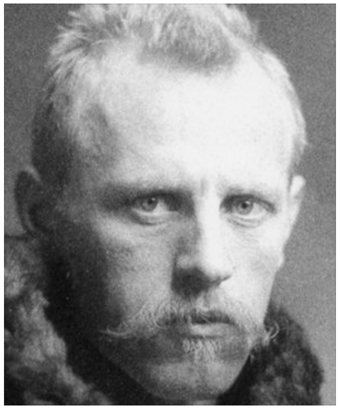
Week 6-7: Wind-driven ocean circulation

Tally’s book, chapter 7

Recap so far…

- Our goal (since week 3) has been to **understand large-scale ocean circulation and its underlying physics, and to learn how to quantify them using available observations.**

1902




Fridtjof Nansen (1861-1930)

Vagn Walfrid Ekman (1874-1954)
Univeristy of Lund

The Fram Expedition (Frist, 1893-1896)

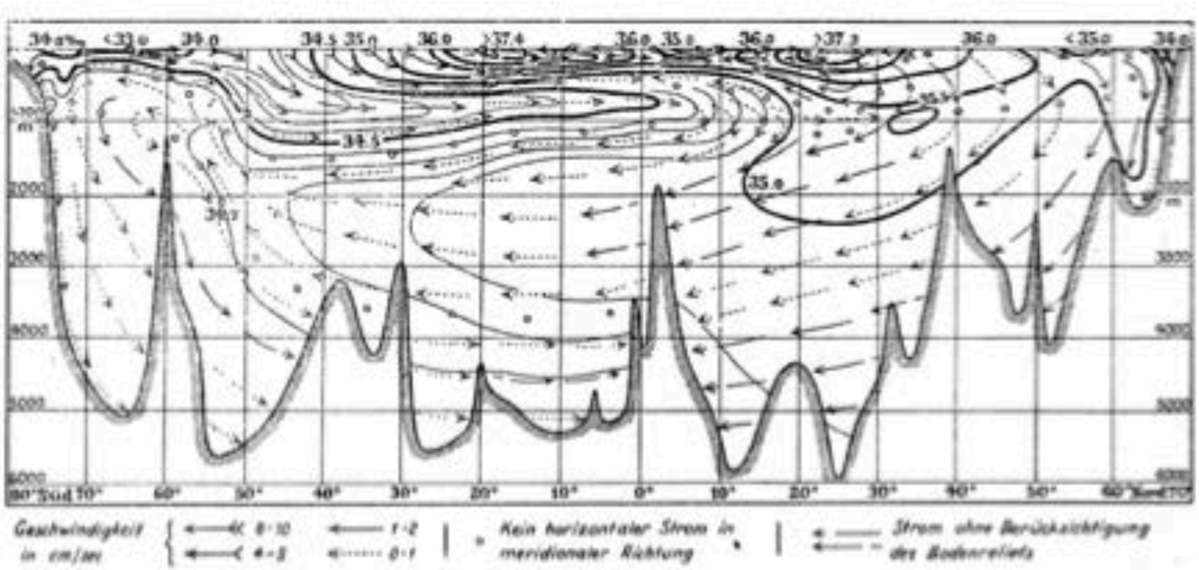
Ekman flow

- Ekman circulation
  - Direct effect of wind on the surface current.
  - Balance of forces: Coriolis effect VS. wind stress
  - Ekman spiral (downward clockwise spiral in NH)
  - Ekman transport (90° to the right of wind direction in NH)
  - Ekman layer : approx. top 20-30m of the ocean

1925

Meteor expedition (1925-27)

- Testing the thermal wind balance
- Alfred Merz



Merz, 1925

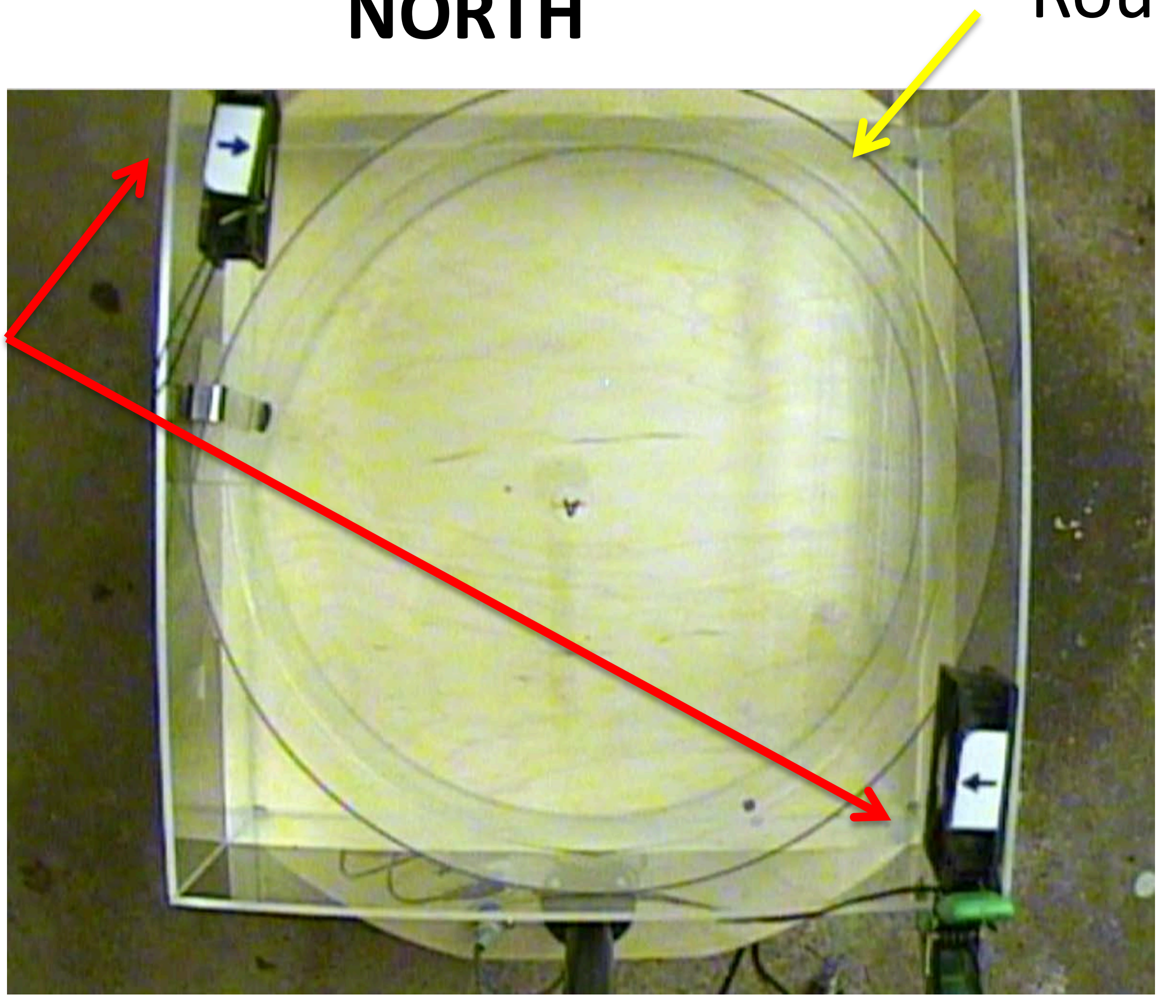
Geostrophic flow

- Balance between Coriolis force and Pressure Gradient Force
- Use the “balance of forces” to determine ocean current speed and direction
  - Assume: frictionless and small Rossby number (slow speed, large-scale)
  - Cyclonic circulation (CCW in NH) around the low pressure
  - Anticyclonic circulation (CW in NH) around the high pressure

Thermal wind

- Calculating geostrophic circulation using T-S measurements
  - YOU WANT: Horizontal current speed and direction
  - YOU NEED: Horizontal pressure gradient
  - AVAILABLE MEASUREMENT: T and S.
  - Use thermal wind relation: practically, we calculate dynamic topography → Steric sea level
    - Dynamic height is higher for the warmer water column
      → Anti-cyclonic flow in subtropics
    - Dynamic height is lower for the colder water column
      → Cyclonic flow in subpolar region
  - Level of no motion
    - We assume that the deep ocean is motionless (u=v=0 in the deep ocean, say z=2,000m) so we can apply thermal wind.
    - The velocity field you get from the dynamic topography is relative to the deep (e.g. 2000m) reference level.

