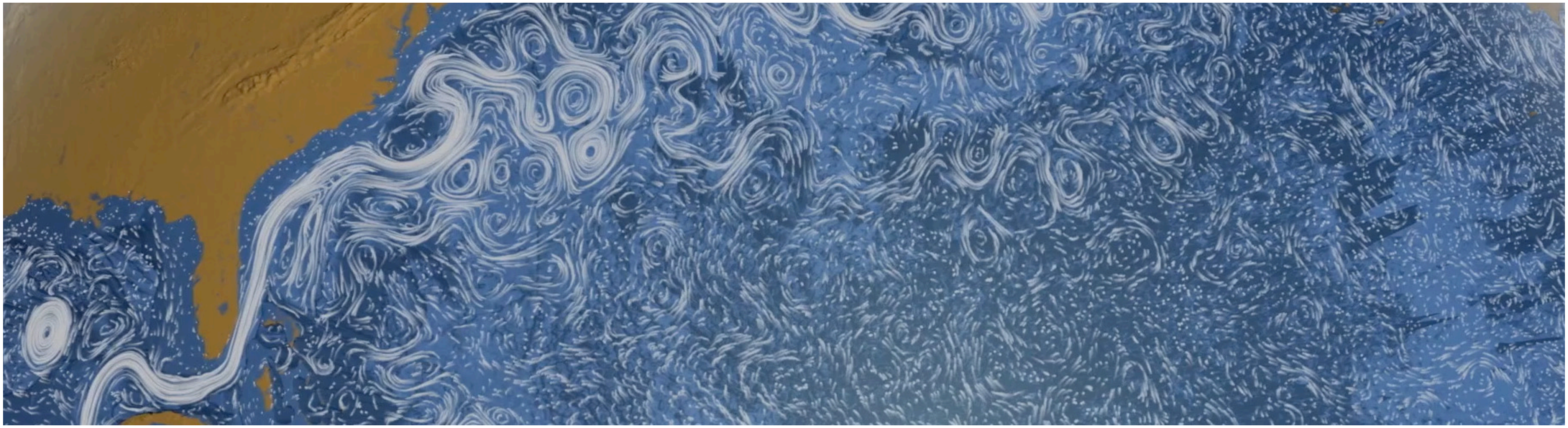


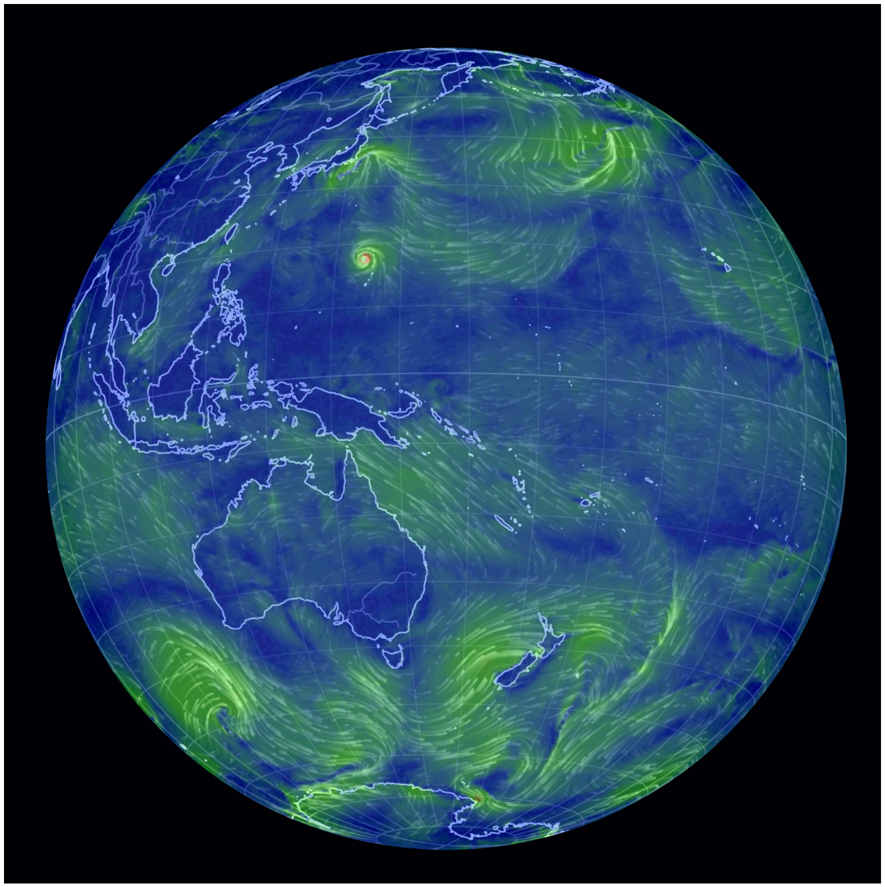
SIO 210: Dynamics IV Geostrophy

Geostrophic balance
Thermal wind
Dynamic height

READING:
DPO: Chapter (S)7.6.1 to (S)7.6.3

Download the Supplement to Chapter 7 for this reading. It is more complete than the official Chapter 7

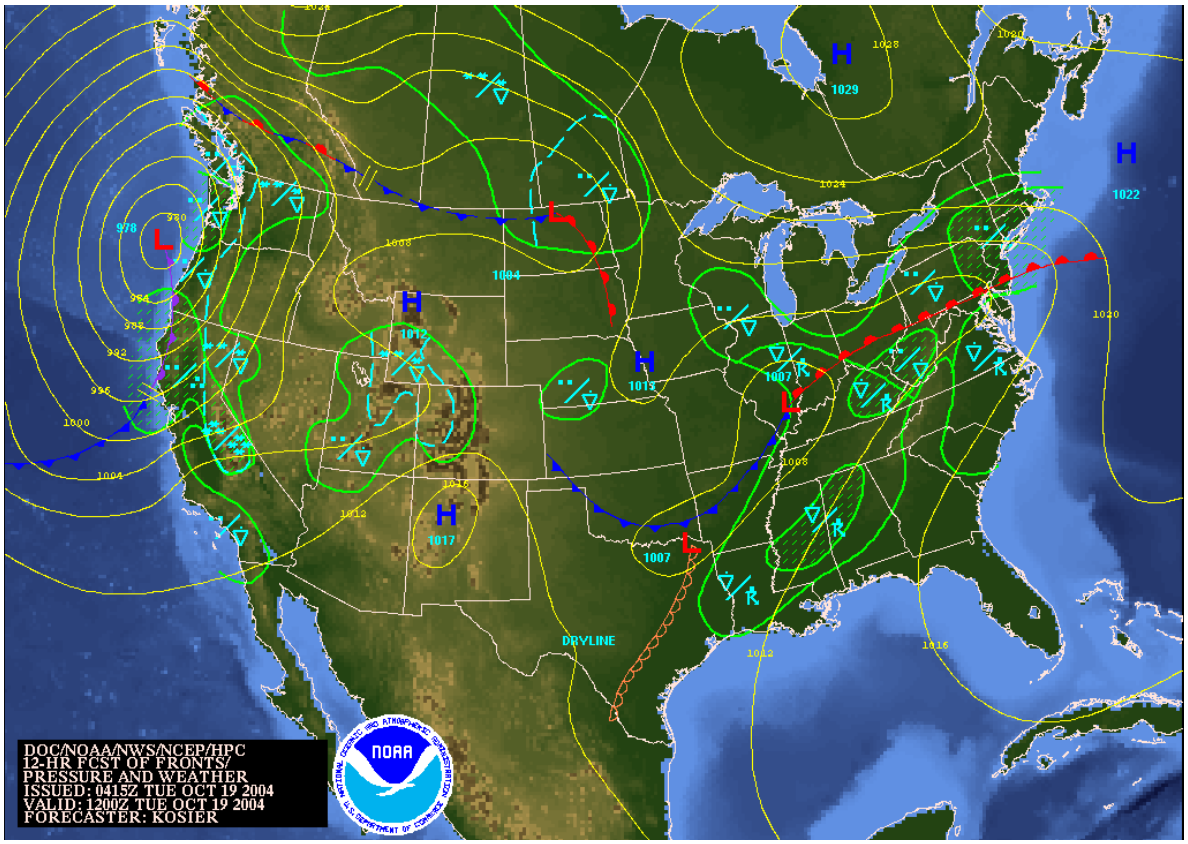
Example from atmosphere of winds: highs and lows



