

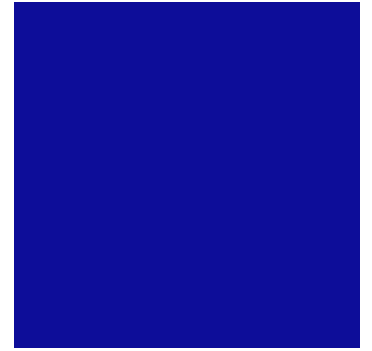
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# General ocean circulation

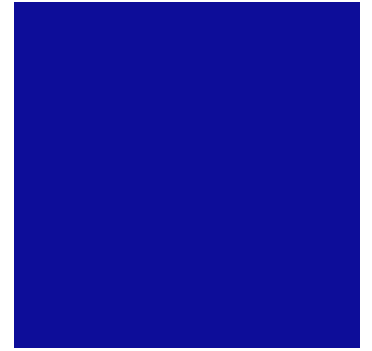
Brian K. Arbic

# Overview

- General atmospheric circulation
- Coriolis force
- Ekman flow
- General ocean circulation—theory
- General ocean circulation—description
- Measuring the general ocean circulation
- Animations

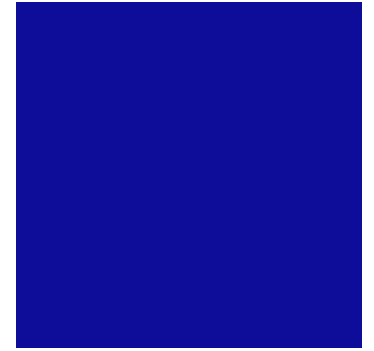


# What do we mean by the general ocean circulation?



- Seawater moving continuously in one direction, in ocean currents (later we will discuss more transitory motions--waves and tides)
- Why are ocean currents important?
  - Affect marine life by bringing nutrients up from deeper waters
  - Affect temperatures by transporting heat, rainfall by providing source of moisture

# Why do we need to discuss the general atmospheric circulation? Isn't this an oceanography school?

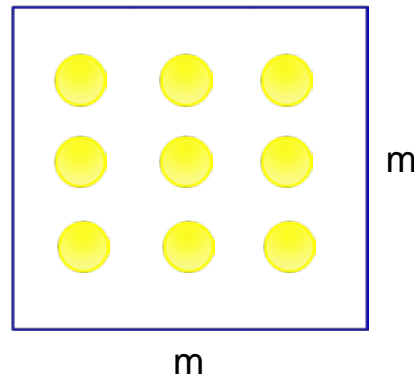


- The atmosphere is the most important forcing agent for the ocean
  - More important than the tides!
- How does the atmosphere force the ocean?
  - Pressure loading
  - Winds
  - Buoyancy fluxes
    - Latent and sensible heat fluxes (which impact ocean temperatures)
    - Evaporation and precipitation (which impact ocean salinities)

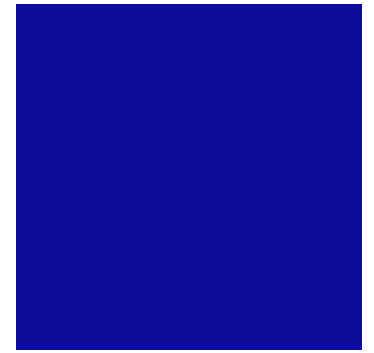
# The Sun

- The dominant source of energy for the climate system – it drives it.
- Delivers annual average of  $344 \text{ W/m}^2$  at top of the atmosphere:

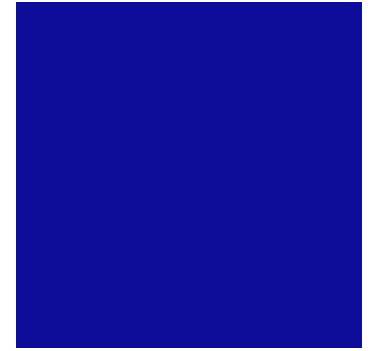
*~9 40W light bulbs  
per square meter*



- Energy is the ability to do work
  - comes in units of Joules (J)
  - energy flux:  $1 \text{ J} / \text{s} = 1 \text{ Watt}$  (energy per unit time, or power)
  - $\text{W/m}^2$ : energy (in J) per second over area of  $1 \text{ m}^2$



# How and why does the atmosphere move?



- Solar heating is uneven—equator receives more heat per unit area than high latitudes
- Atmosphere (and ocean) respond by moving warm fluid to poles and returning cold fluid to the equator, thus moderating the temperature difference between the equator and poles
- These circulations are similar to convection cells in a heated room

# Uneven solar heating

- Equatorial regions receive more heat per unit area because:
  - Higher incidence angle
    - spreads energy over smaller areas
    - implies that sunlight passes through thinner column of atmosphere, leading to less absorption
    - leads to less reflection from ocean
  - Albedo is lower

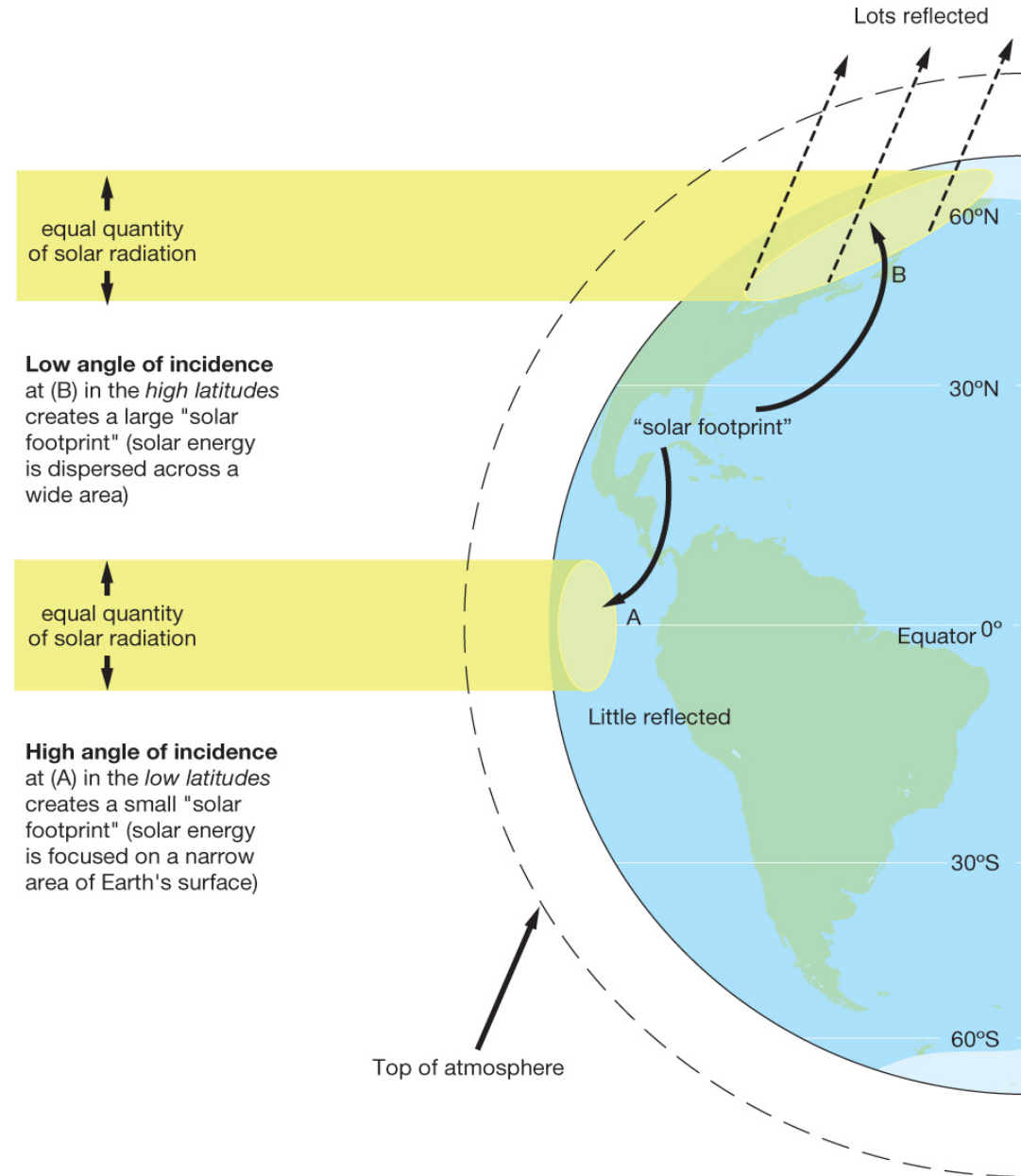
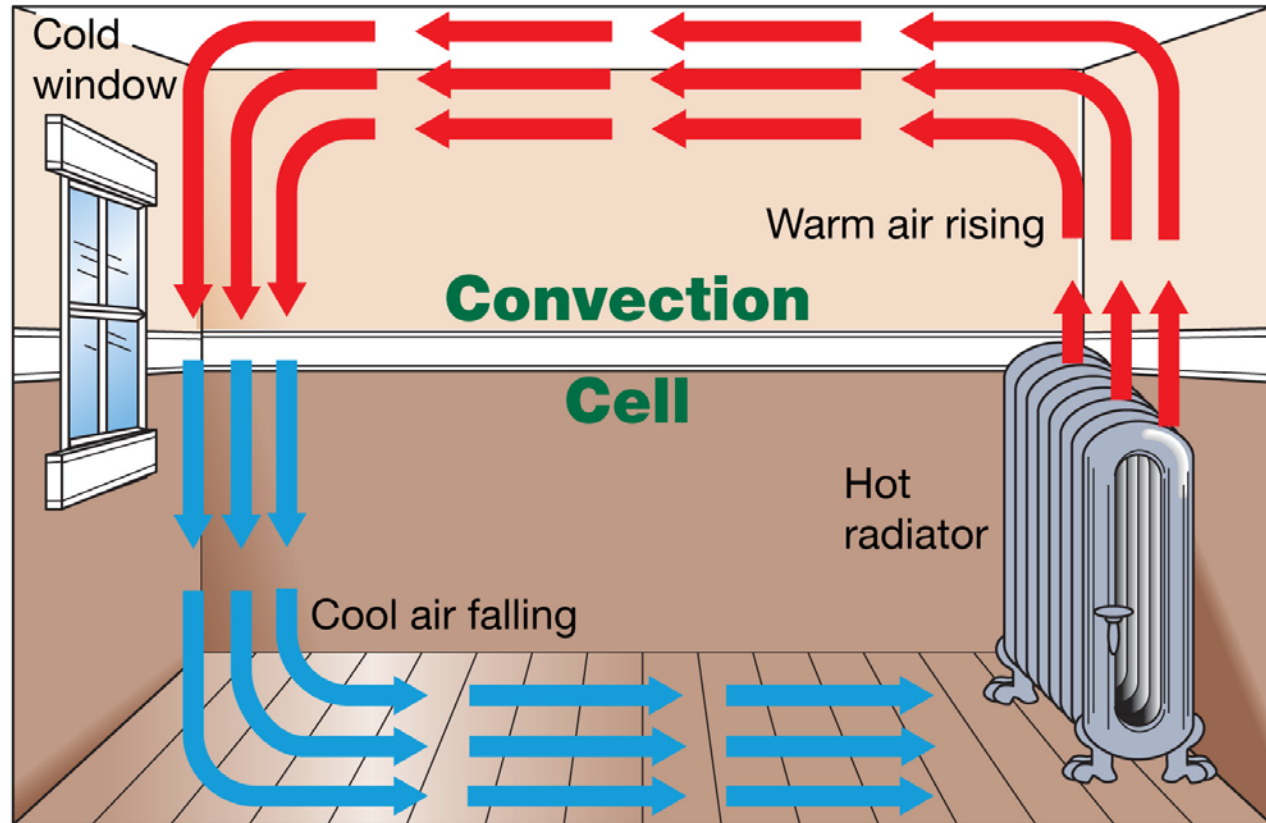


Fig. 6-2 page 165, Trujillo and  
Thurman

# Example of convection – in a room

- Warm air, less dense (rises)
- Cool air, more dense (sinks)



