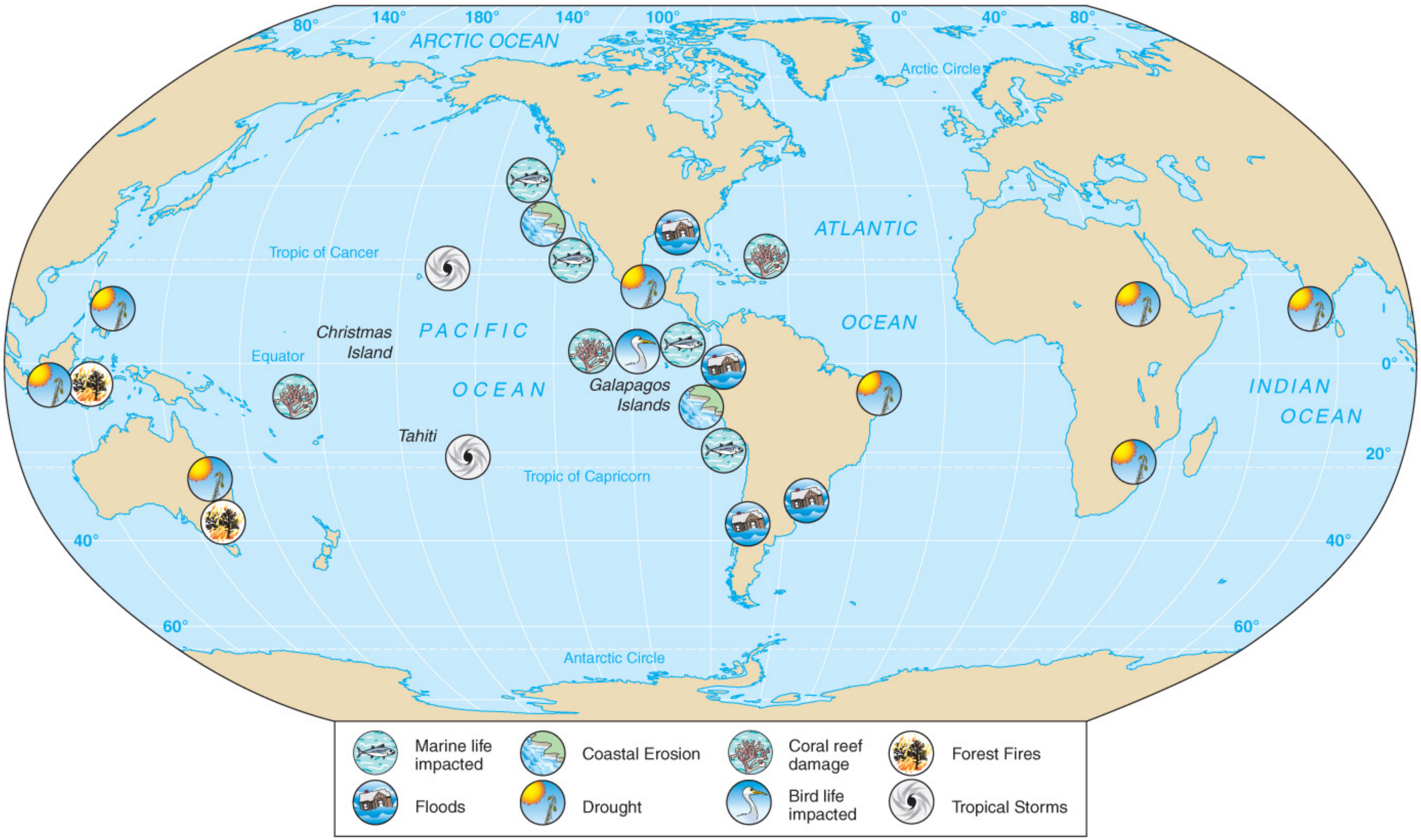

(b) Jan 2000

# How often do El Niño Events occur?

- 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

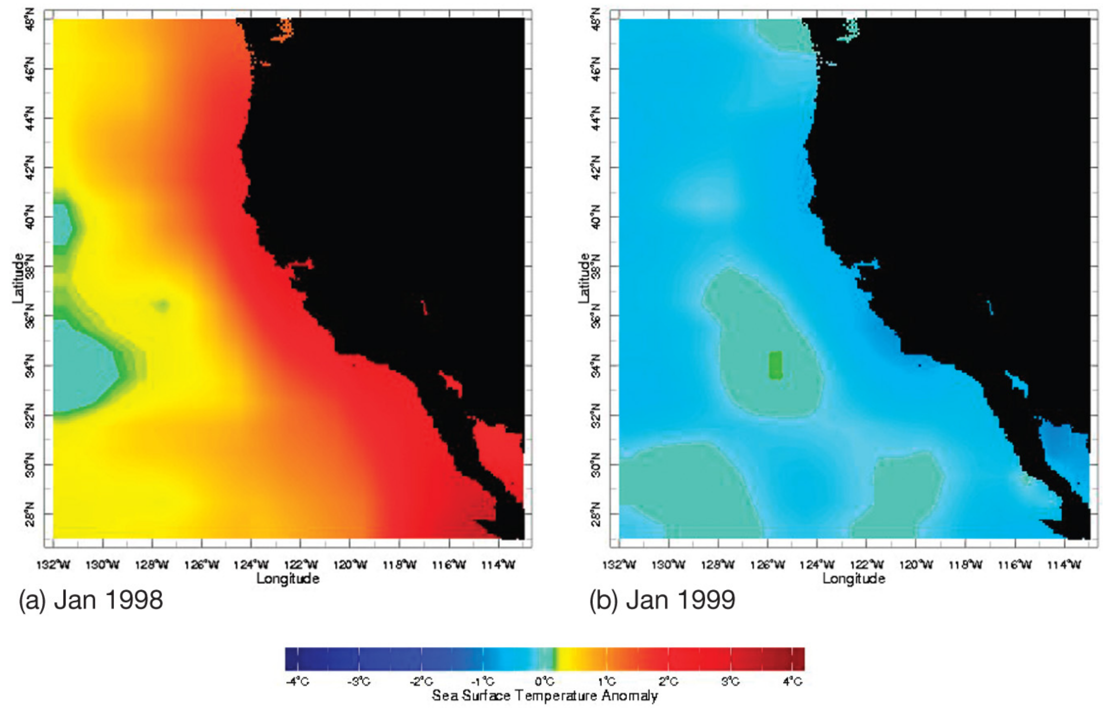


# ENSO has Global Impacts



# Notable ENSO Events