- High and low pressure centers
- (Typhoons/hurricanes have low pressure centers)
- Wind is clockwise around the highs and counterclockwise around lows due to Coriolis (northern hemisphere)

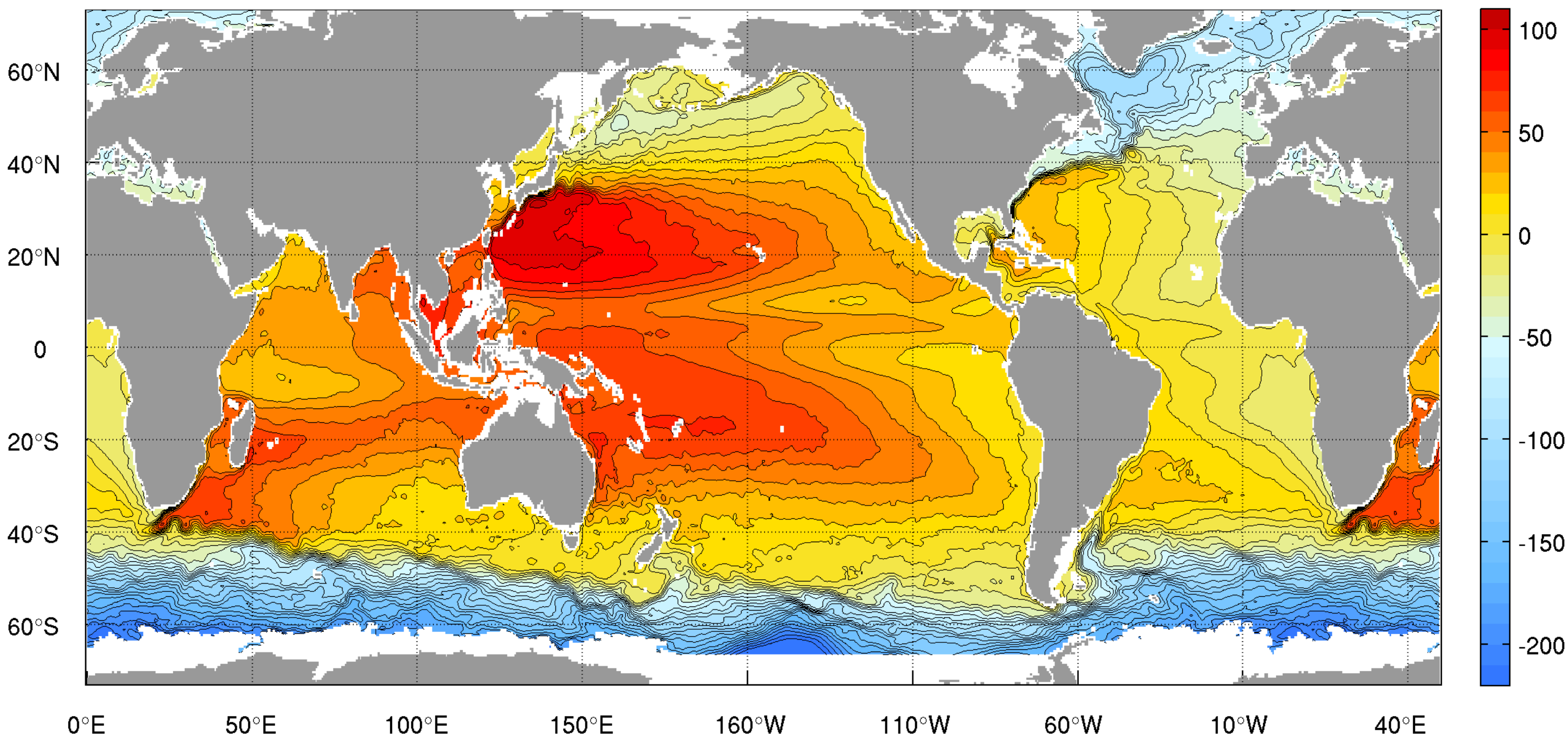
https://earth.nullschool.net/#current/wind/surface/level/orthographic=-203.32,-10.80,322

Example from atmosphere of nearly geostrophic flow



- NWS daily weather map
- High and low pressure centers

Example from ocean: surface height
Flow is along contours of constant sea surface height



Maximenko et al., GRL, 2003 (DPO Fig. 14.2)

Force balance with rotation to here
2. Geostrophic flow

Three equations in local Cartesian coordinates:

Geostrophic & hydrostatic

Horizontal (x) (west->east)

acceleration + advection + Coriolis = pressure gradient force + viscous term

Horizontal (y) (south->north)

acceleration + advection + Coriolis = pressure gradient force + viscous term

Vertical (z) (down->up)

acceleration +advection (+ neglected very small Coriolis) = pressure gradient force + effective gravity (including centrifugal force) + viscous term

Complete force balance with rotation (equations)