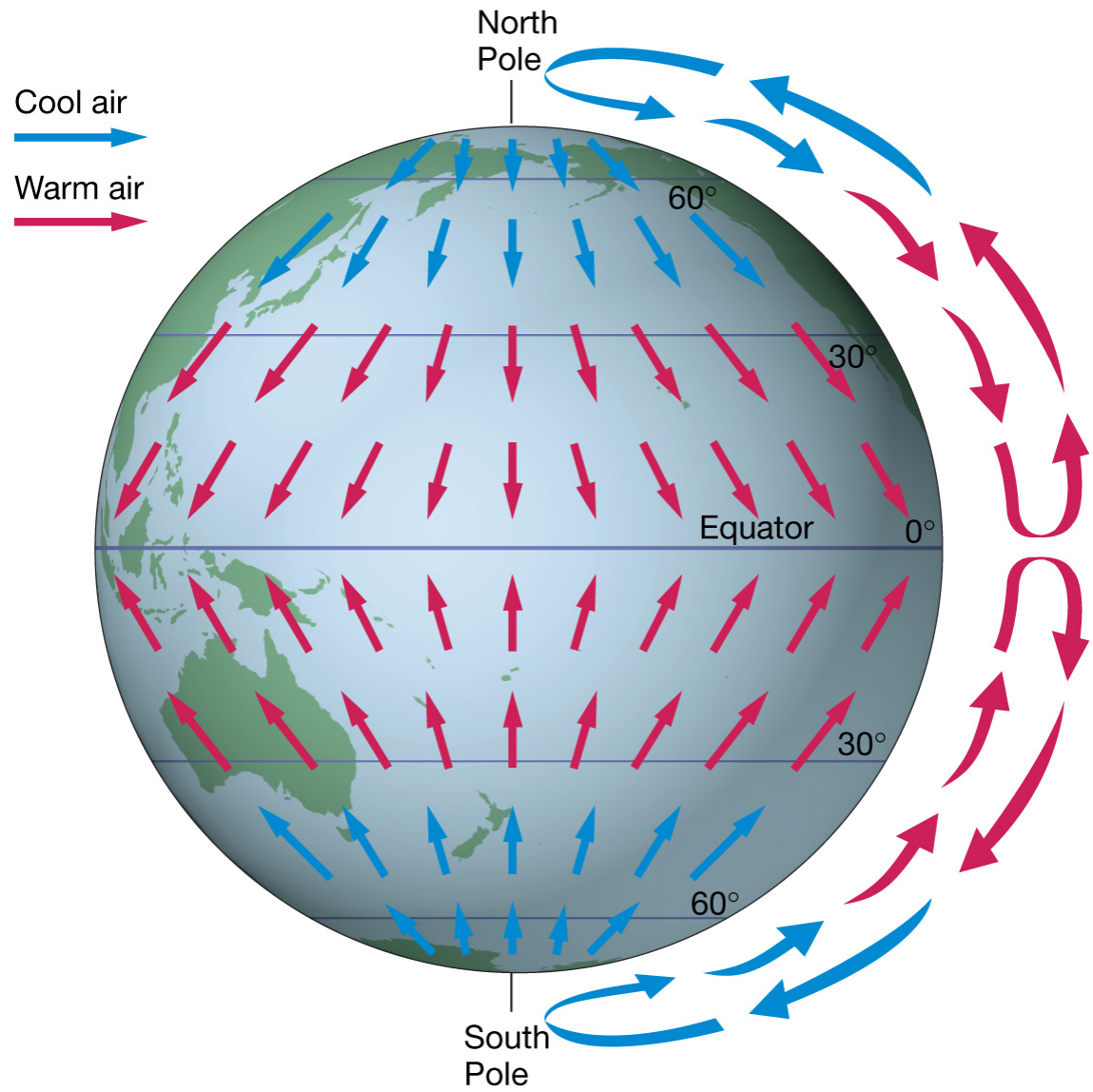
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Figure 6.5, page 167, Trujillo and Thurman



# Circulation on a non-rotating Earth

- Air (wind) always moves from regions of high pressure to low
- Convection or circulation cell
- Next we will discuss how Earth's rotation alters this simple picture

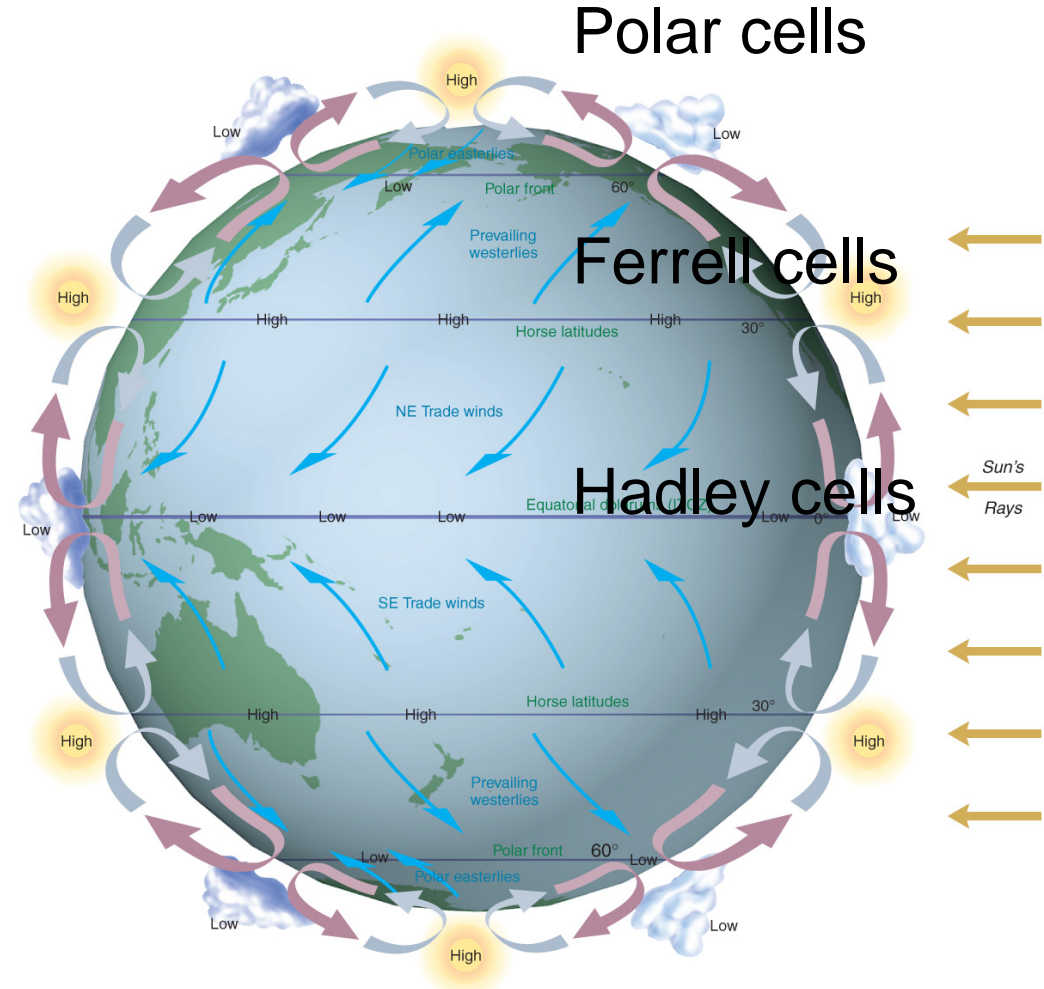


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Fig. 6.7, page 169, Trujillo and Thurman

# Global atmospheric circulation

- Low pressure zones
  - Equatorial low
  - Subpolar lows
  - Overcast skies with lots of precipitation
- High pressure zones
  - Subtropical highs
  - Polar highs
  - Clear skies

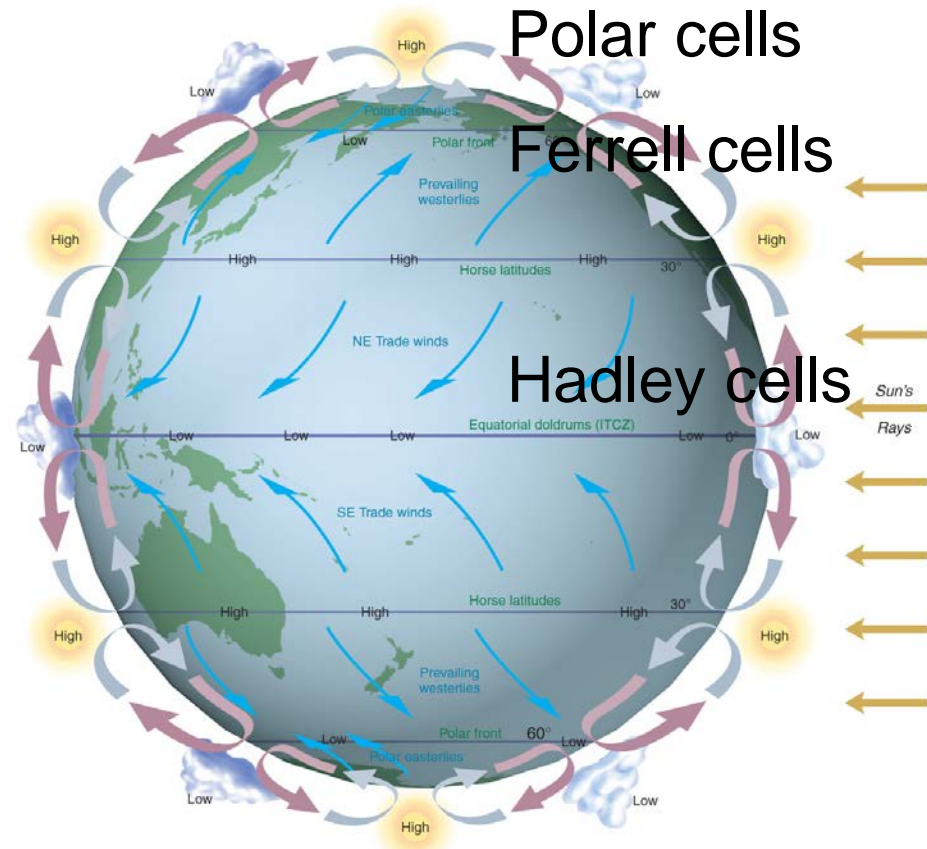


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Fig. 6.10, page 173, Trujillo and Thurman

# Global wind belts

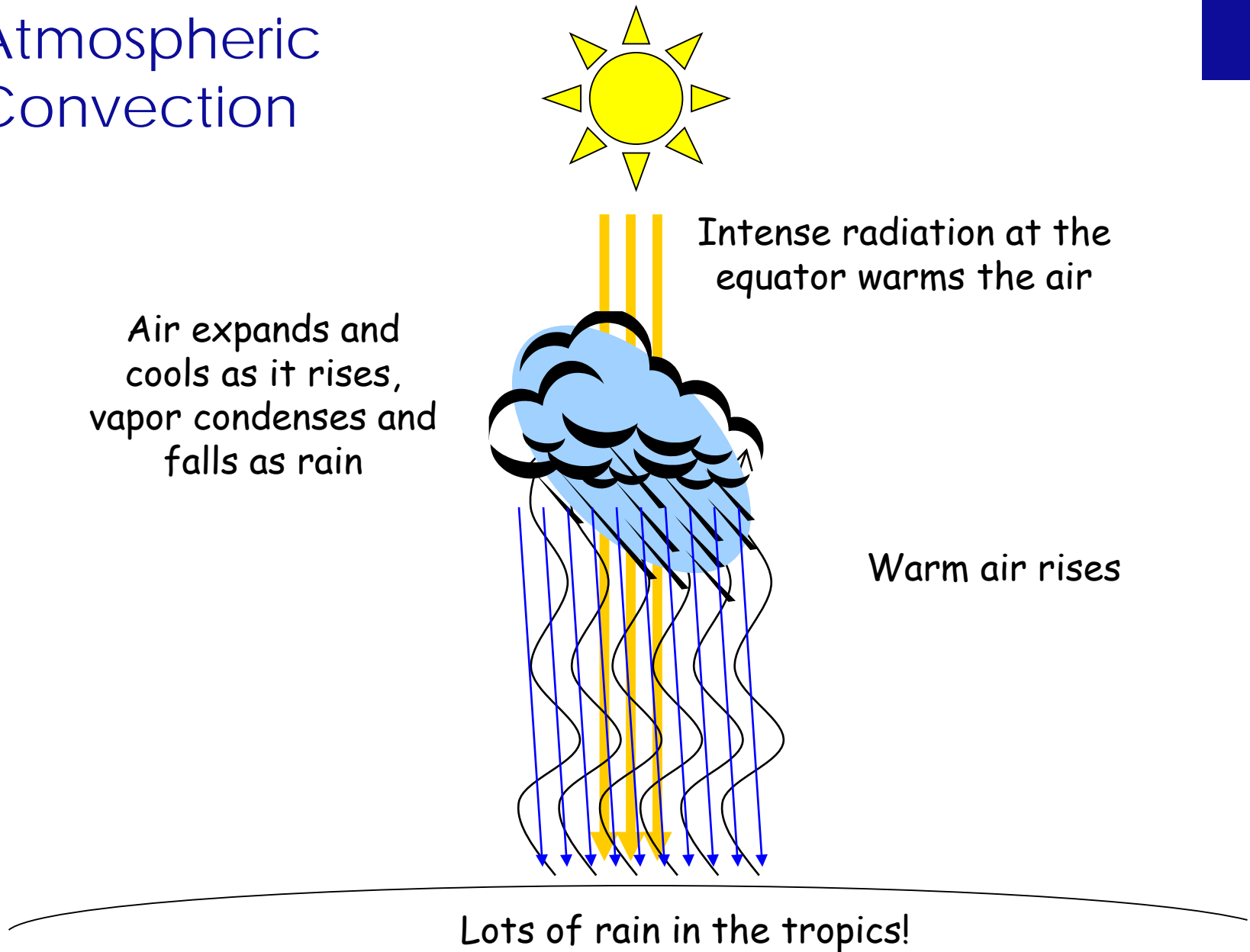
- Trade winds (named for direction wind flows from):
  - Northeast trades in Northern Hemisphere
  - Southeast trades in Southern Hemisphere
- Prevailing westerlies
- Polar easterlies
- Boundaries between wind belts
- Doldrums or Intertropical Convergence Zone (ITCZ)
- Horse latitudes ( $30^{\circ}$  N&S)
- Polar fronts ( $60^{\circ}$  N&S)