Tank experiment for Ekman flow



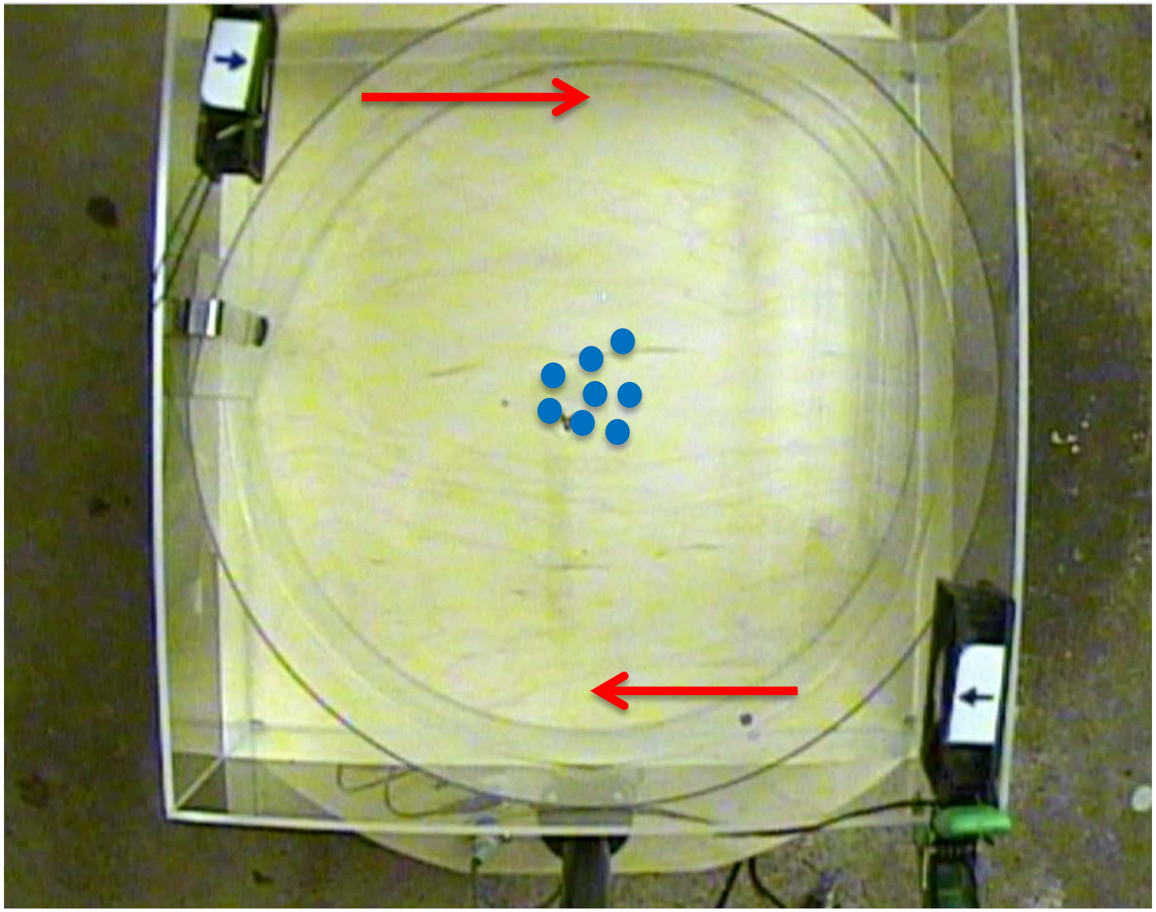
The view of the camera on top of the tank

The “anti-cyclonic” wind stress caused the surface Ekman flow to **converge** in the center

NORTH

Computer fan

WEST

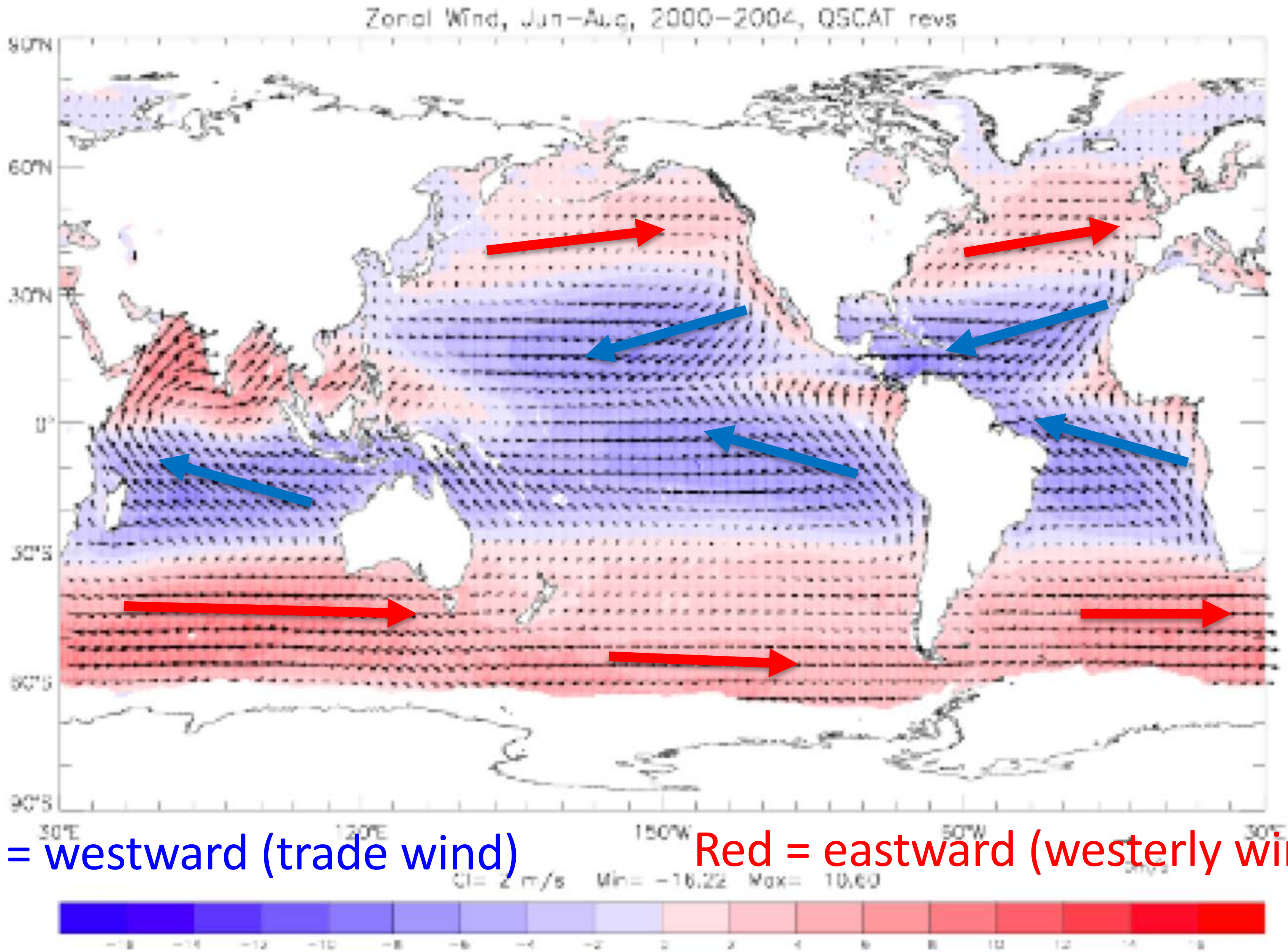


EAST

Wind-driven vertical motion

- Cyclonic wind stress ➔ Ekman upwelling
- Anti-cyclonic wind stress ➔ Ekman downwelling (Ekman pumping)