Inertial motion

Geostrophic flow

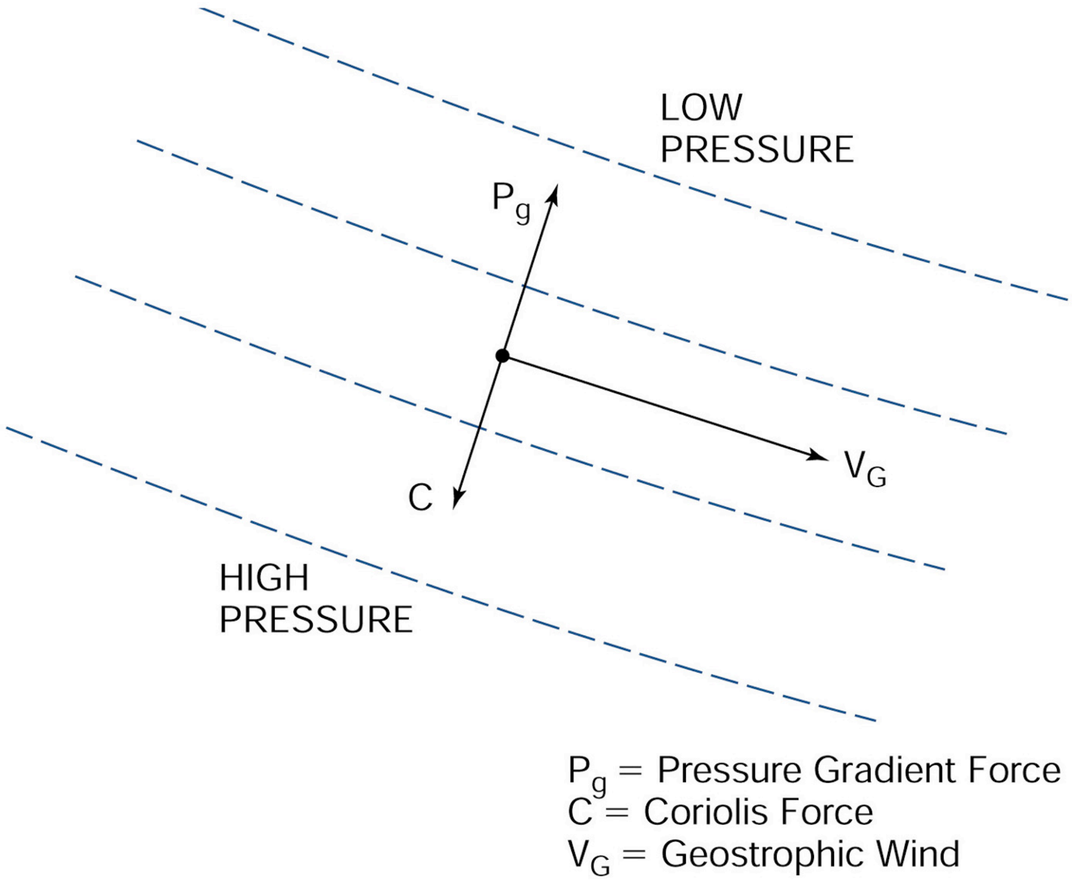
x: $\partial u/\partial t + u\,\partial u/\partial x + v\,\partial u/\partial y + w\,\partial u/\partial z - fv =$
$- (1/\rho)\partial p/\partial x + \partial/\partial x(A_H \partial u/\partial x) +$
$\partial/\partial y(A_H \partial u/\partial y) + \partial/\partial z(A_V \partial u/\partial z)$ (7.11a)

y: $\partial v/\partial t + u\,\partial v/\partial x + v\,\partial v/\partial y + w\,\partial v/\partial z + fu =$
$- (1/\rho)\partial p/\partial y + \partial/\partial x(A_H \partial v/\partial x) +$
$\partial/\partial y(A_H \partial v/\partial y) + \partial/\partial z(A_V \partial v/\partial z)$ (7.11b)

z: $\partial w/\partial t + u\,\partial w/\partial x + v\,\partial w/\partial y + w\,\partial w/\partial z$ (+neglected small Coriolis) =
$- (1/\rho)\partial p/\partial z - g + \partial/\partial x(A_H \partial w/\partial x) +$
$\partial/\partial y(A_H \partial w/\partial y) + \partial/\partial z(A_V \partial w/\partial z)$ (7.11c)

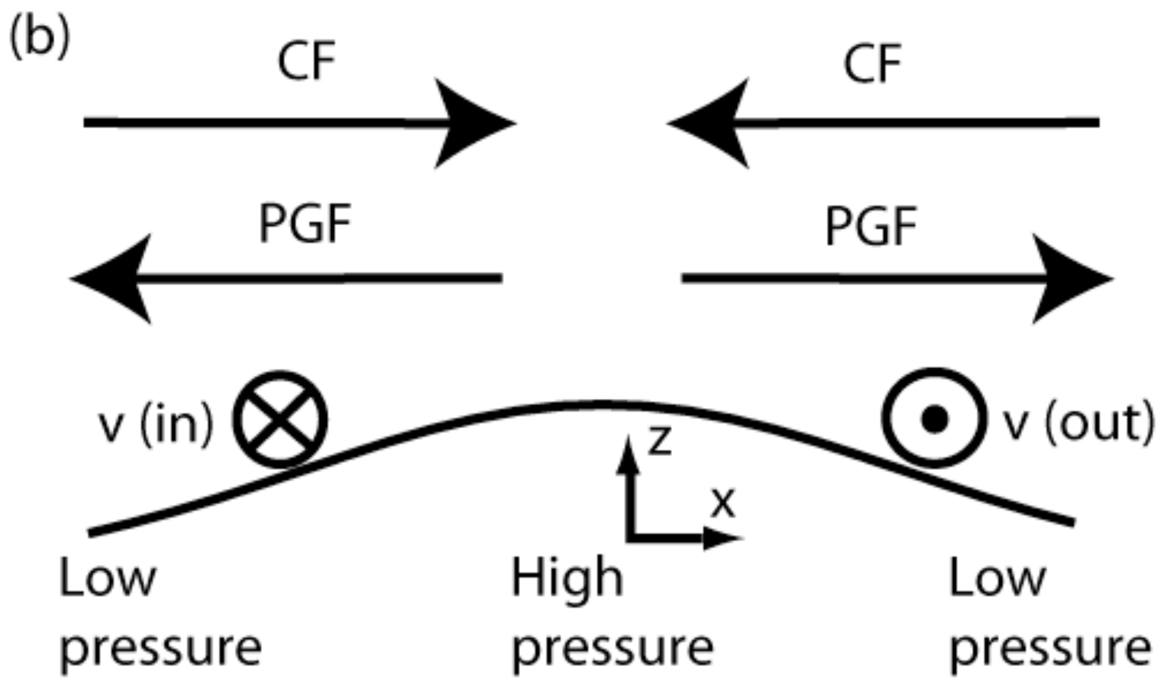
(where g contains both actual g and the effect of centrifugal force)

Geostrophy: Pressure gradient force (pgf) balanced by Coriolis force



Northern hemisphere: flow to the right of the PGF

Geostrophic balance



Northern Hemisphere.

Looking at a cross-section

Think of ball rolling down hill from high to low pressure, turning to the right (NH) due to Coriolis

DPO Fig. 7.9

Geostrophic (and hydrostatic) force balance

Three (approximate) equations:

Horizontal (x) (west-east)

Coriolis = pressure gradient force

$$-fv = -(1/\rho)\partial p/\partial x$$

Horizontal (y) (south-north)

Coriolis = pressure gradient force

$$fu = -(1/\rho)\partial p/\partial y$$

Vertical (z) (down-up)

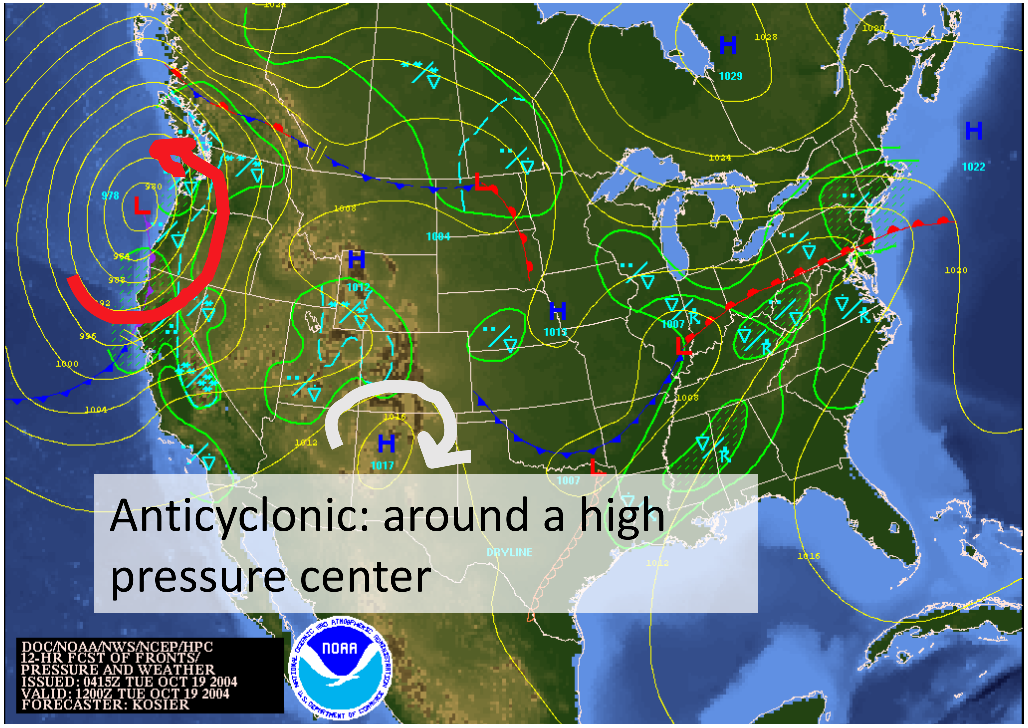
0 = pressure gradient force + effective gravity