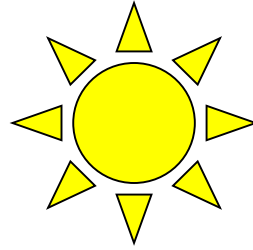
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Fig. 6.10, page 173, Trujillo and Thurman

# Atmospheric Convection



# Hadley Circulation



Rising air is now dry...



some of the rising  
air flows north

some of the rising  
air flows south

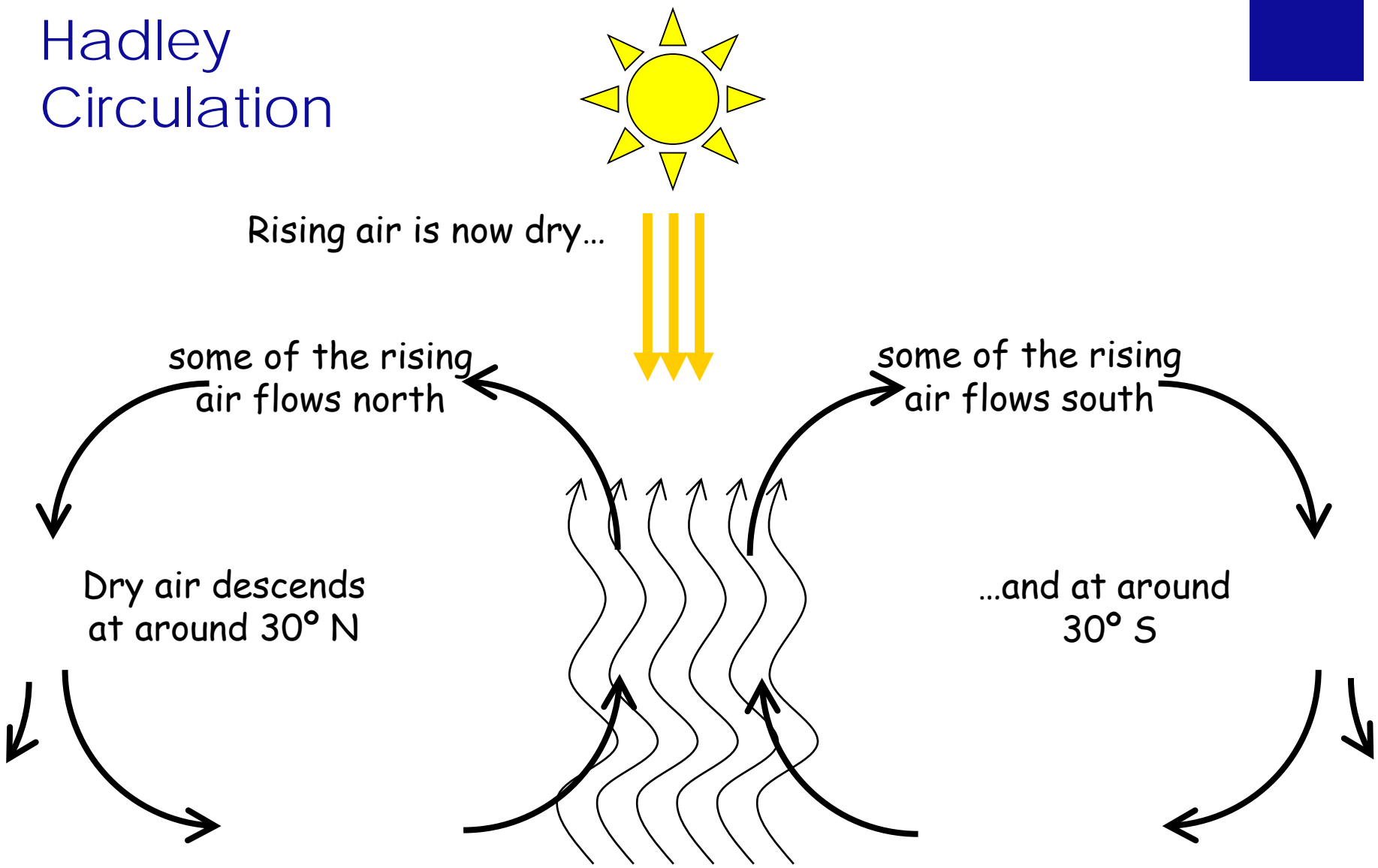
Dry air descends  
at around  $30^{\circ}$  N

...and at around  
 $30^{\circ}$  S

Deserts

The descending air flows N and S

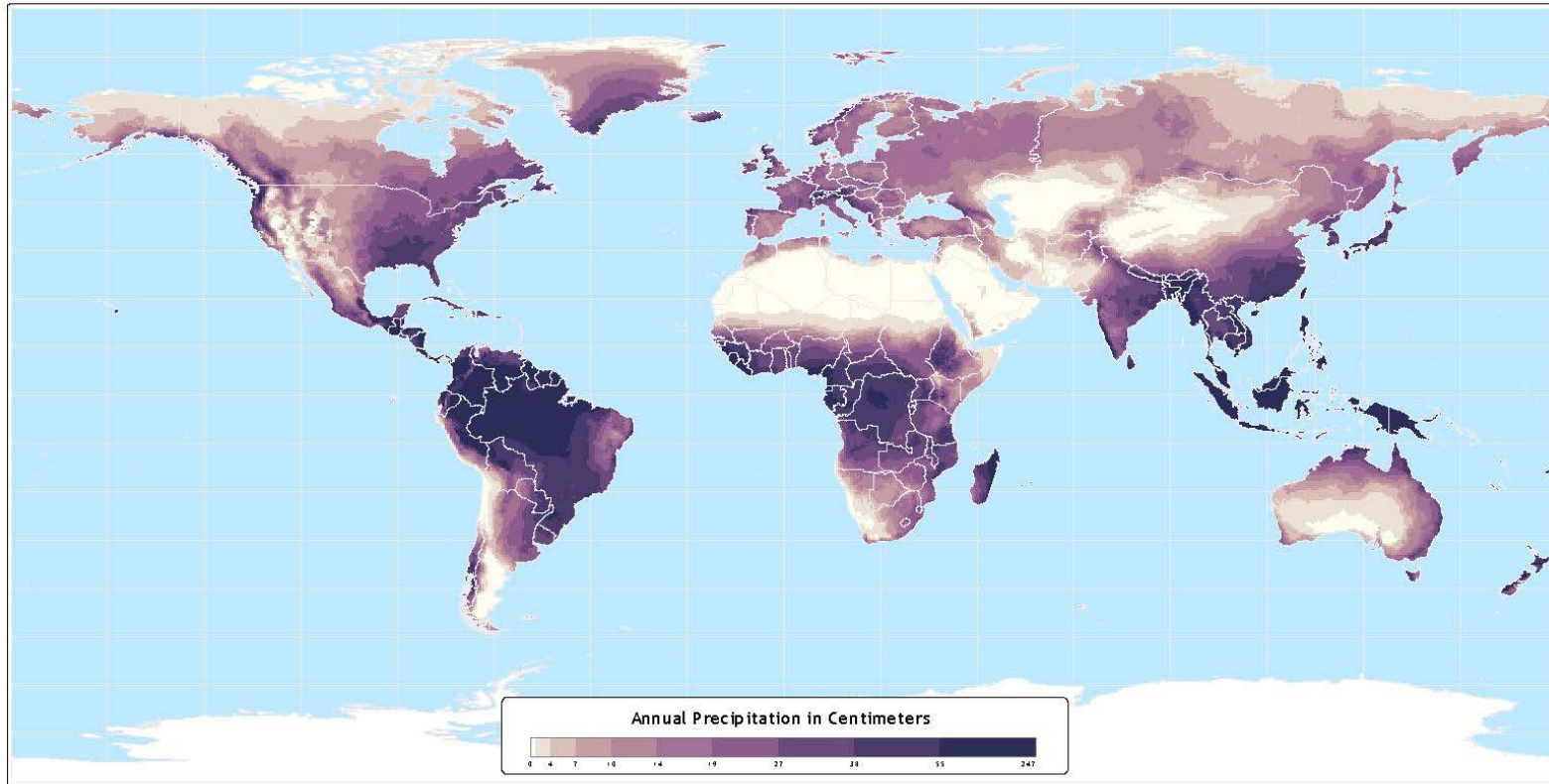
Deserts







# Annual Total Precipitation

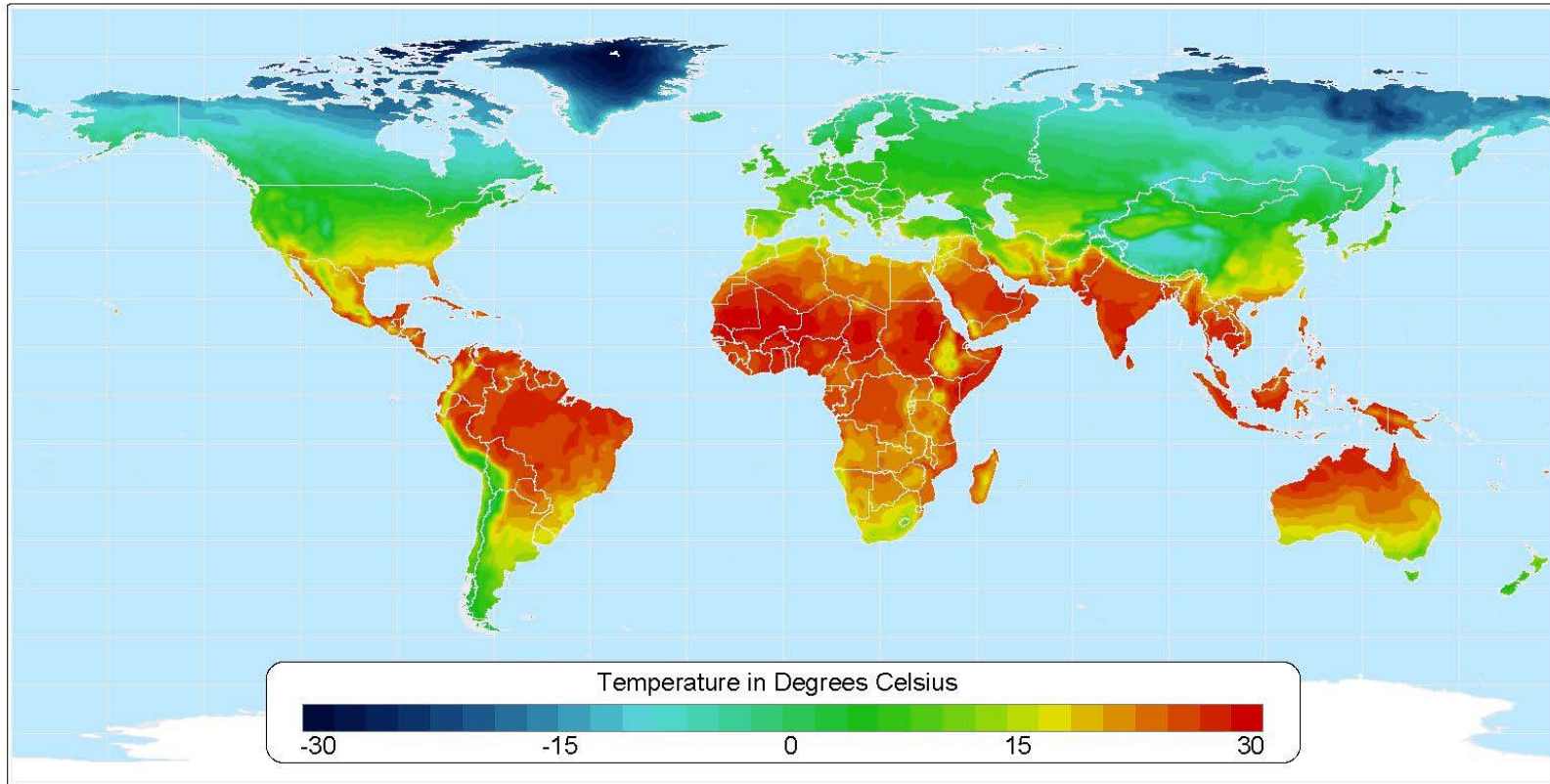


Data taken from: CRU 0.5 Degree Dataset (New et al)

**Atlas of the Biosphere**  
Center for Sustainability and the Global Environment  
University of Wisconsin - Madison



# Average Annual Temperature

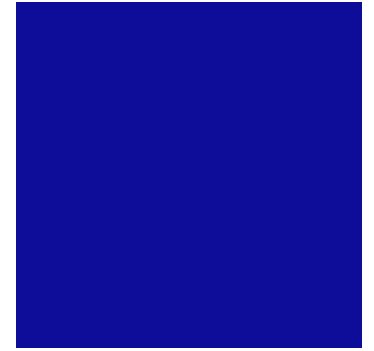


Data taken from: CRU 0.5 Degree Dataset (New, et al.)