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



# Predicting El Niño Events

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

# 7.5 – How Do Deep-Ocean Currents Form?

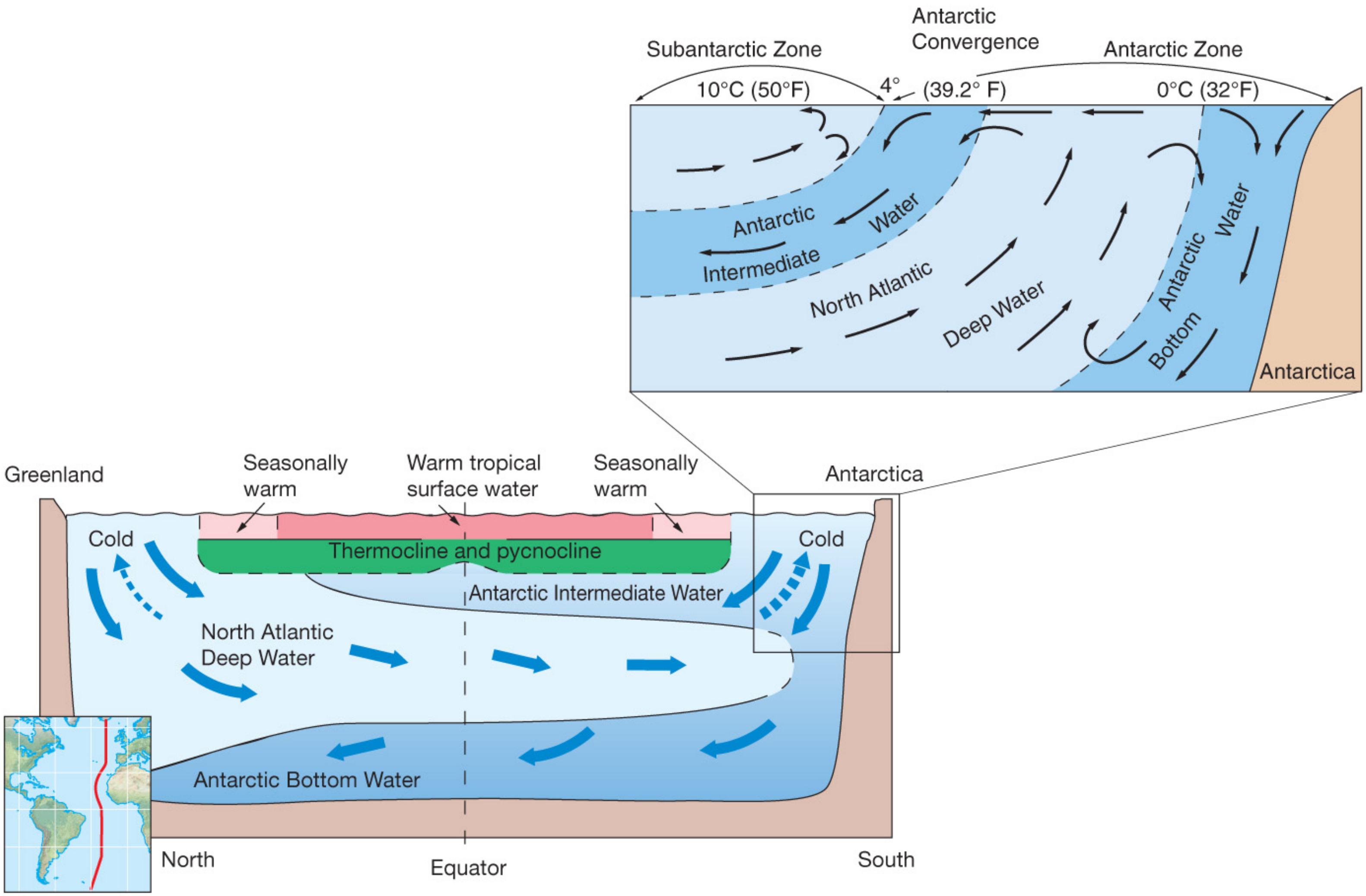
- Occur below the pycnocline
- As a consequence, they effect 90% of ocean waters
- They are created by variations in density of the ocean water
- This circulation system is then called thermohaline (temperature and salinity of ocean waters control their density)
- Thermohaline circulation is very slow: 10 to 20 km/yr