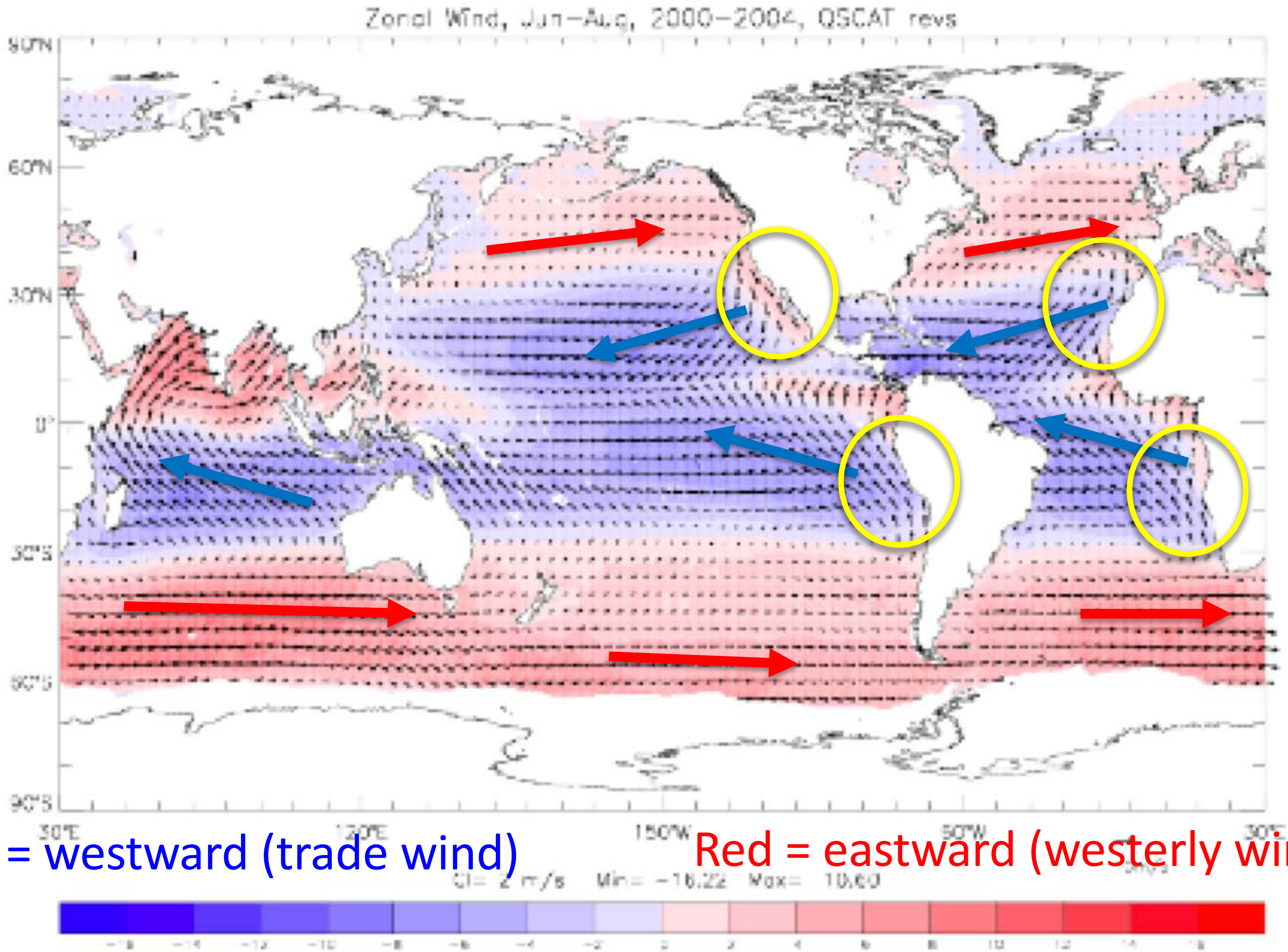
Observed wind stress



Blue = westward (trade wind)

Red = eastward (westerly wind)