**Atlas of the Biosphere**  
Center for Sustainability and the Global Environment  
University of Wisconsin - Madison

# Animation of atmospheric circulation

- Animation is of vertically integrated water vapor over the air column
- Animation from model run at NCAR (National Center for Atmospheric Research), Boulder, Colorado





# Coriolis effect

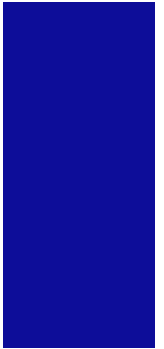
- Objects in a rotating frame such as the Earth experience the Coriolis effect, sometimes called the Coriolis force
- Deflection is **ALWAYS** to the right in the Northern Hemisphere and to the left in the Southern Hemisphere

# Coriolis effect

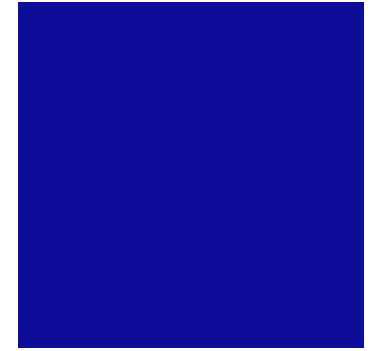
[http://en.wikipedia.org/wiki/Coriolis\\_effect](http://en.wikipedia.org/wiki/Coriolis_effect)

[http://www.youtube.com/watch?v=\\_36MiCUS1ro](http://www.youtube.com/watch?v=_36MiCUS1ro)

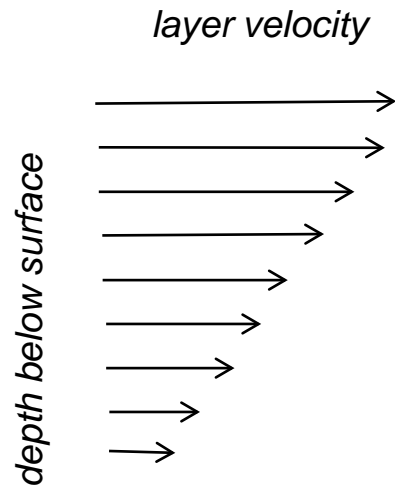
<http://kids.britannica.com/comptons/art-152826/The-path-of-a-rocket-launched-from-the-North-Pole?&articleTypeId=31>



# Action of wind on ocean



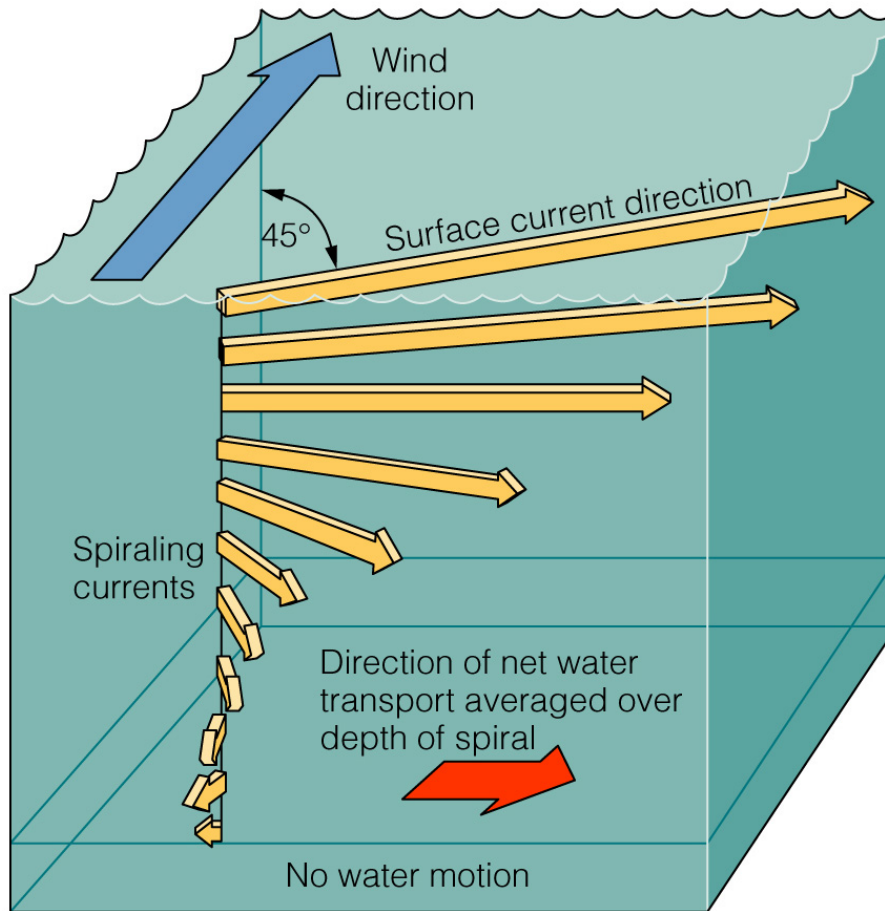
- Energy transferred from winds to ocean by friction, setting surface layer in motion
- Internal friction between successive layers transfers energy from surface to depth
- Wind-driven friction sets surface ocean in motion in series of thin layers



*Each successive layer driven  
by one above it, energy loss  
leads to progressive  
decrease in velocity*

- Each layer of water is subject to the Coriolis effect, and is deflected to the right (N. Hemisphere) or left (S. Hemisphere)

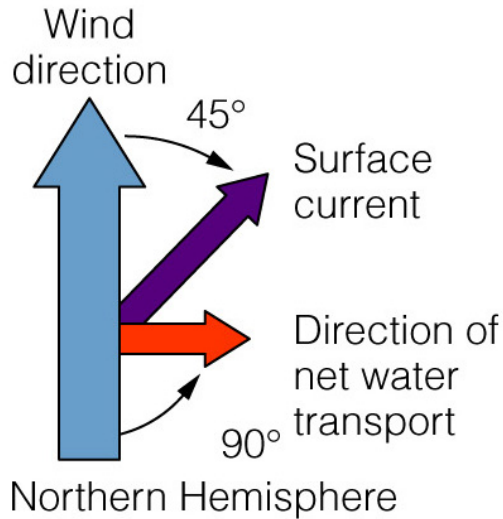
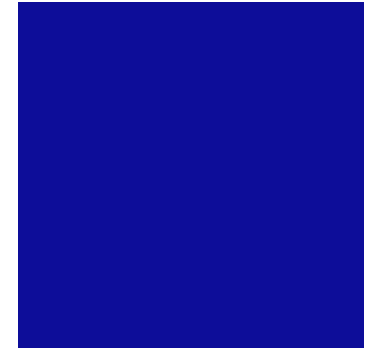
# Ekman spiral



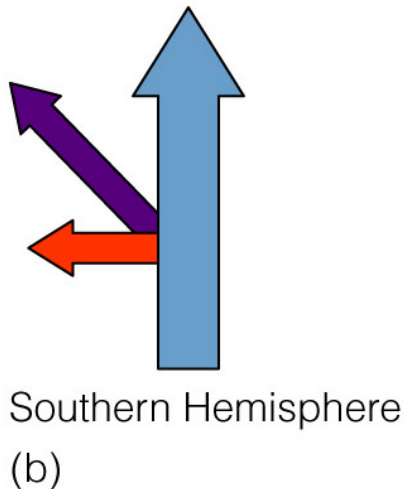
(a)

- Successive layers offset to one another due to Coriolis deflection
- Work inspired by Nansen who observed that icebergs move at angle to wind
- Formal theory published by Ekman in 1905

# Ekman transport



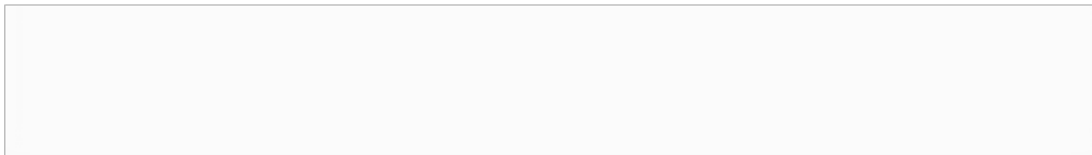
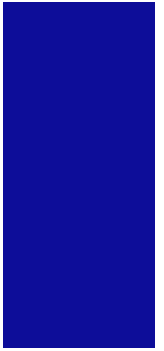
- Net movement of water in the spiral is  $90^\circ$  to the wind



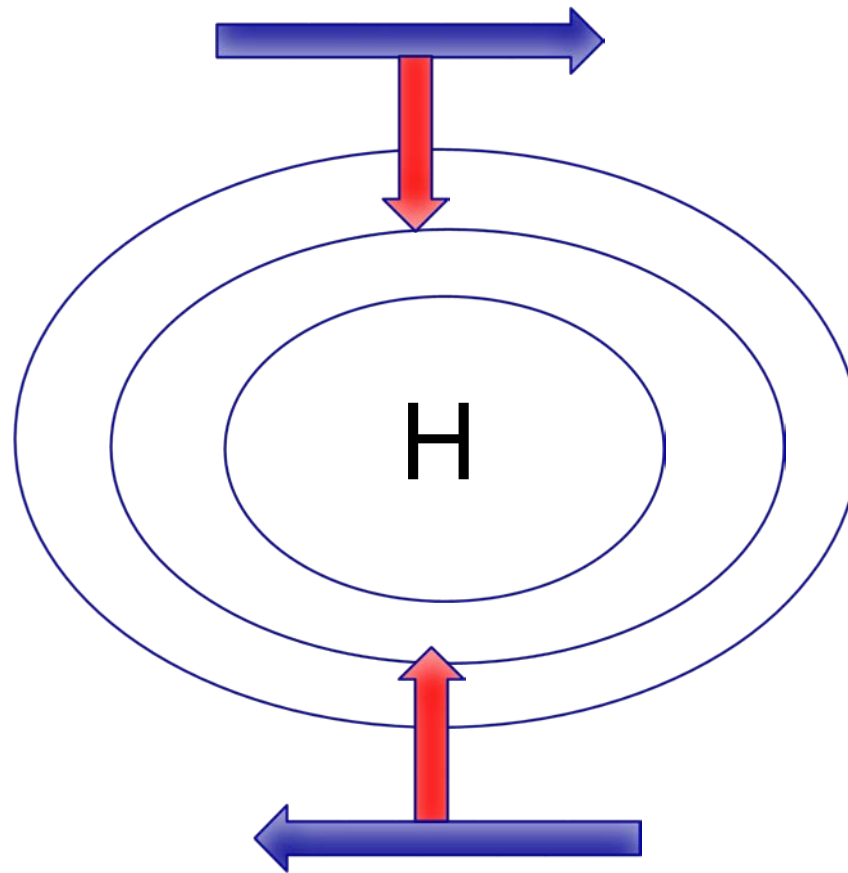
- Wind-driven movement of water at angle to wind direction is called Ekman transport

# Ekman vs Pressure-driven flow

- Ekman flow limited to upper ~100 m, whereas pressure gradient driven flow occurs in any place where pressure gradient is felt
- Winds can indirectly influence currents down to the ocean bottom



Example of winds, sea surface height, and induced pressure field (N. Hemisphere)