$$0 = -(1/\rho)\partial p/\partial z - g$$

Definitions: Cyclonic and Anticyclonic

NWS daily weather map

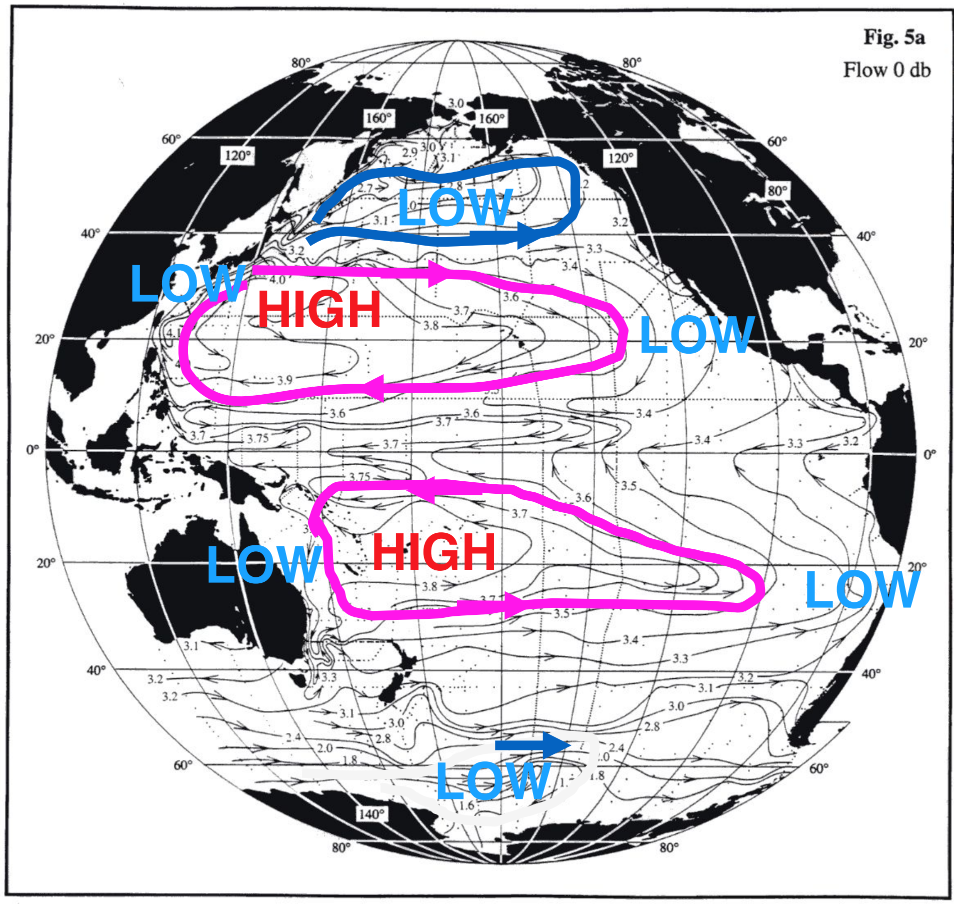
Cyclonic: around a low pressure center



Cyclonic is counterclockwise in the northern hemisphere, clockwise in the southern hemisphere. (Direction of a hurricane or 'cyclone', with low pressure in the center.)

Geostrophic flow in the ocean

Surface height/pressure and surface geostrophic circulation



Northern Hemisphere:

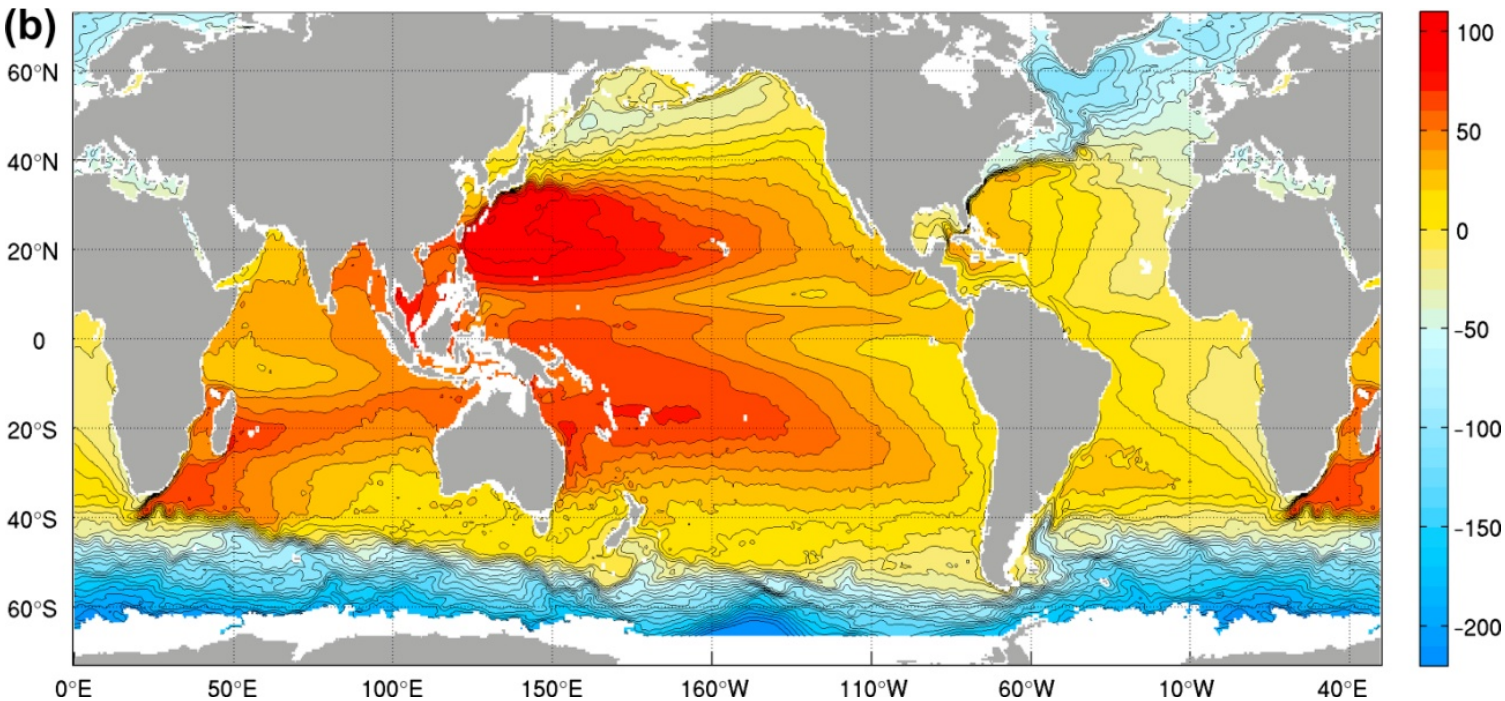
Circulation is counterclockwise around the Low (cyclonic) and clockwise around the High (anticyclonic).