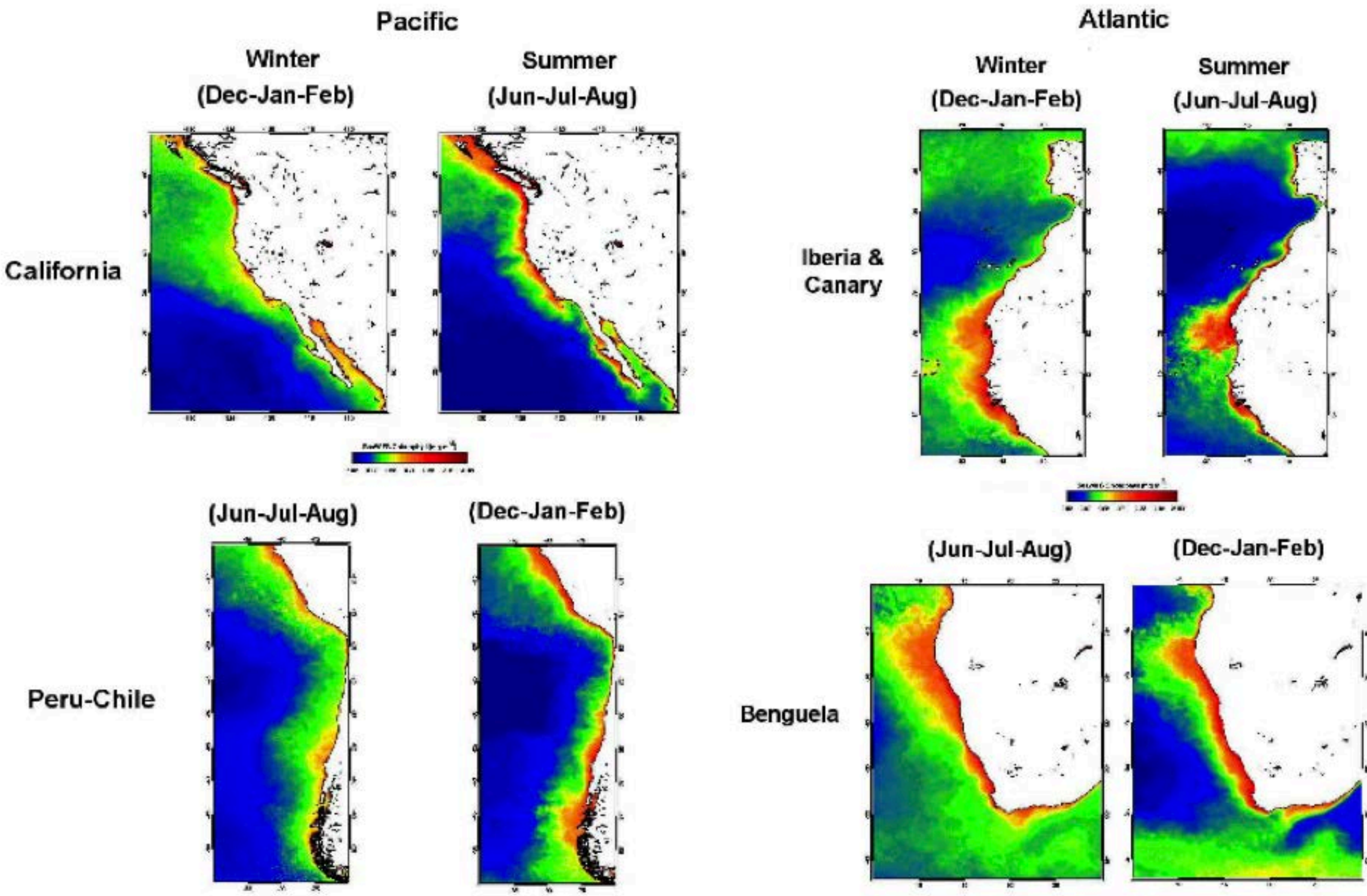
Wind along the eastern boundary



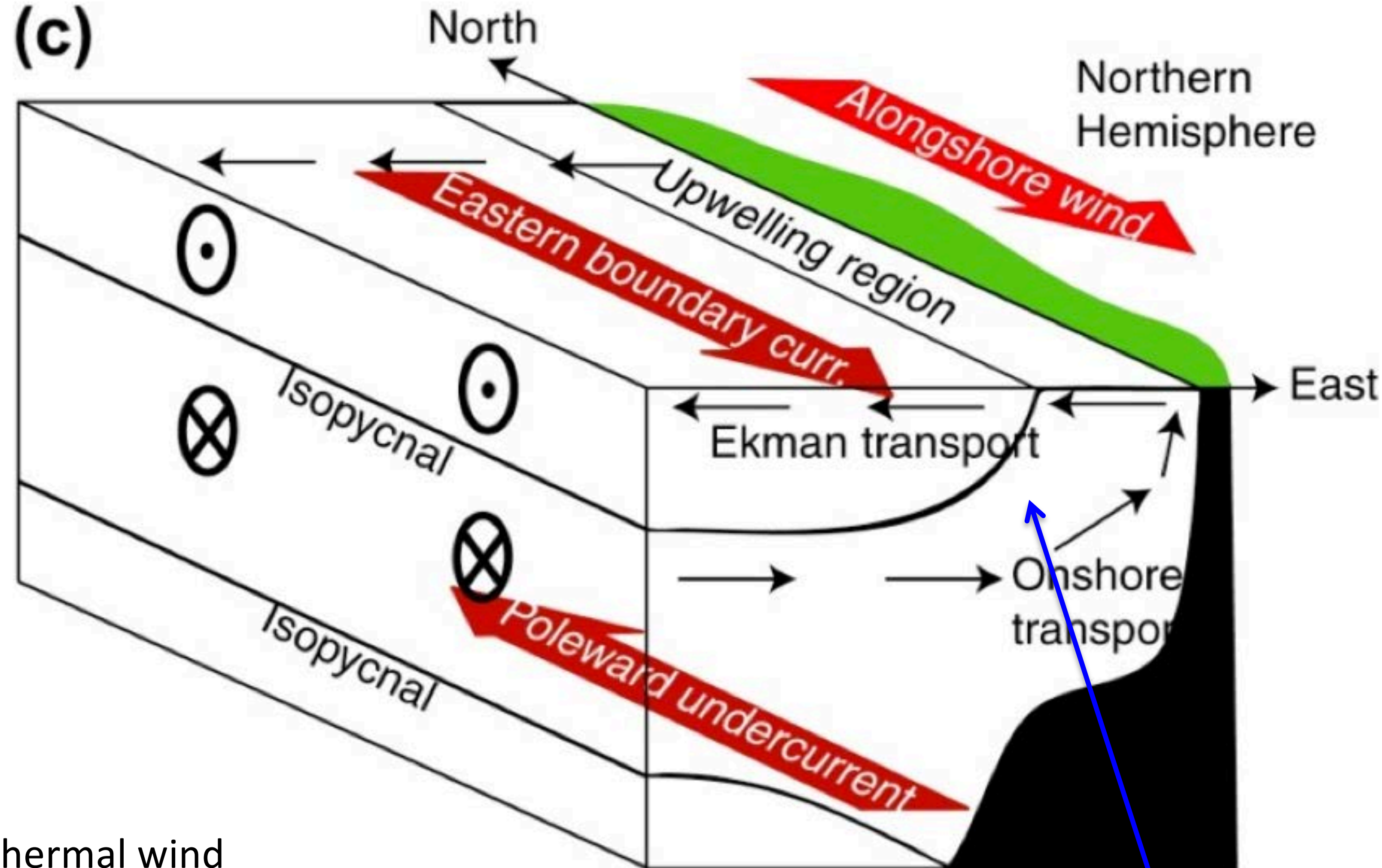
Blue = westward (trade wind)

Red = eastward (westerly wind)

Eastern boundary current system



Coastal Ekman upwelling

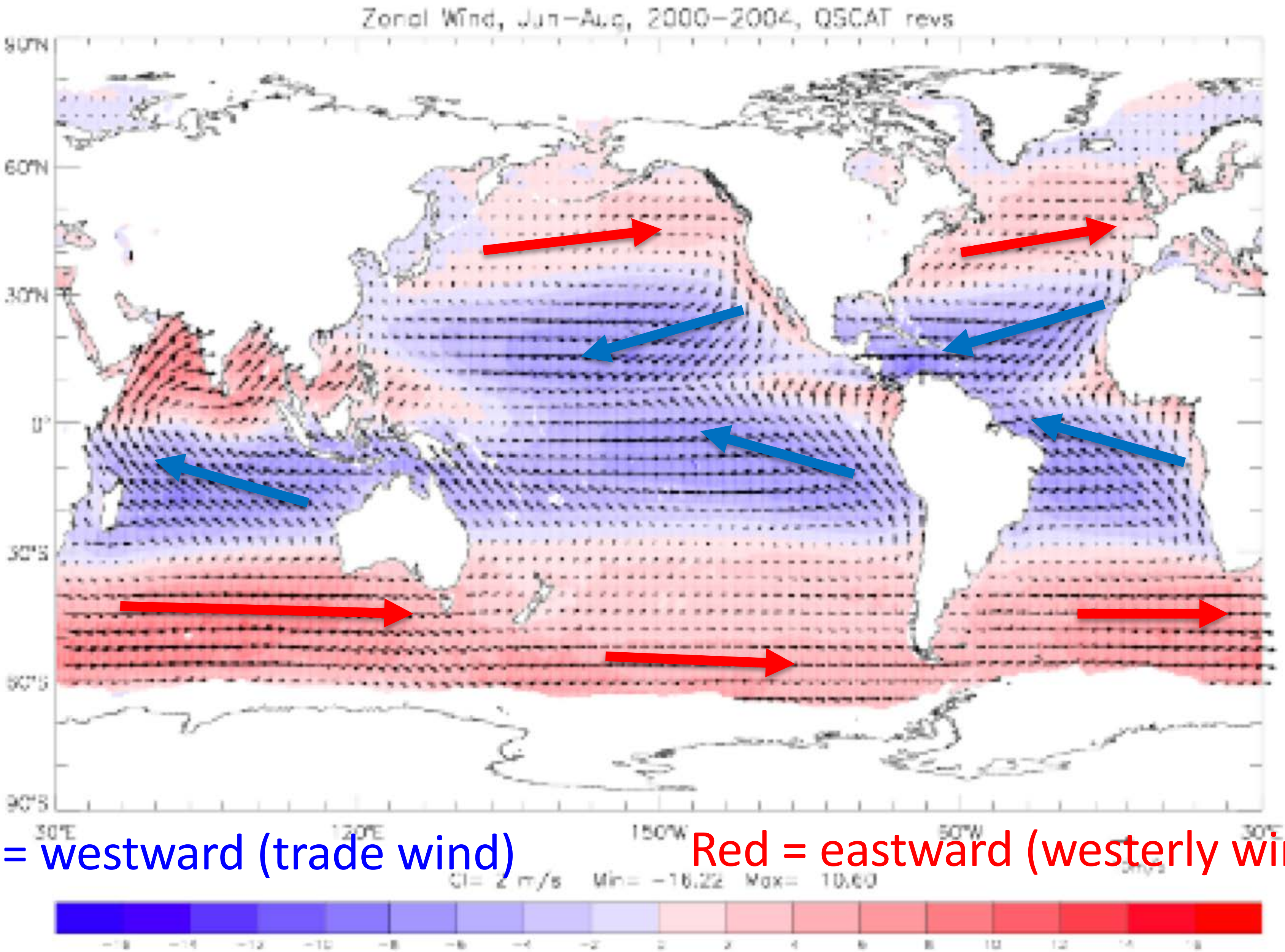


Thermal wind

$$\frac{\partial v_g}{\partial z} = -\frac{g}{f\rho}\frac{\partial \rho}{\partial x}$$