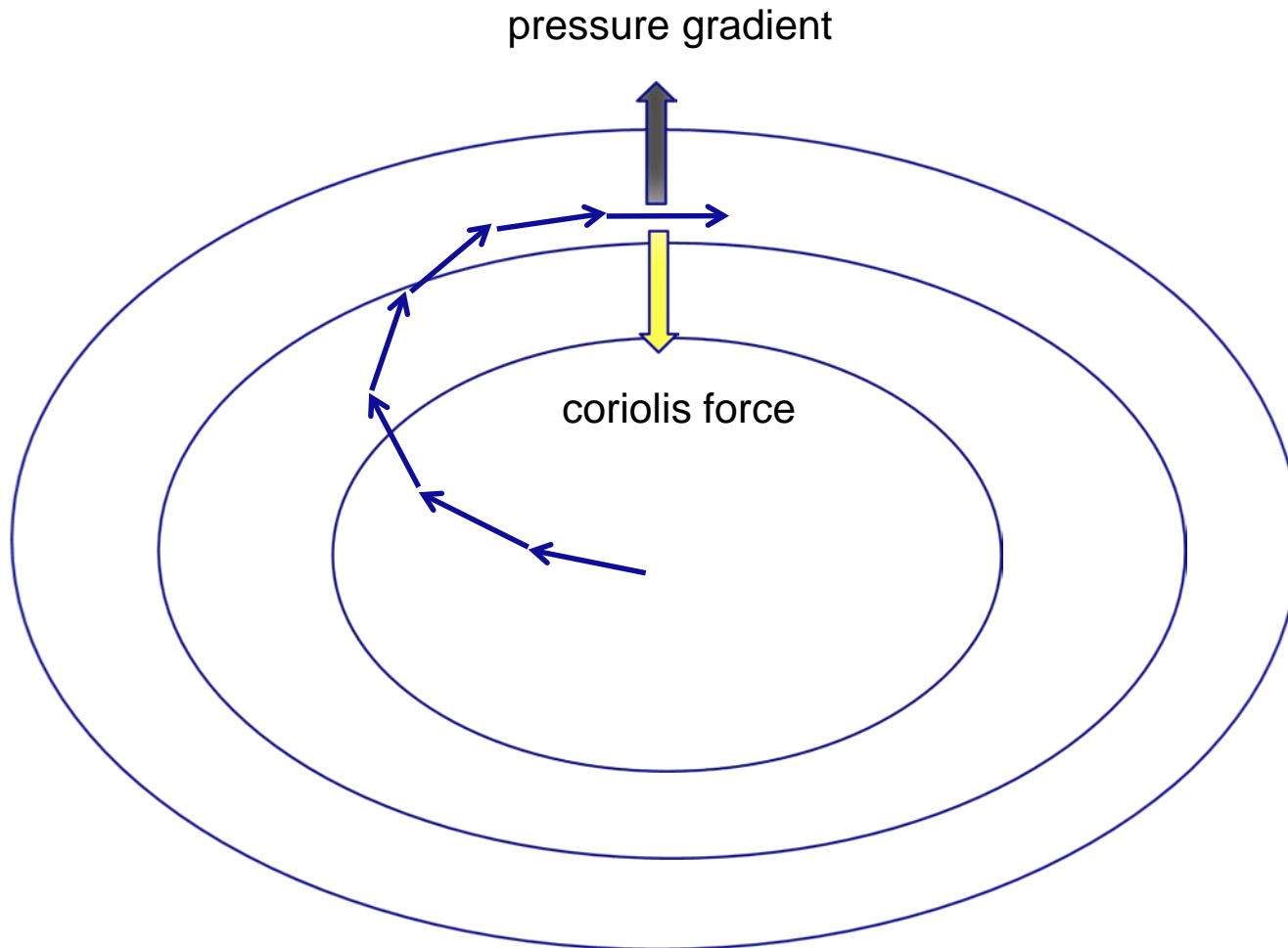


# Geostrophic flow

- Water will flow away from the peak of pile, away from the highest pressure
- As it flows, water is deflected to the right in Northern Hemisphere, to the left in Southern Hemisphere
- **When outward pressure gradient force is balanced by an equal and opposite Coriolis force, the flow is in geostrophic balance**
- Steeper pressure gradients produce stronger currents
- Greater pressure gradient force balanced by greater Coriolis force (deflection increases with increasing speed)

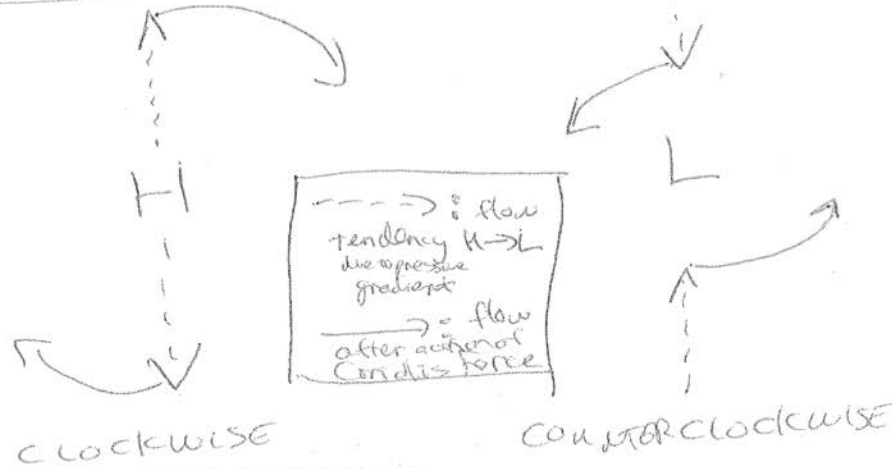


# Example geostrophic flow (high pressure, N. Hemisphere)

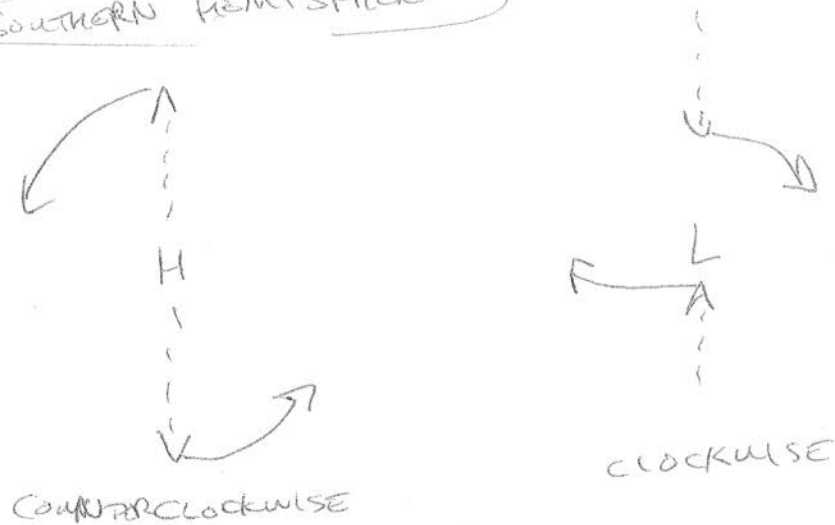


# ROTATION DIRECTION FOR HIGH & LOW PRESSURE SYSTEMS

## NORTHERN HEMISPHERE



## SOUTHERN HEMISPHERE



# Example application—rotation of hurricanes

*Let's watch a simulation of a hurricane, from the website of NOAA's Geophysical Fluid Dynamics Laboratory—is it rotating in the sense you expect for a low pressure system in the Northern Hemisphere?*

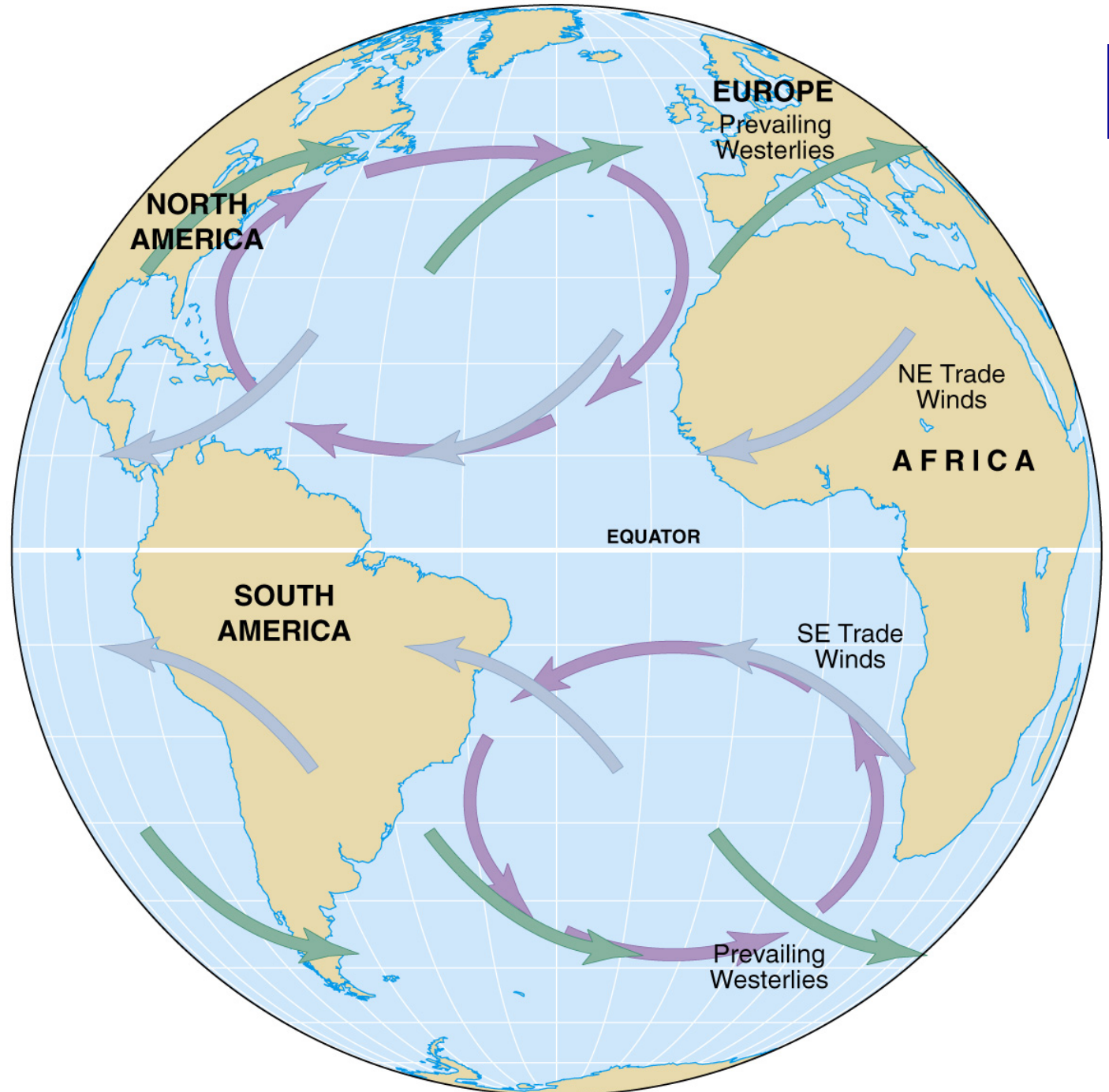
<http://www.gfdl.noaa.gov/flash-video?vid=katrina-rh-draft5&title=Hurricane%20Katrina%20Model%20Relative%20Humidity%20Loop>

# WIND DRIVEN CURRENTS

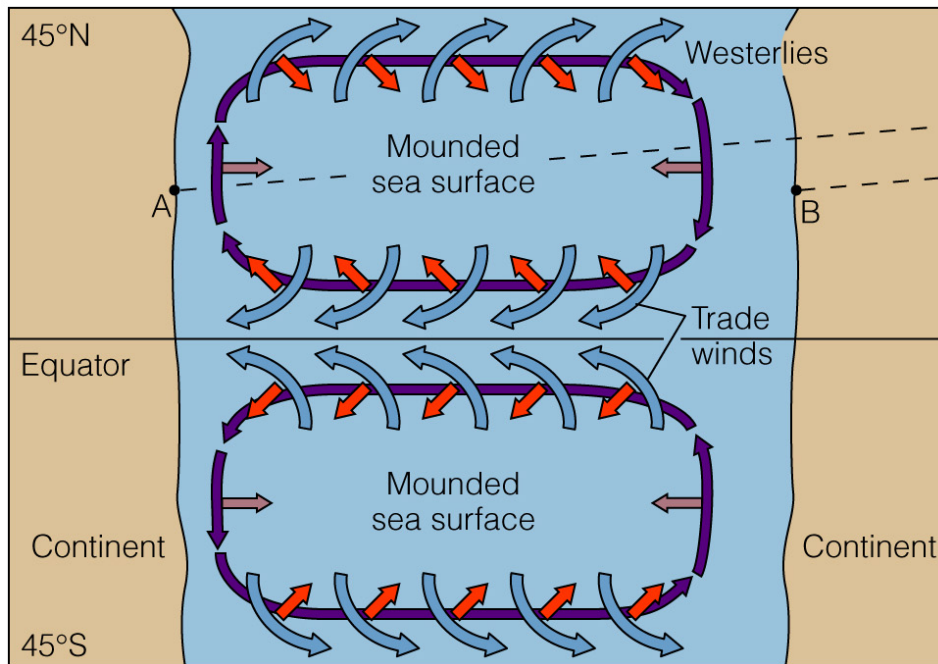
The westerlies (green) and trade winds (blue) drive water into the center of subtropical basins.