Southern Hemisphere:

Cyclonic is clockwise, etc..

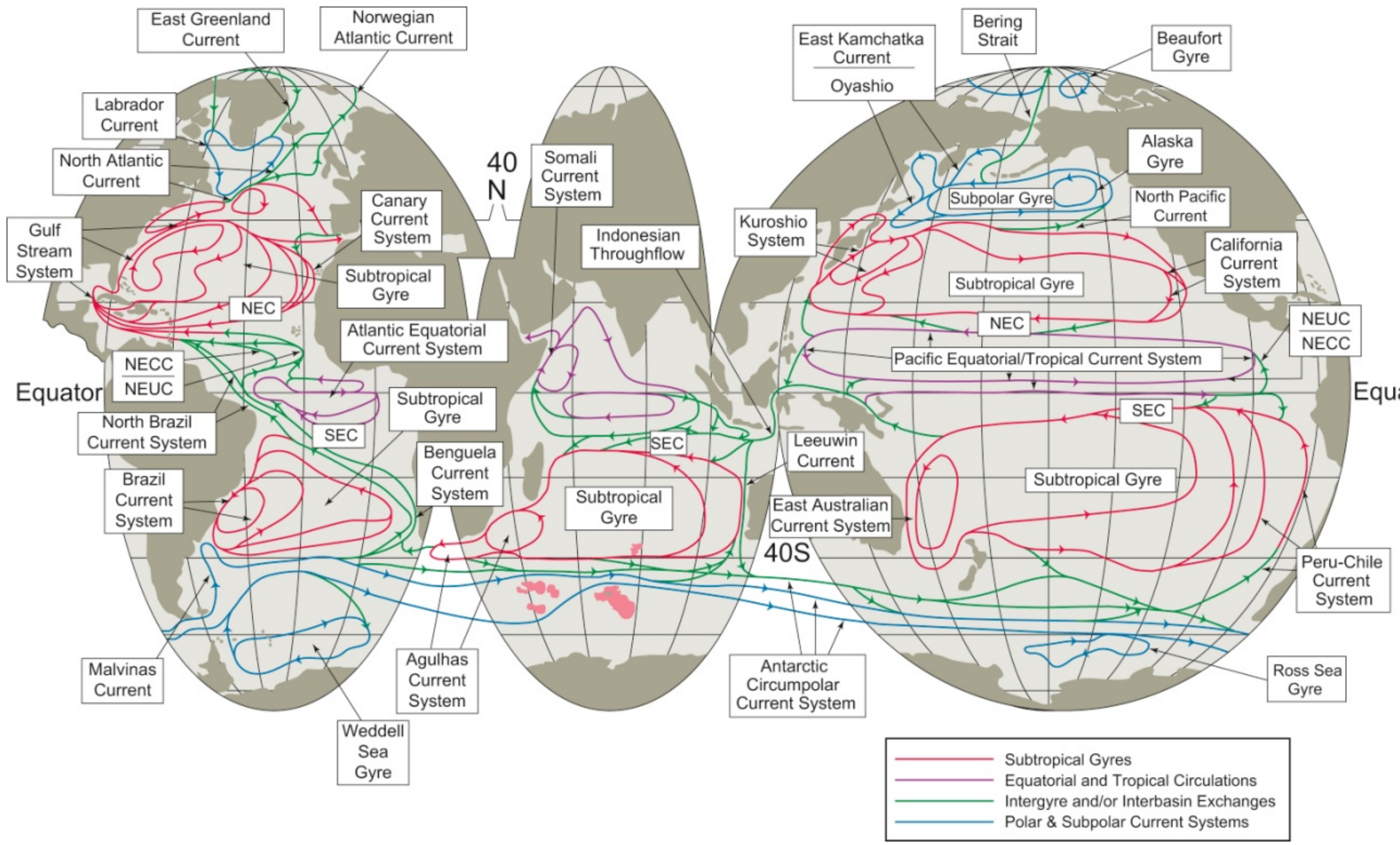
Reid, 1997

Sea surface height



DPO Fig. 14.2

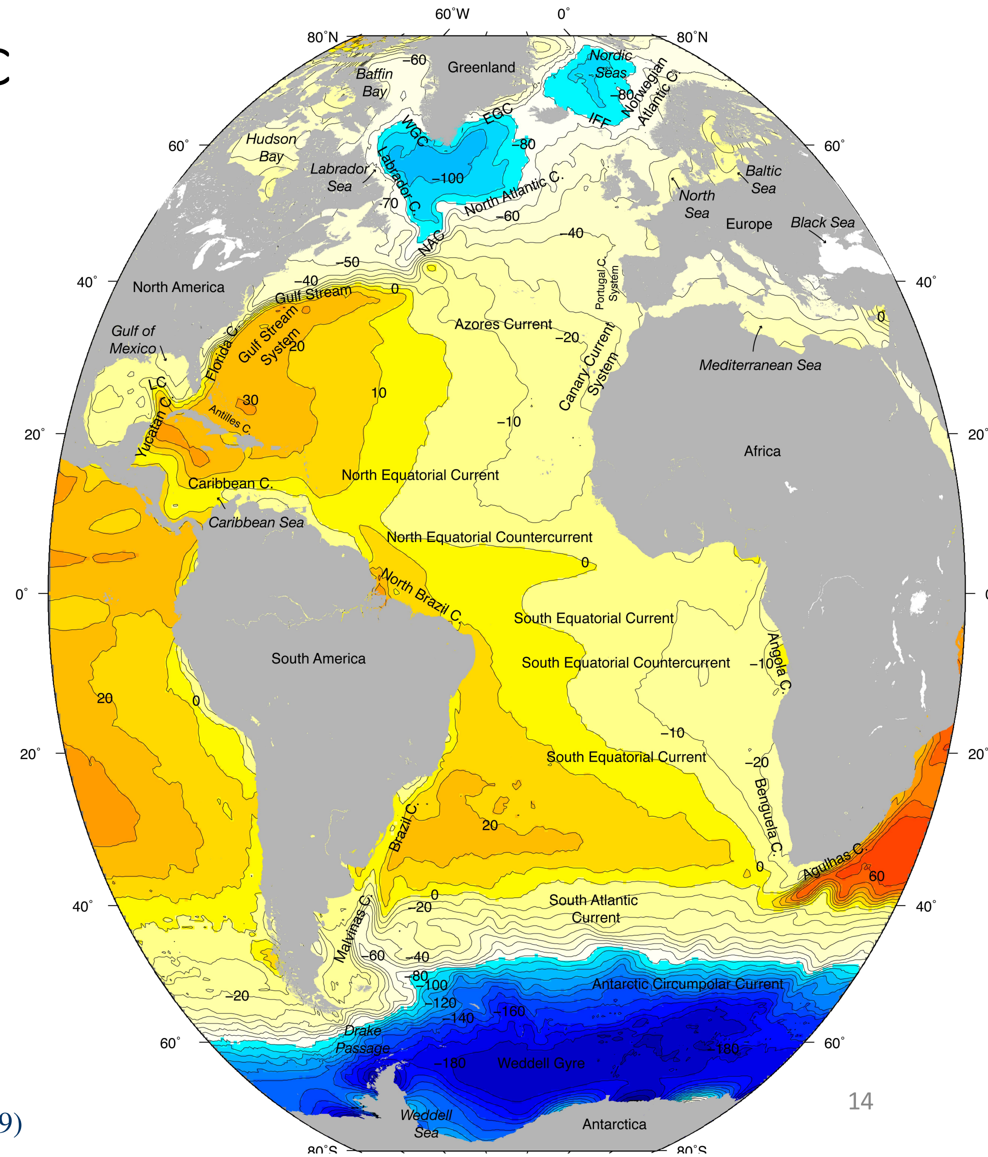
Example from ocean: schematic of upper ocean circulation, which is geostrophic