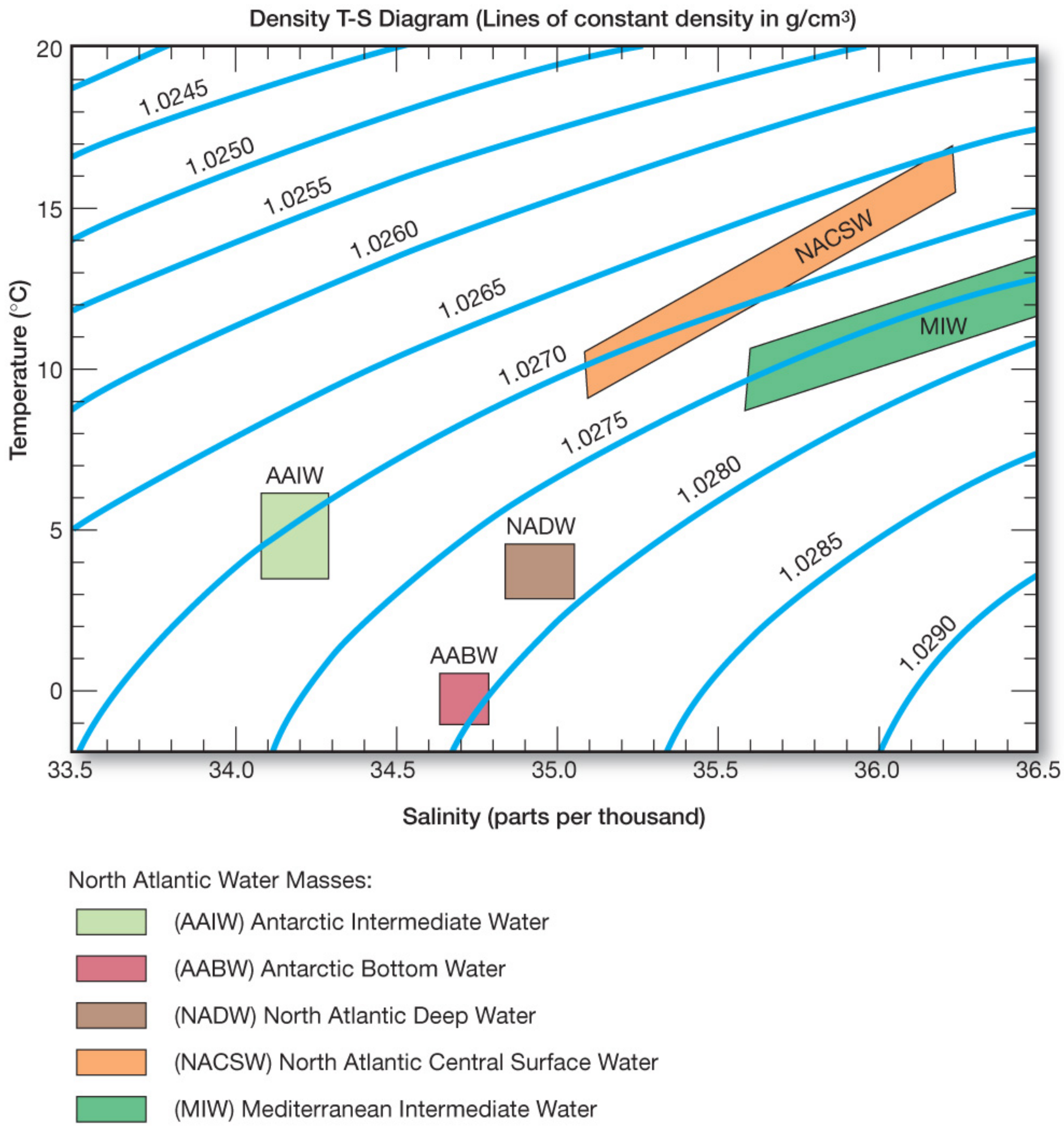
# Origin of Thermohaline Circulation

- Originates in high latitude surface ocean
- Cooled, now dense surface water sinks and changes little
- Formation of sea ice increases the salinity, hence the density, of the water left behind, which starts to sink

- Deep-water masses can be identified on a temperature–salinity (T–S) diagram
  - Identifies deep water masses based on temperature, salinity, and resulting density