Density gradient $\frac{\partial \rho}{\partial x} > 0$

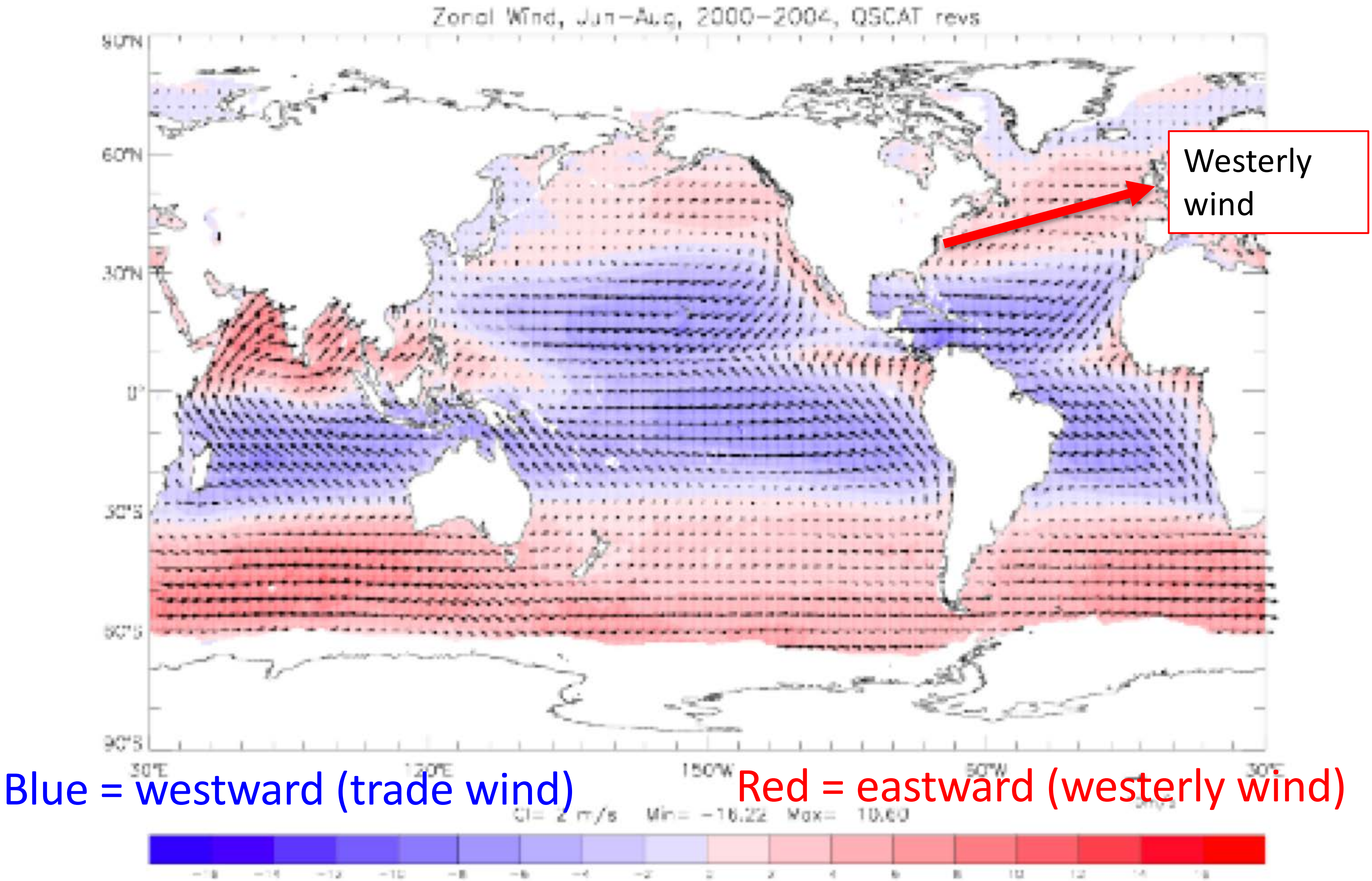
Observed wind stress



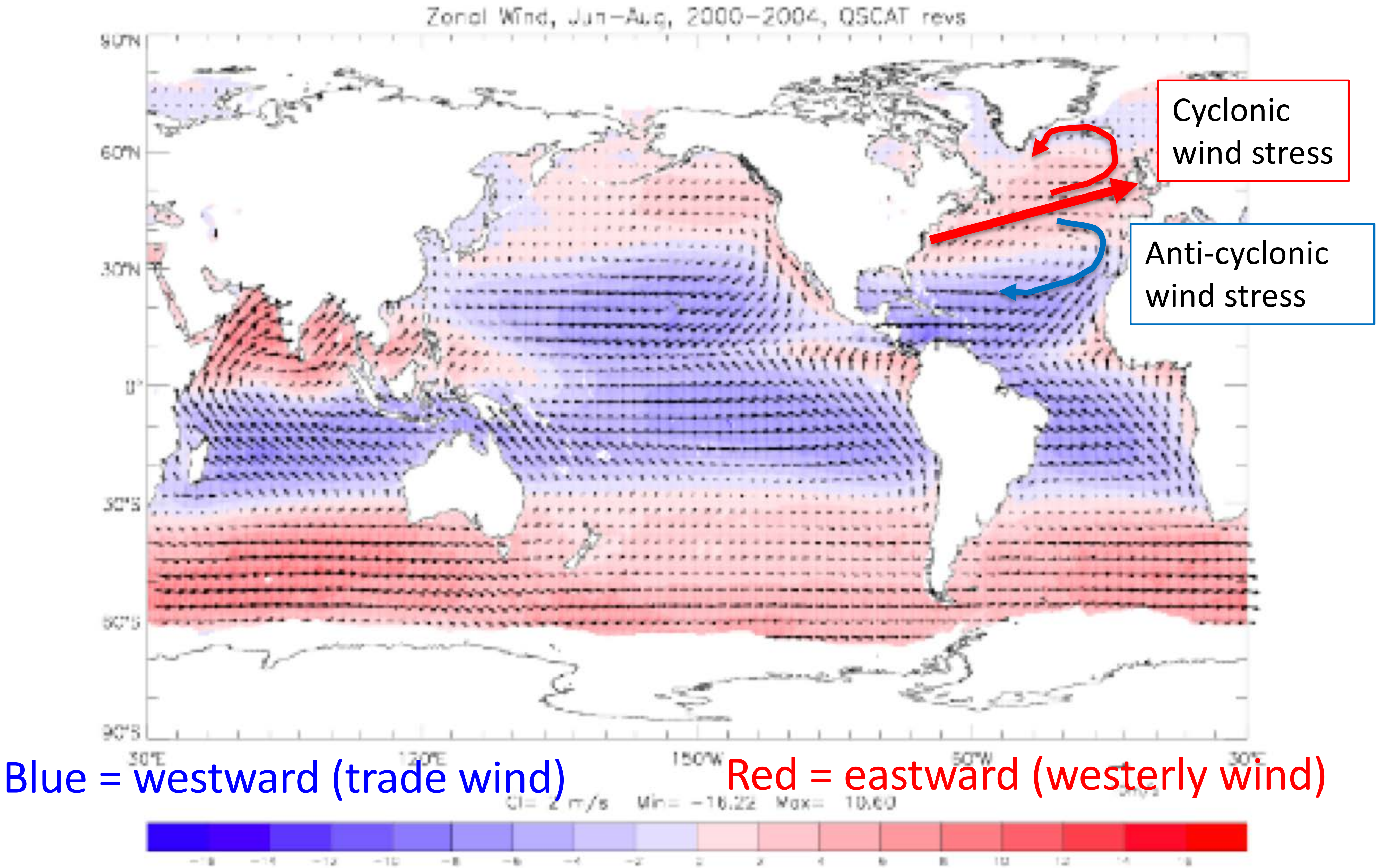
Blue = westward (trade wind)