Schmitz (1995) (DPO Fig. 14.1)

Sea surface height in the Atlantic

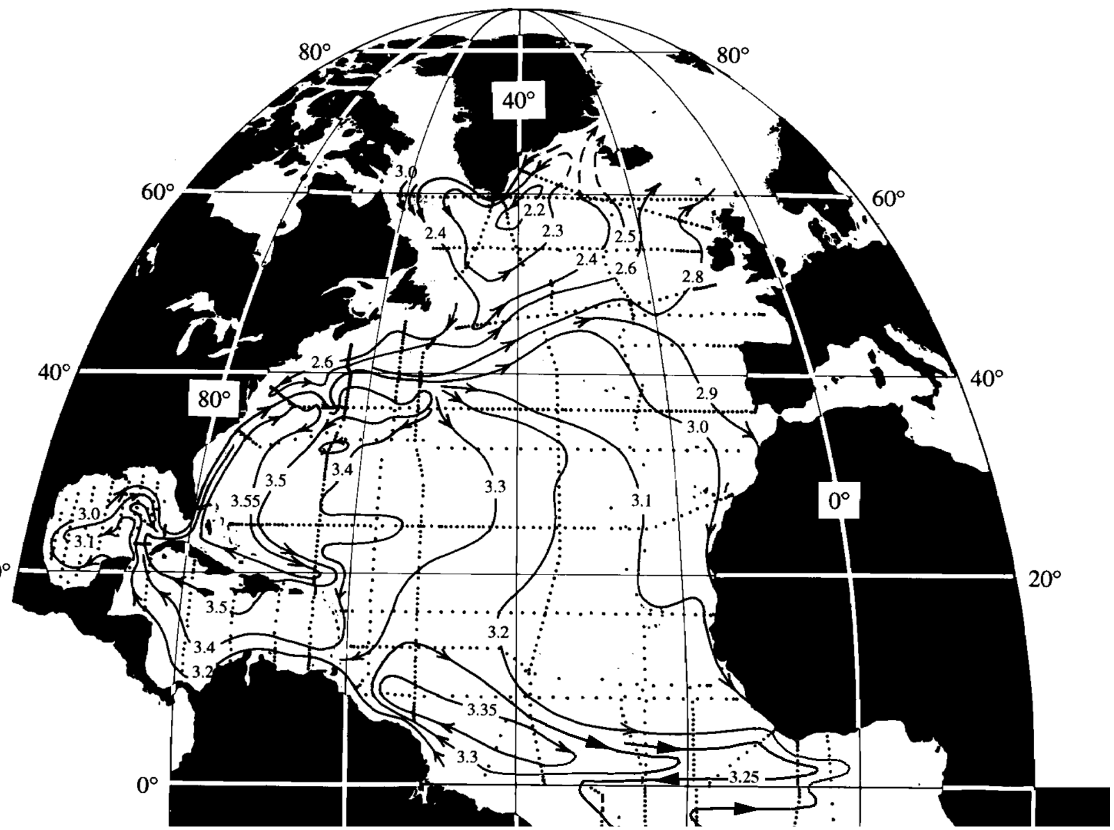
(Using Niiler et al., 2003, surface heights based on drifters)



DPO Fig. S9.1

Steric height at the sea surface in the N. Atlantic.

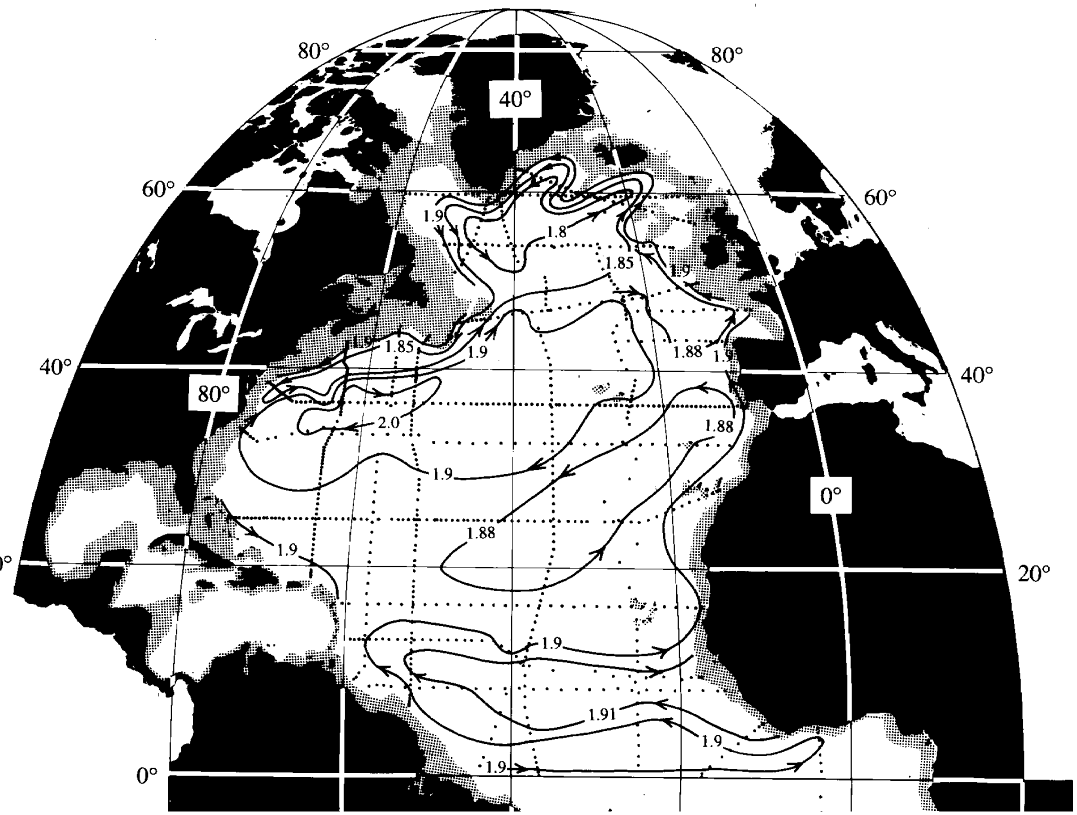
Values are similar to sea surface height in meters. (Reid, 1994)



 DPO Fig. 9.2a

Steric height at 1000 dbar in the N. Atlantic.