# Thermohaline Circulation



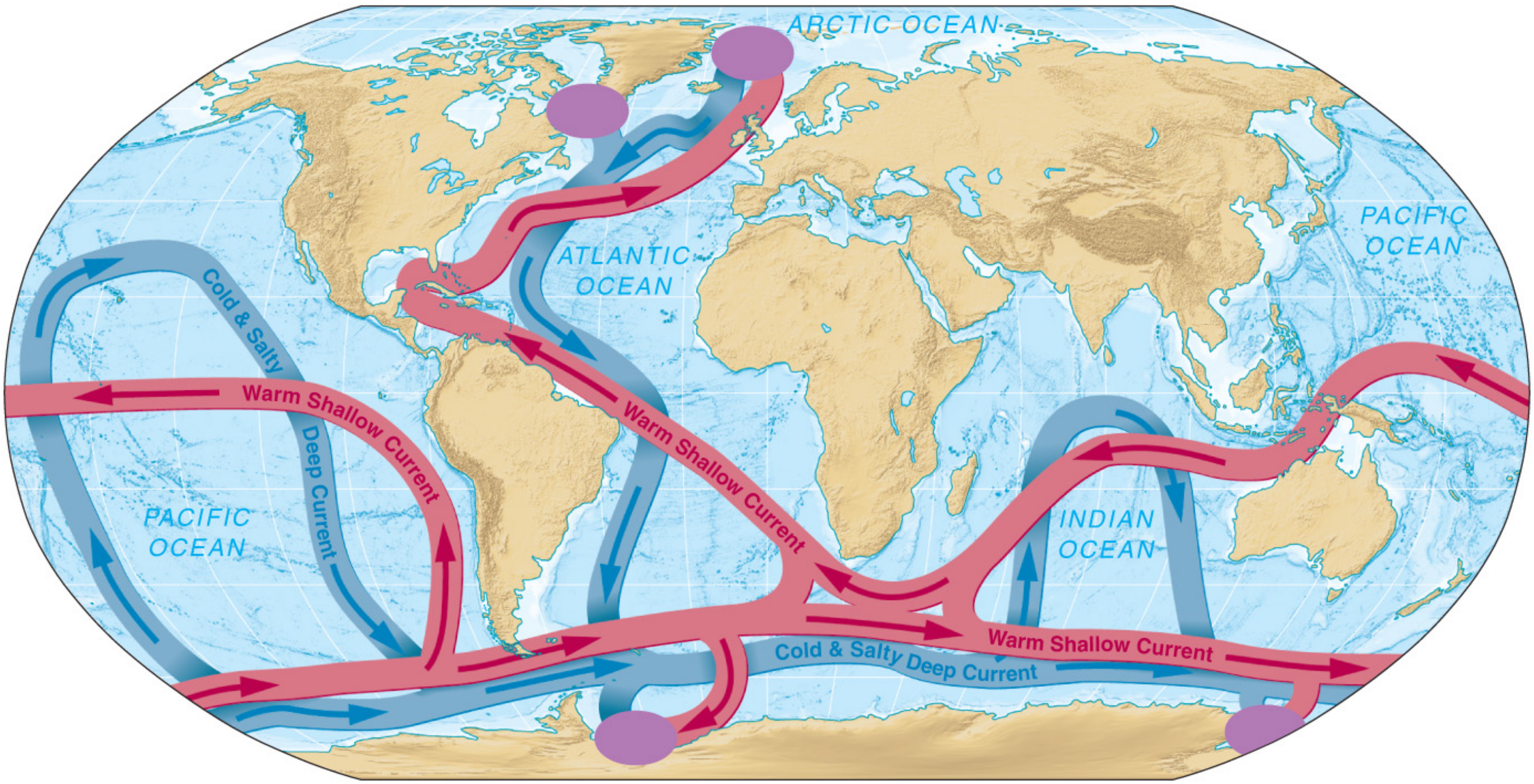


Density T-S Diagram (Lines of constant density in g/cm3)
Temperature (°C)
Salinity (parts per thousand)
20
15
10
5
0
33.5
34.0
34.5
35.0
35.5
36.0
36.5
1.0245
1.0250
1.0255
1.0260
1.0265
1.0270
1.0275
1.0280
1.0285
1.0290
NACSW
MIW
AAIW
NADW
AABW
North Atlantic Water Masses:
(AAIW) Antarctic Intermediate Water
(AABW) Antarctic Bottom Water
(NADW) North Atlantic Deep Water
(NACSW) North Atlantic Central Surface Water
(MIW) Mediterranean Intermediate Water

# 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



- Dissolved oxygen in deep water
  - examples from the Cretaceous (greenhouse time)

- Conveyor-belt circulation and climate change
  - Plate tectonics changes geography
  - Climate changes affect deep-water circulation

# 7.6 – Can Power from Currents Be Harnessed as a Source of Energy?

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