Red = eastward (westerly wind)

Observed surface wind stress

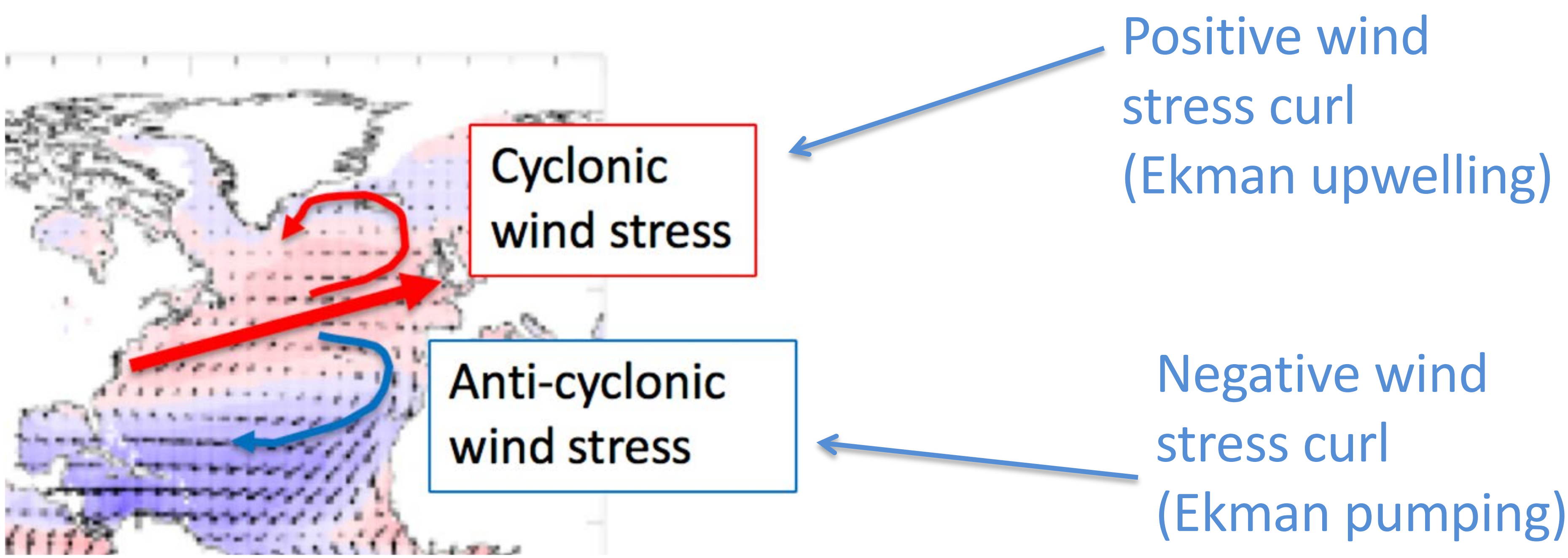


Observed surface wind stress

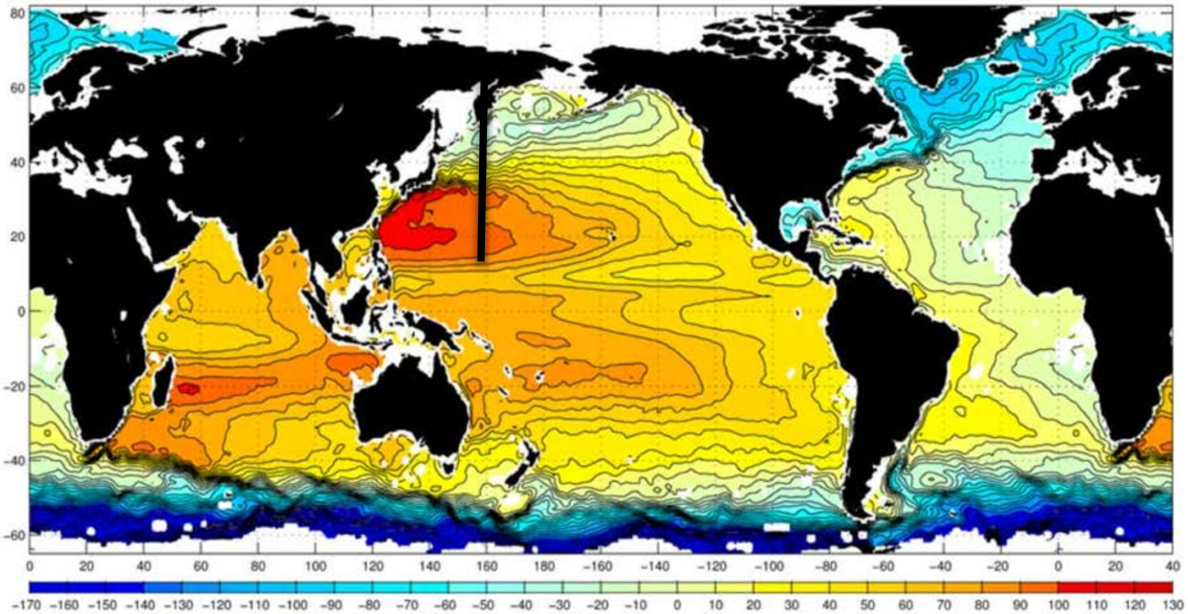


Wind stress curl

- Wind stress curl measures the spin of the wind stress
  - Use your right hand
  - Counter clockwise = thumb up = positive curl
  - Clockwise = thumb down = negative curl
  - Vertical velocity depends on the wind stress curl

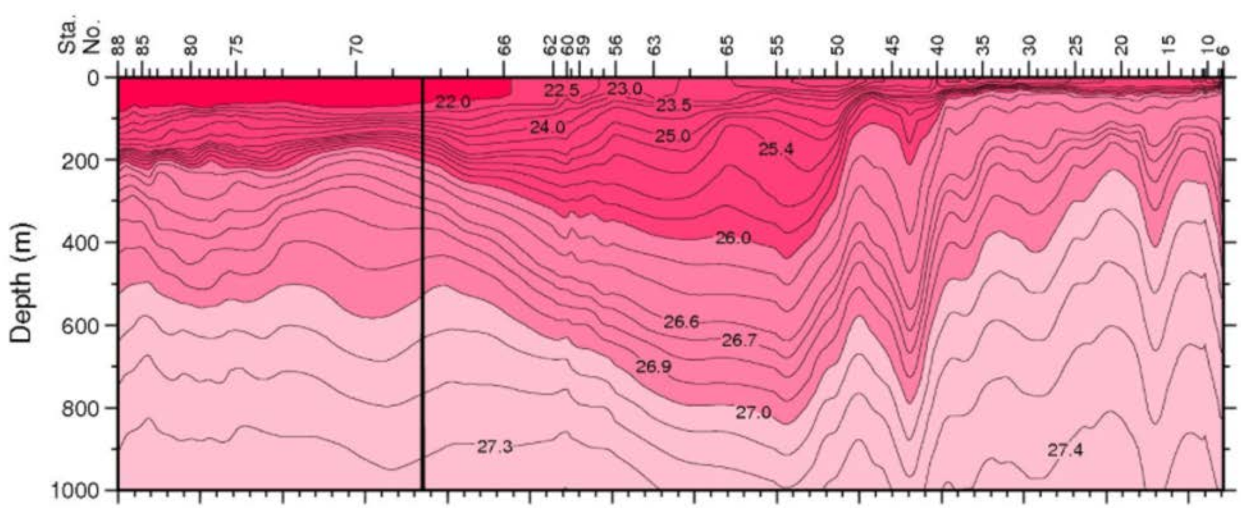


Effect of Ekman upwelling/downwelling on the ocean density structure



The high SSH of the western subtropics is reflected in the deep thermocline (i.e. high steric height).