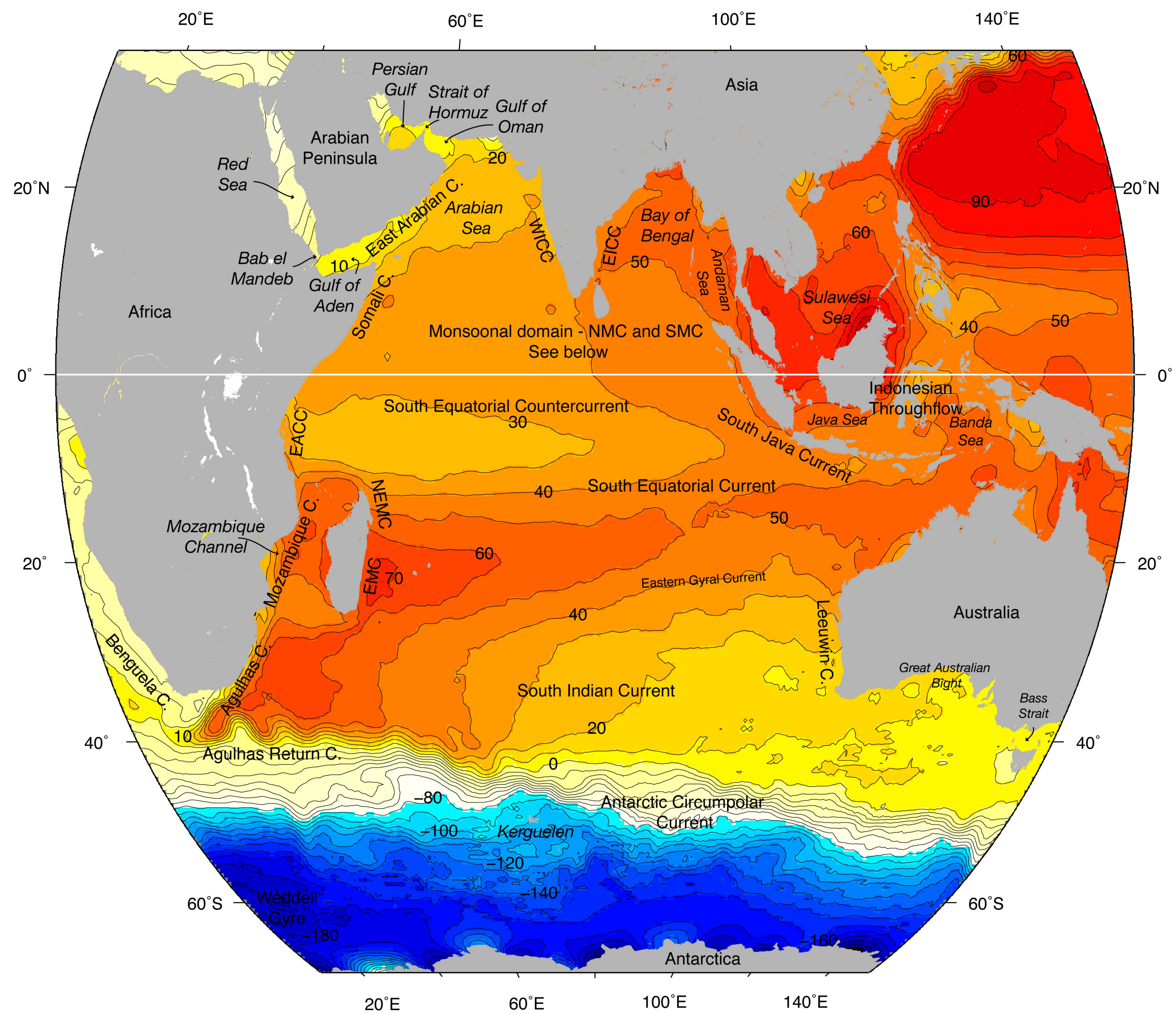
Values are similar to sea surface height in meters. (Reid, 1994)



DPO Fig. S9.2b

Sea surface height in the Indian.

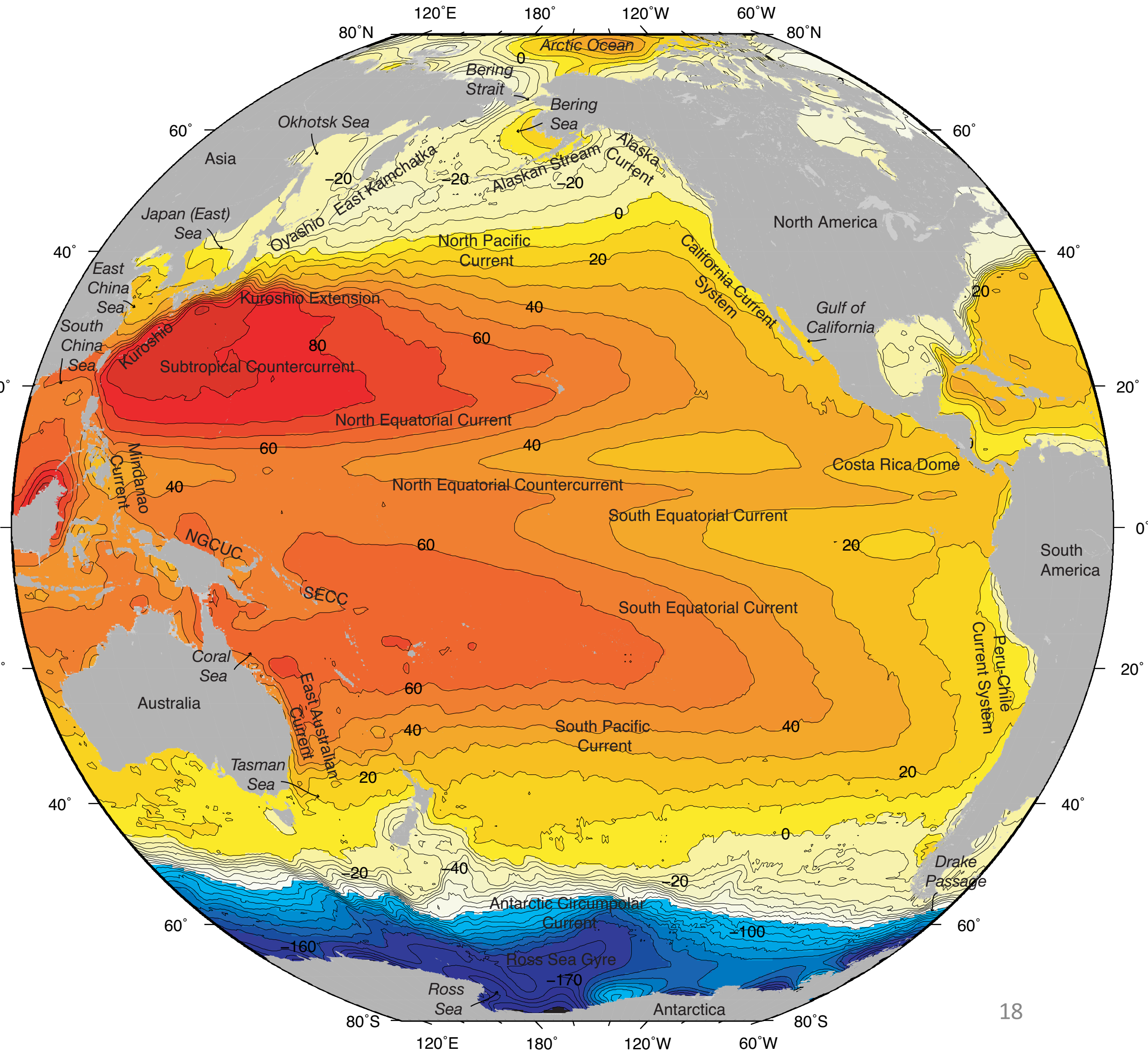
(Using Niiler et al., 2003, surface heights based on drifters)



DPO Fig. S11.1

Sea surface height in the Pacific.