This pileup leads to a high pressure which then (because of the Coriolis force) leads to the gyre circulations shown in purple.

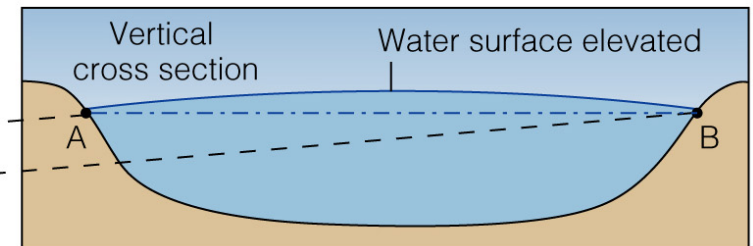
The presence of continents plays a key role in gyre locations.



# Geostrophic gyres



(a) Ekman transport Winds Gyre currents

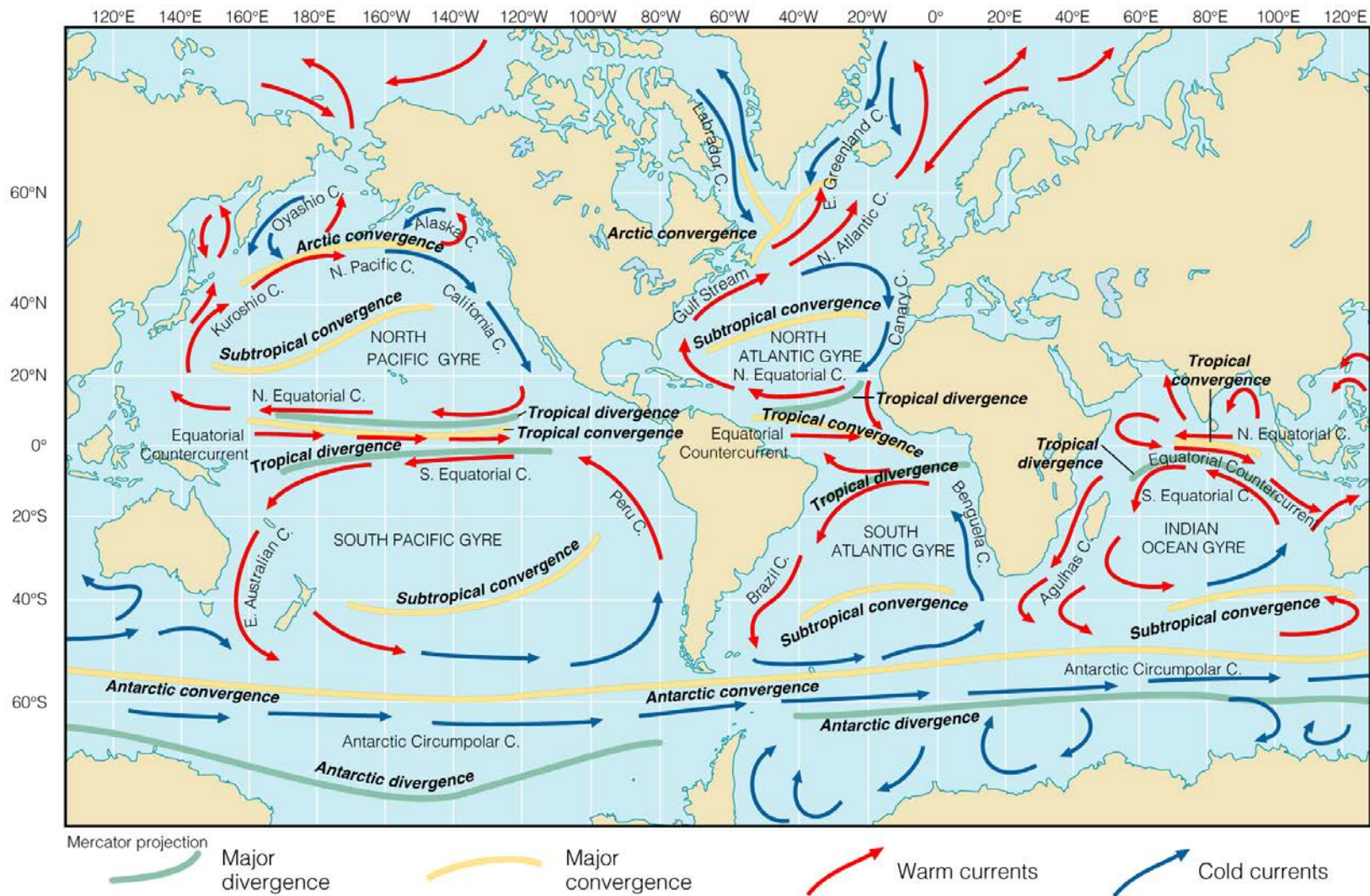


Sea surface slope is an extreme vertical exaggeration

- Water surface in center is only ~2 m high, over distance of 30 degrees longitude (~3000 km)
- Equivalent to ~ 1  $\mu\text{m}$  in height per meter horizontally



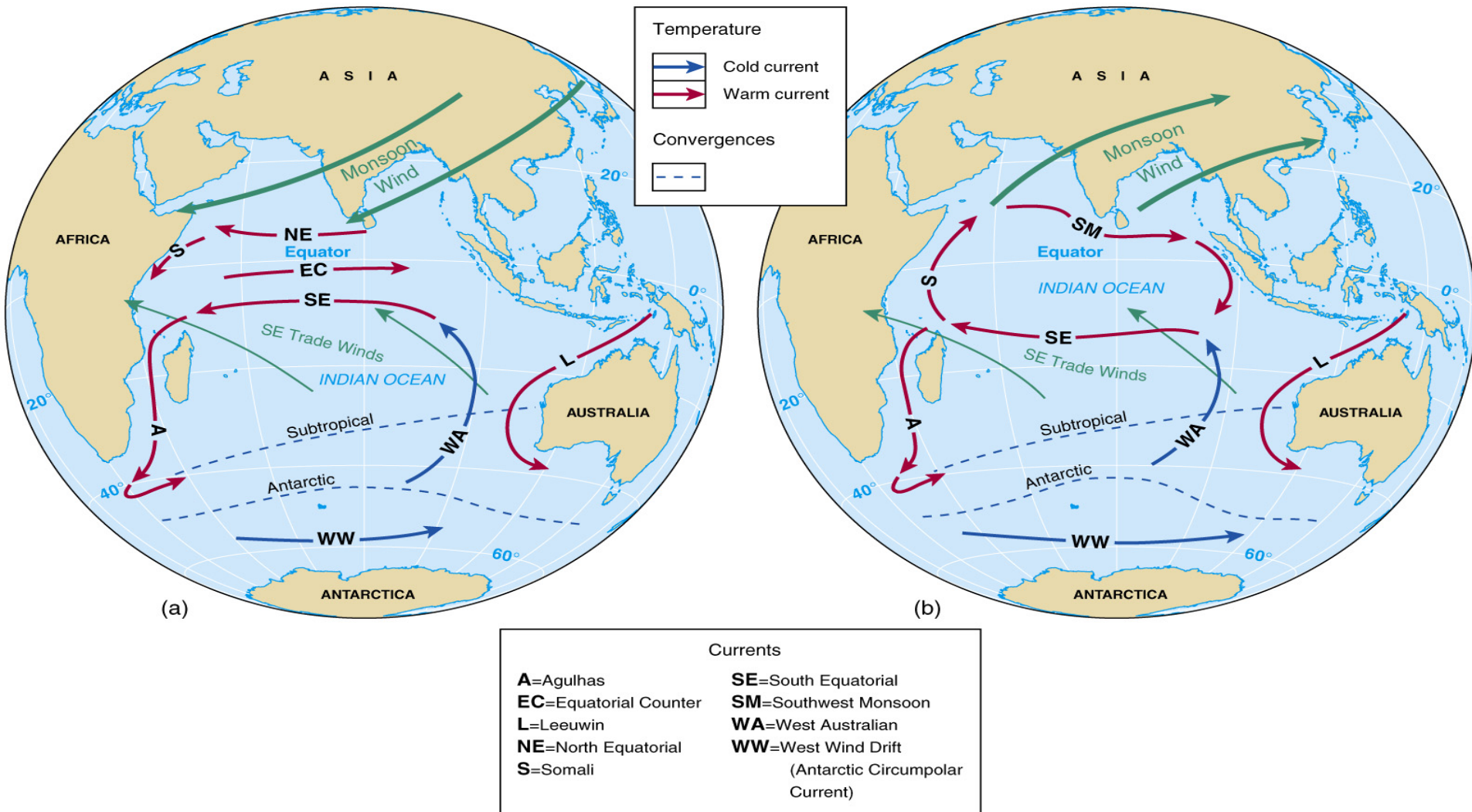
# Real world geostrophic gyres



North Indian Ocean is unique because of monsoons—

Somali Current reverses direction.

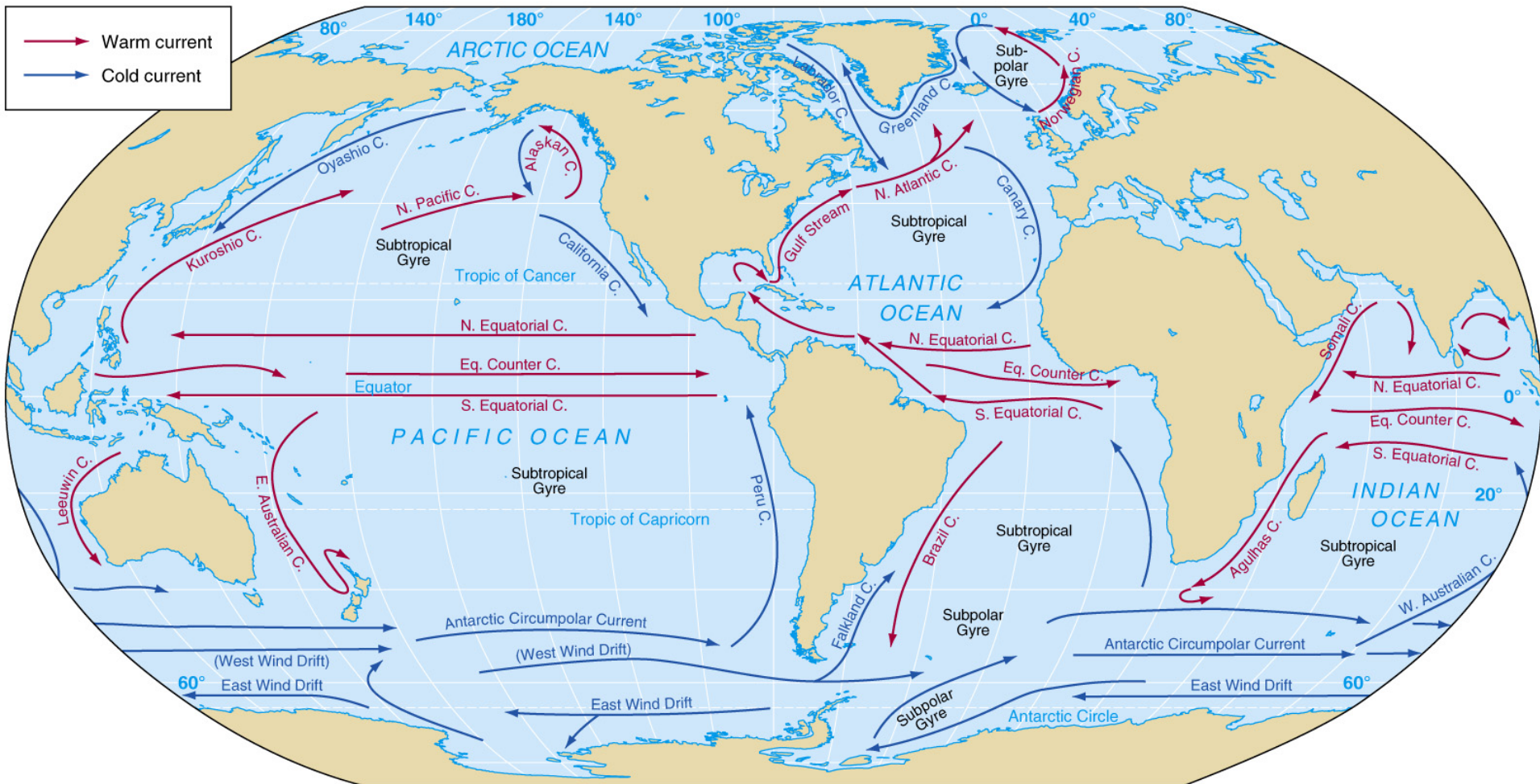
Northeast Monsoon (winter)      Southeast Monsoon (summer)