Figure 1. 1992–2002 mean absolute sea level η_0 obtained as described in this paper. Contour interval is 10 cm. Sea level is computed from the values of $\nabla\langle\eta\rangle$ estimated according to (2) on 1° spatial grid with the condition of zero global mean.



Wind-driven gyres

- Ekman flow is only active in top 20-30m of the ocean.
- Geostrophic circulation extends much deeper depths, over several hundreds of meters.
- → Ekman upwelling/downwelling can drive the horizontal geostrophic circulation.

1947: Sverdrup balance

- Consider 3-way balance between Coriolis, pressure gradient and frictional forces

$$-fv = -\frac{1}{\rho_0}\frac{\partial p}{\partial x} + \frac{1}{\rho_0}\frac{\partial \tau_x}{\partial z}$$

$$fu = -\frac{1}{\rho_0}\frac{\partial p}{\partial y} + \frac{1}{\rho_0}\frac{\partial \tau_y}{\partial z}$$

Sverdrup balance

- Consider 3-way balance between Coriolis, pressure gradient and frictional forces

$$-\frac{\partial}{\partial y}: \quad -fv = -\frac{1}{\rho_0}\frac{\partial p}{\partial x} + \frac{1}{\rho_0}\frac{\partial \tau_x}{\partial z}$$

$$+\frac{\partial}{\partial x}: \quad fu = -\frac{1}{\rho_0}\frac{\partial p}{\partial y} + \frac{1}{\rho_0}\frac{\partial \tau_y}{\partial z}$$

$$f\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) + \beta v = \frac{1}{\rho_0}\frac{\partial}{\partial z}\left(\frac{\partial \tau_y}{\partial x} - \frac{\partial \tau_x}{\partial y}\right)$$

Theory for the ocean gyres

- Integrating from top to bottom of the ocean,

$$\beta V_S = \frac{1}{\rho_0}\left(\frac{\partial \tau_y}{\partial x} - \frac{\partial \tau_x}{\partial y}\right)$$

Northward motion leads to increased planetary spin

Curl of the wind stress
The input of spin by the wind

Positive (negative) wind stress curl → northward (southward) motion for water column

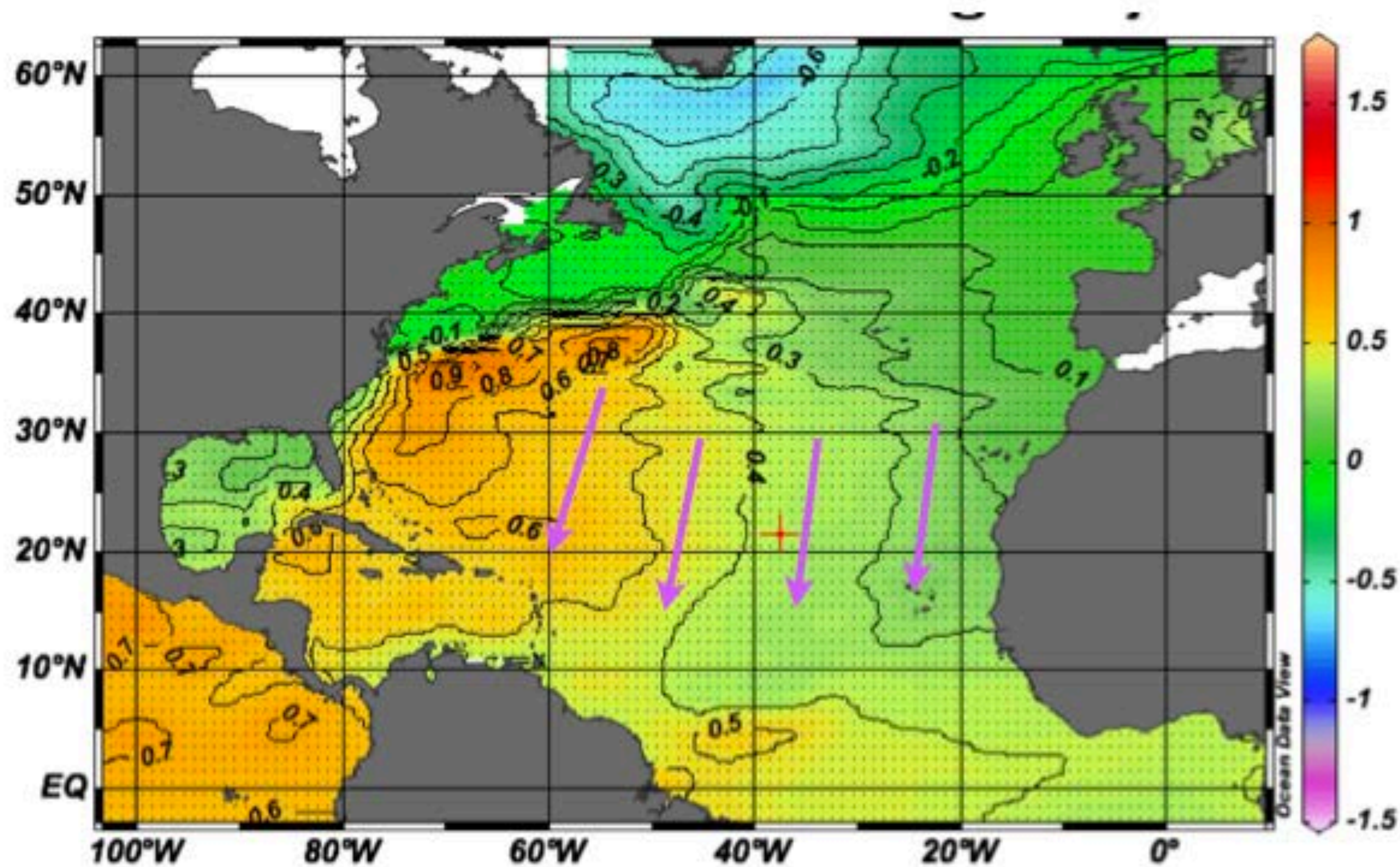
The beta (β) effect

- Coriolis parameter changes with latitude. $df/dy = \beta$.
- The β effect has profound influence on geophysical fluid dynamics.
- One of the examples is the ocean gyres where the spin of wind stress drives horizontal (north-south) motion.

Vorticity (spin) balance

- Wind stress can introduce spin into the ocean.
- Fluid can spin up/down (relative vorticity)
- Coriolis parameter (f) measures the planetary spin (planetary vorticity)
- f increases poleward. Thus, poleward motion increases its planetary spin.