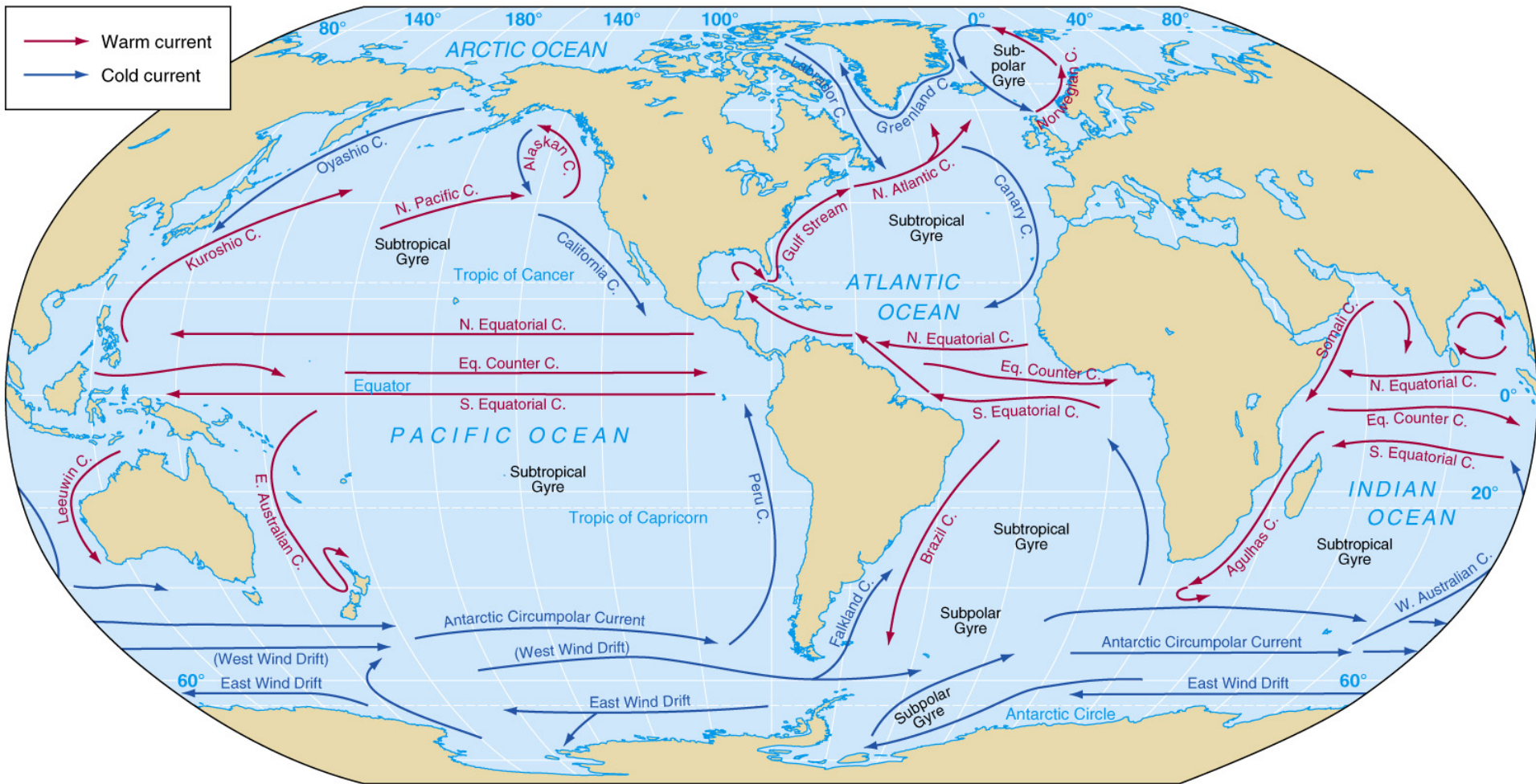


The Atlantic, Pacific, & Indian Oceans all have equatorial countercurrents. The North and South Equatorial Currents pile up water on the western sides of the basins, which then causes downhill (eastward) flow along the equator. Note the Coriolis force is very weak near the equator.





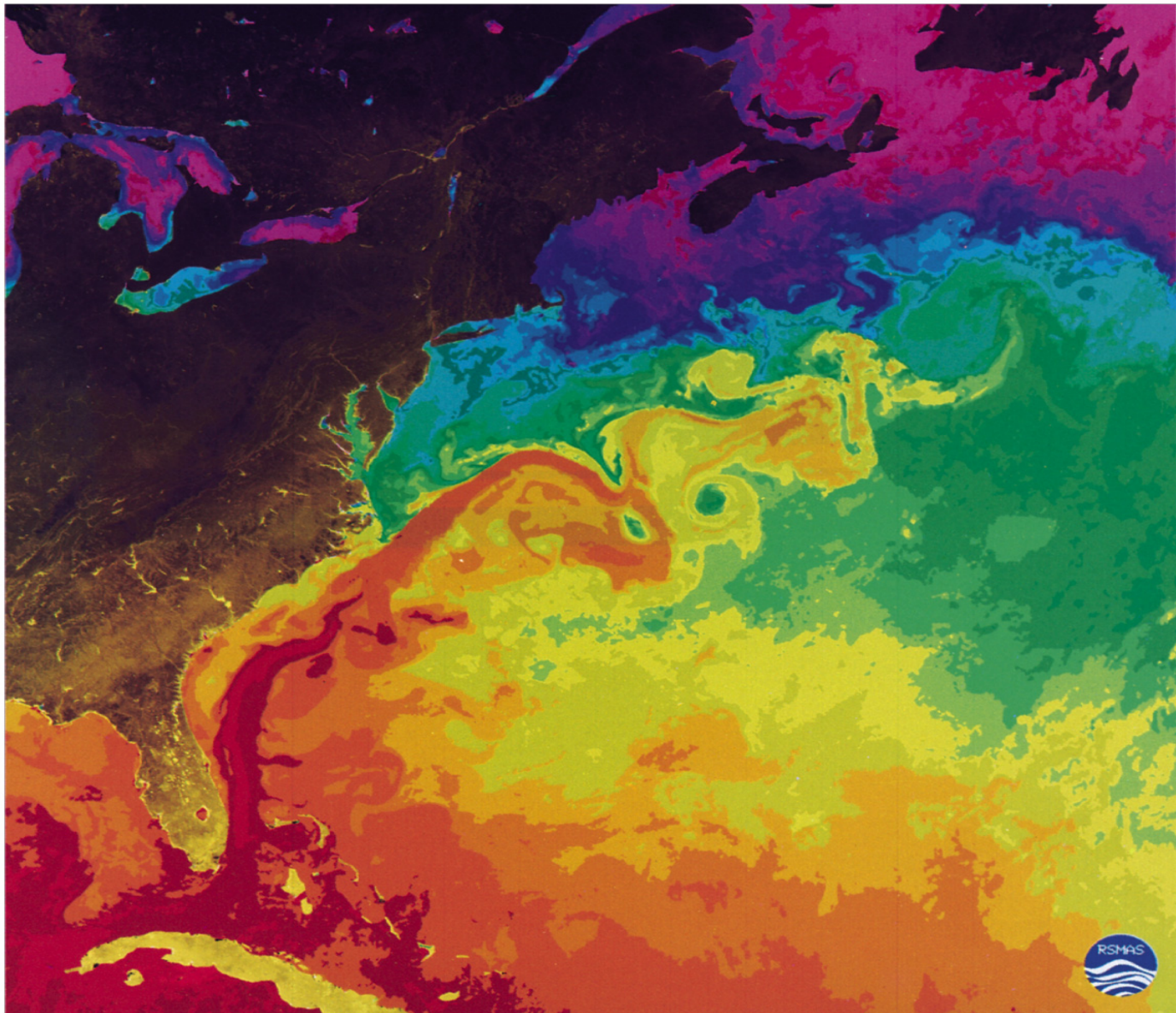
In the Southern Ocean no continents block the way. There the Antarctic Circumpolar Current (also called the West Wind Drift) follows the wind completely around the earth. This is the ocean's largest current in terms of water carried—130 million cubic meters per second (130 Sverdrups).



# What is western intensification?

- Top of hill of water in subtropical gyres displaced toward west
- Western boundary currents intensified
- Friction acting on intense western boundary currents balances vorticity input by wind
  - Faster (flows as large as 1 meter per second)
  - Narrower
  - Deeper
  - *Warm*

Note the narrowness of the Gulf Stream in this image of sea surface temperatures.

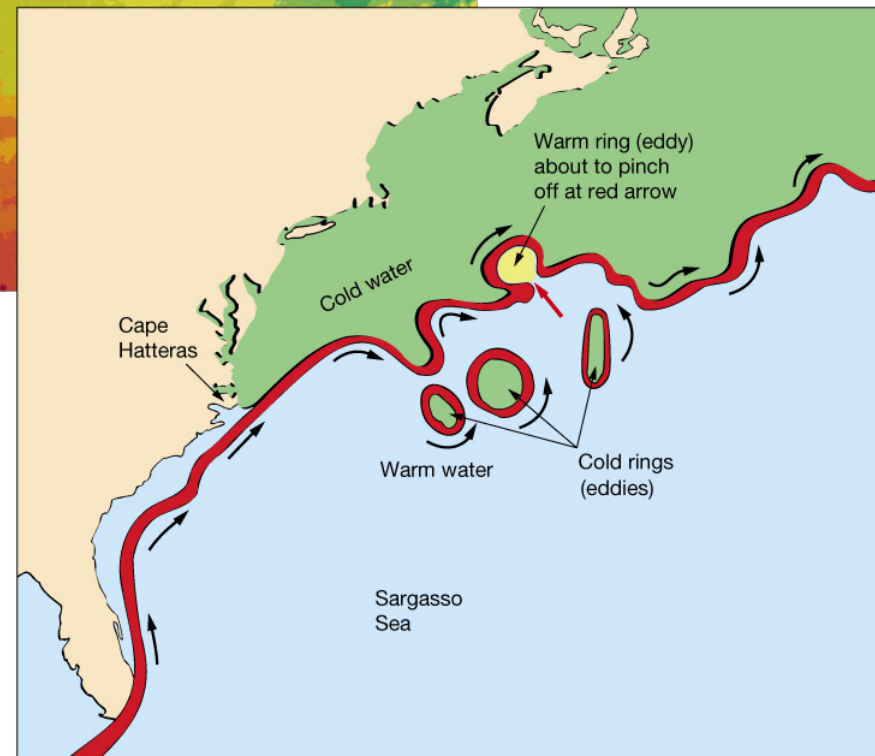
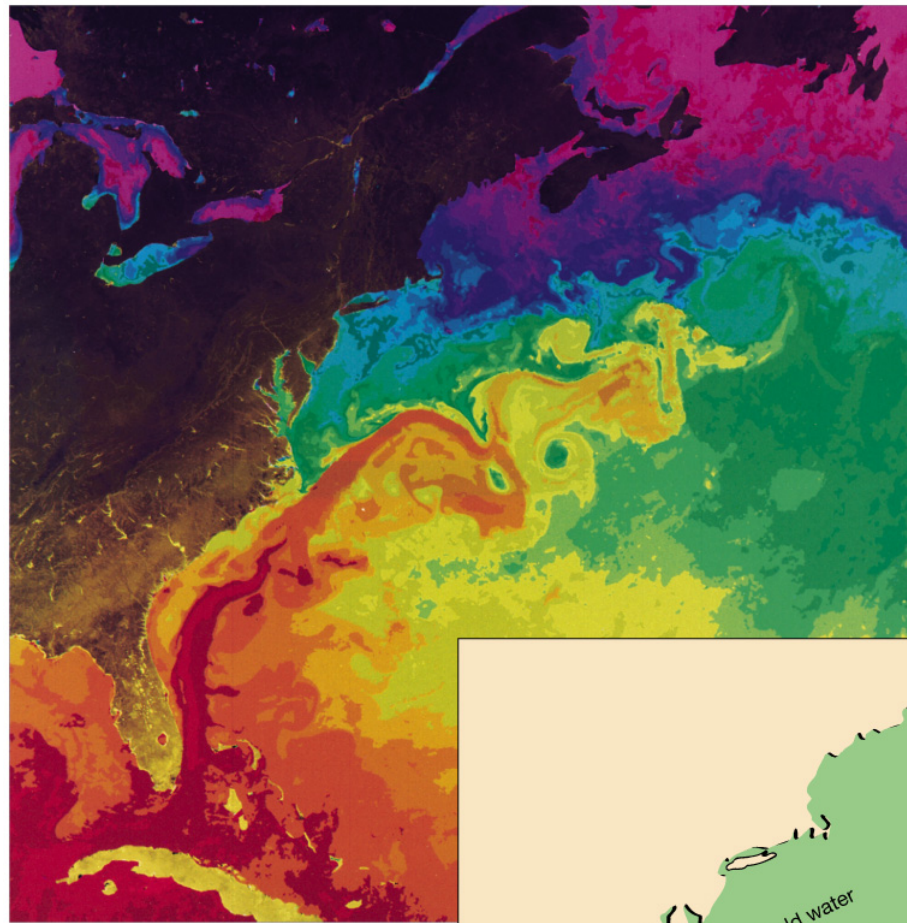