SSH fields: southward interior flow



Issues with Sverdrup circulation

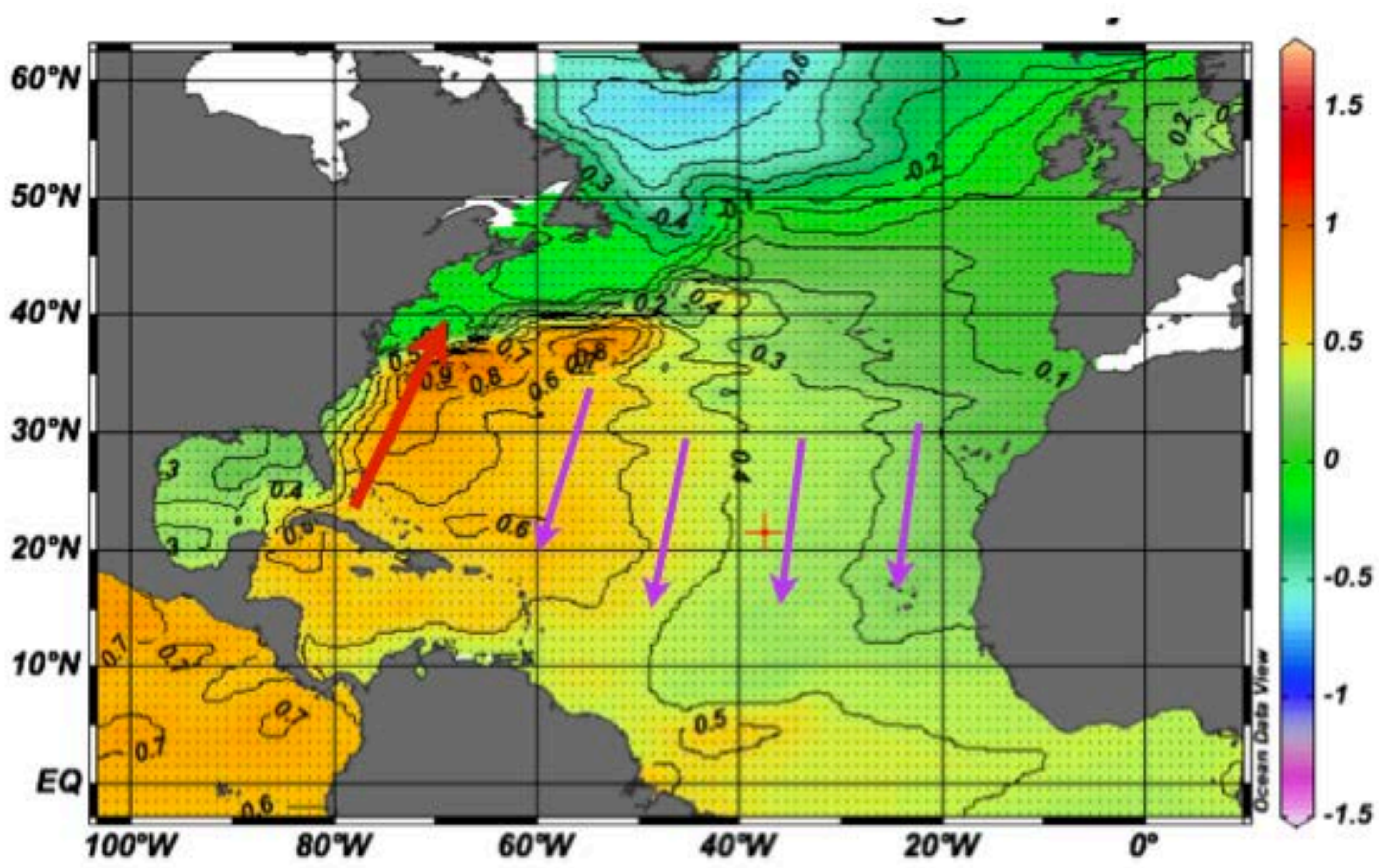
- Sverdrup circulation is equatorward everywhere in the subtropics (wind stress curl <0)
- Does not conserve mass (poleward return flow is required)

1948

- H. Stommel developed the theory for the western boundary current, followed by Munk (1950) and Fofonoff (1954).

Western boundary current

- Northward return pathway for the Sverdrup circulation



Rossby waves (as observed by satellite SSH)

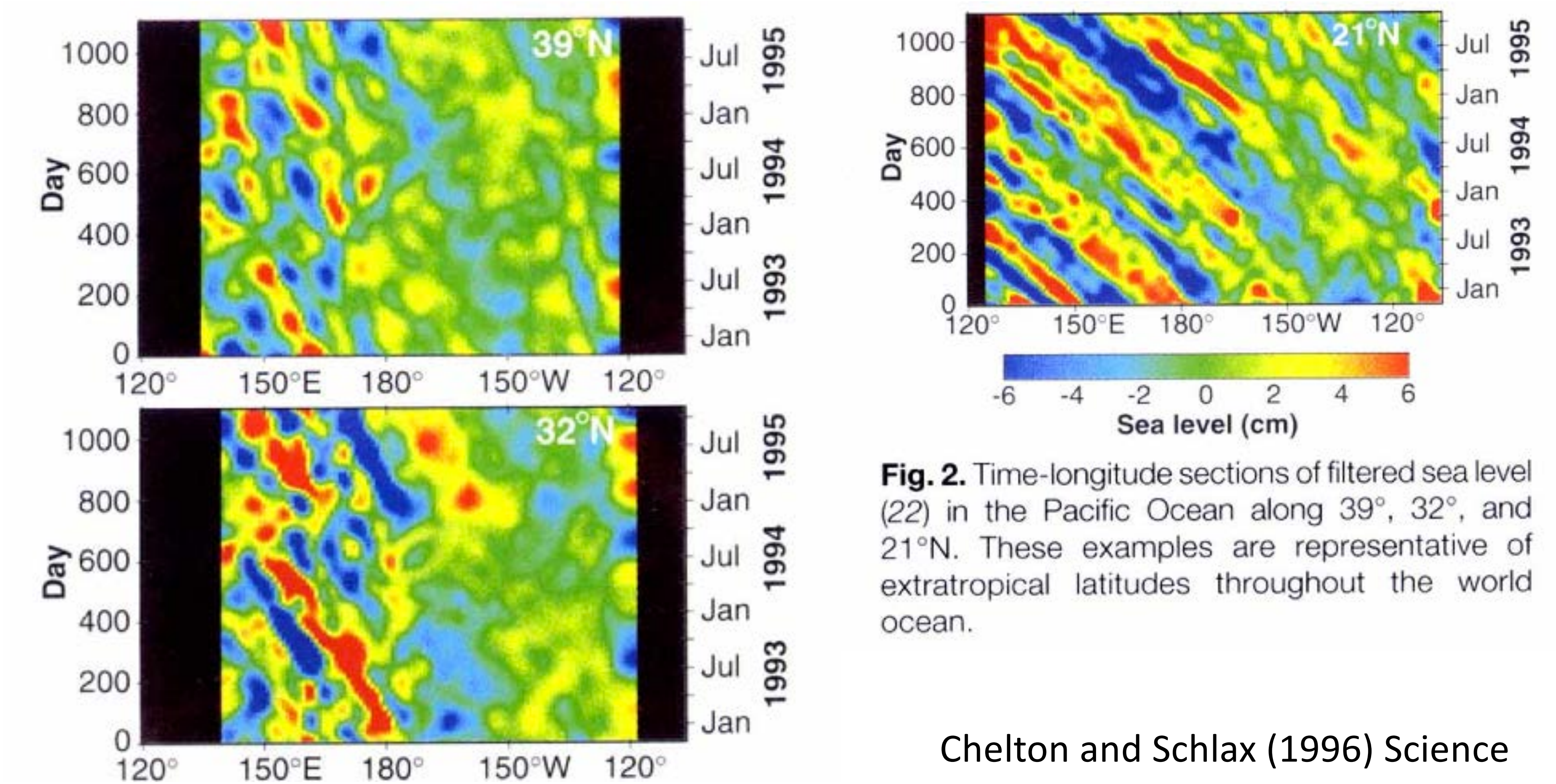


Fig. 2. Time-longitude sections of filtered sea level (*22*) in the Pacific Ocean along 39°, 32°, and 21°N. These examples are representative of extratropical latitudes throughout the world ocean.

Chelton and Schlax (1996) Science

Rossby wave propagates westward. It also transfers large scale energy to the west.

Subtropical gyre circulation

- Atmosphere applies negative wind curl (clockwise spin) over the subtropical NH oceans
  - Transient response: Rossby waves are excited, transferring the spin (energy) towards the western boundary
  - Frictional dissipation at the western boundary is the ultimate sink of the spin (energy)

- Steady response: Sverdrup circulation transports mass southward, which is balanced by the northward western boundary current