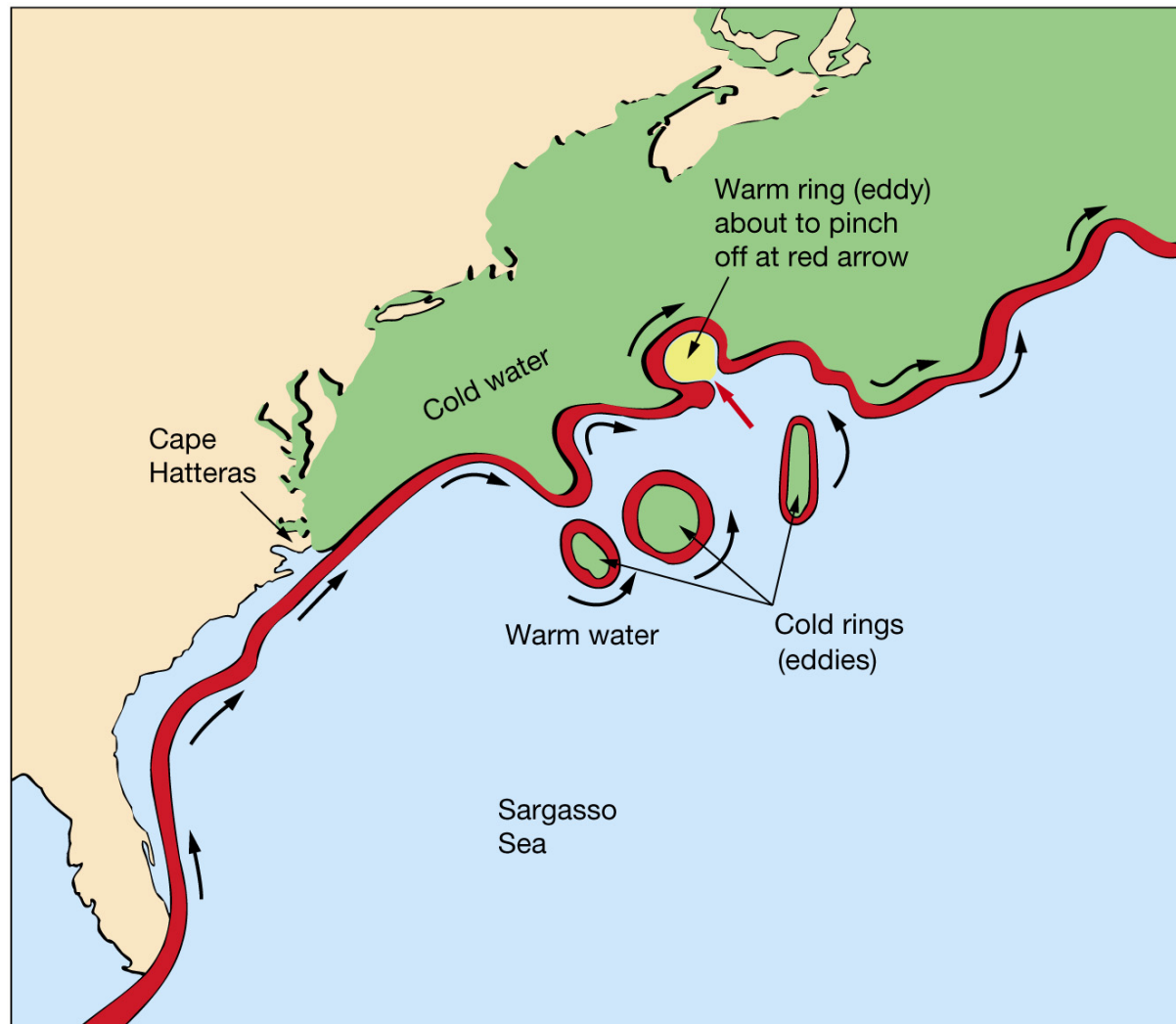
Warm and cold  
core rings

Seen in surface  
temperature as  
well as in sea  
surface height.

Gulf Stream is  
warm. Red is  
warm, blue cold.  
It sheds warm  
and cold core  
rings.



These rings typically have diameters of about 500 km, and can last for months. Marine life is much more abundant in cold-core rings than in warm-core rings.



# Key question—how are ocean currents measured?

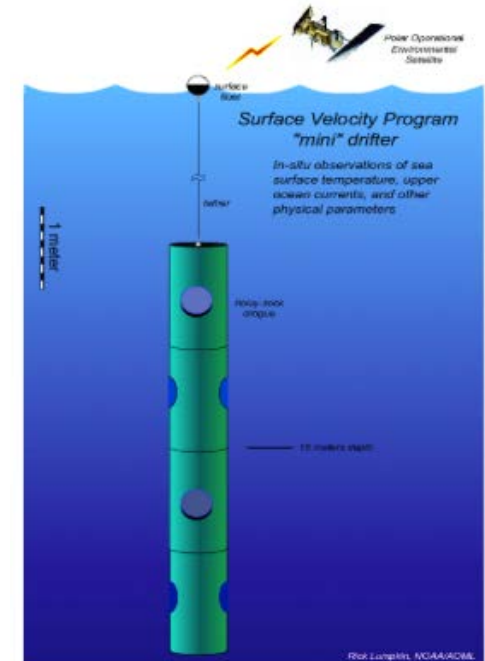
- Direct methods

- Floating device tracked through time (e.g. ARGO floats <http://www.argo.ucsd.edu> and drifters <http://www.aoml.noaa.gov/phod/dac/index.php>)

- Fixed current meter

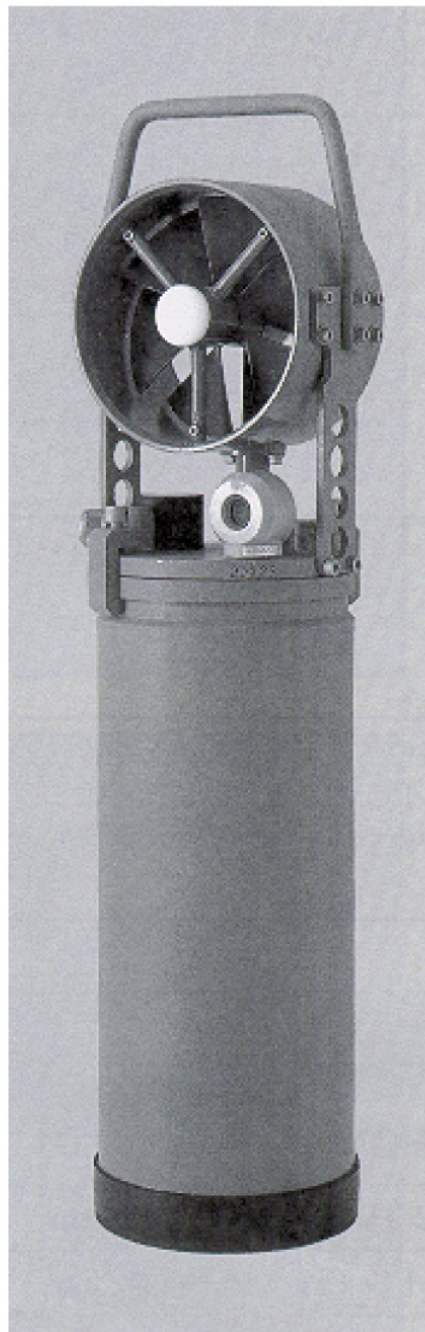
- Indirect methods

- Chemical tracers
- Pressure gradients computed from temperature and salinity
- Satellite altimeter data
- Doppler flow meter



# Subsurface current meter.

On top is a rotor which measures speed. Not shown is the vane which measures current direction. The case is hollow and is used to store the information. Its attached to a mooring.



(b)

Satellite altimeter data, current generation:

<http://sealevel.jpl.nasa.gov/technology>



Satellite altimeter data, next generation:

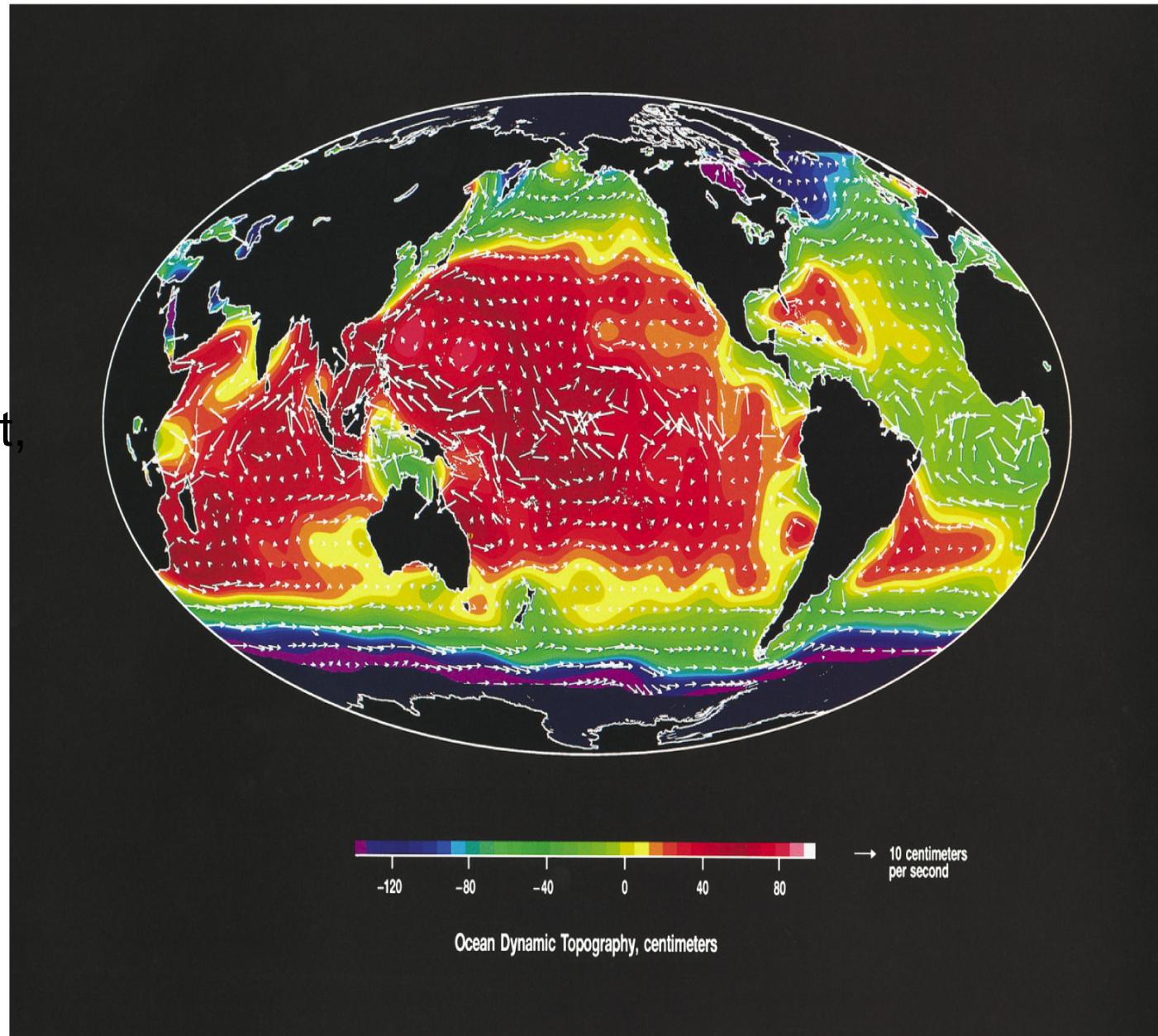
<http://swot.jpl.nasa.gov>



Satellite altimeter data.

Shown averaged over one year.

Red denotes high sea surface height, blue denotes low. From the tilt (slope) of the sea surface we infer surface currents (little arrows).



The high pressures arise from Ekman flow

# Animations of wind-driven circulation in ocean

- From the Parallel Ocean Program (POP) model run by the Department of Energy, typically on about 4000 processors
- From current generation satellite altimeter data