(Using Niiler et al., 2003, surface heights based on drifters)



DPO Fig. S10.1

'Thermal wind': to observe geostrophic circulation below sea surface

- At the sea surface: geostrophic flow follows contours of constant height which are the same as contours of constant pressure

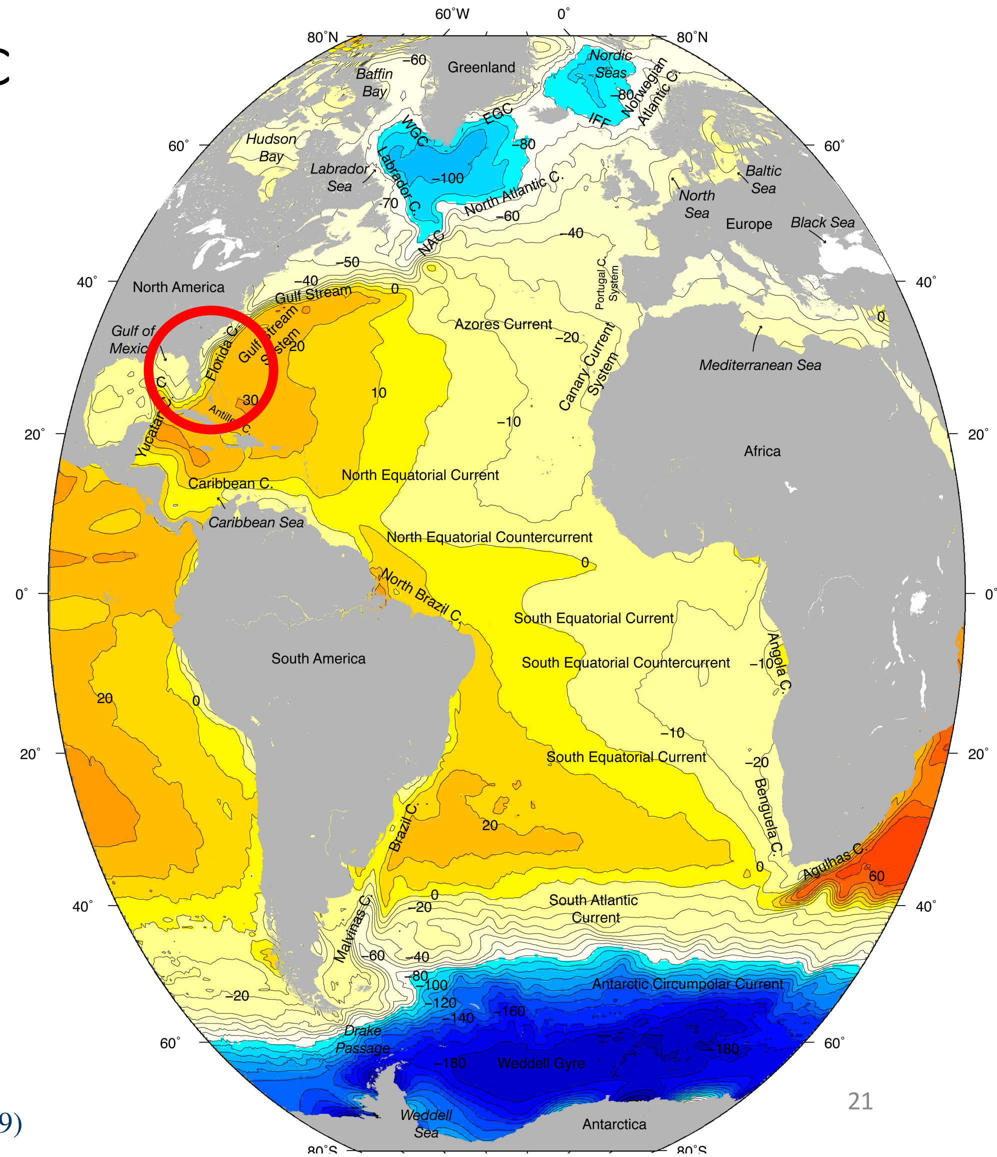
- WE WANT: Current speed and direction below the sea surface
- WE MEASURE: Density (temperature, salinity)
- We need to calculate the pressure field at depth

- Isopycnal slopes tell us that the geostrophic current is varying with depth ("vertically sheared")
- Most currents we see are wind-driven and therefore strongest at the sea surface, decaying with depth
- We therefore make a very educated (or very uneducated guess) at the geostrophic current speed and direction at some depth, and use the density field to figure out how the current changes with depth AT THAT LOCATION in latitude and longitude
- Example - Gulf Stream ----->>

Sea surface height in the Atlantic

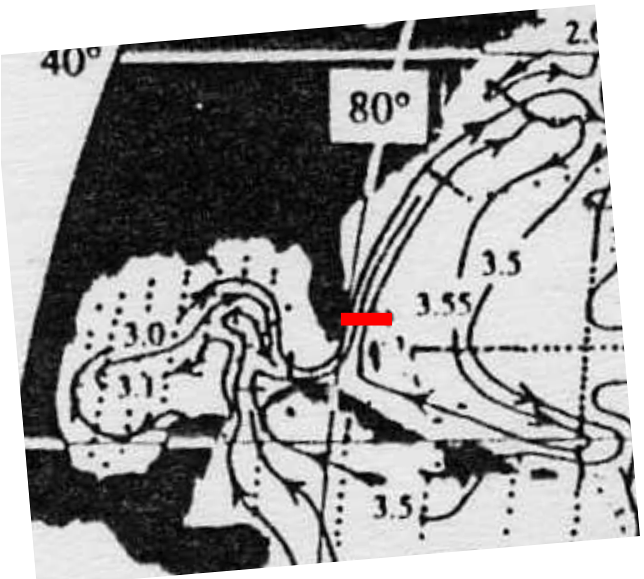
(Using Niiler et al., 2003, surface heights based on drifters)

Focus on Gulf Stream east of Florida

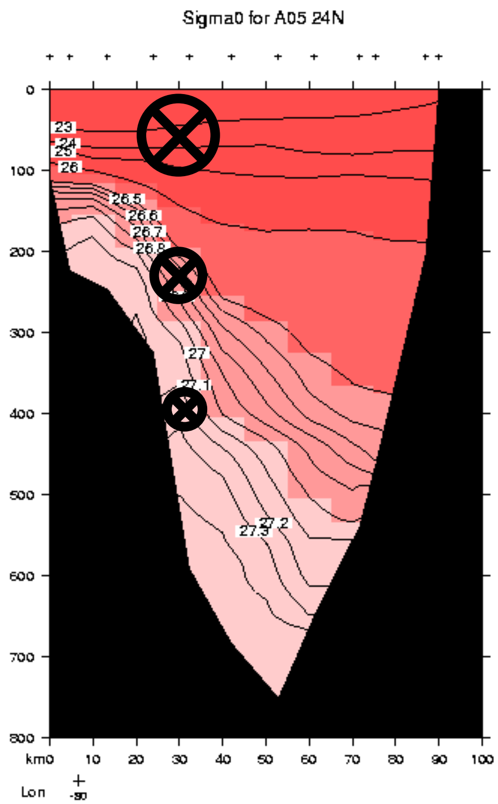


DPO Fig. S9.1

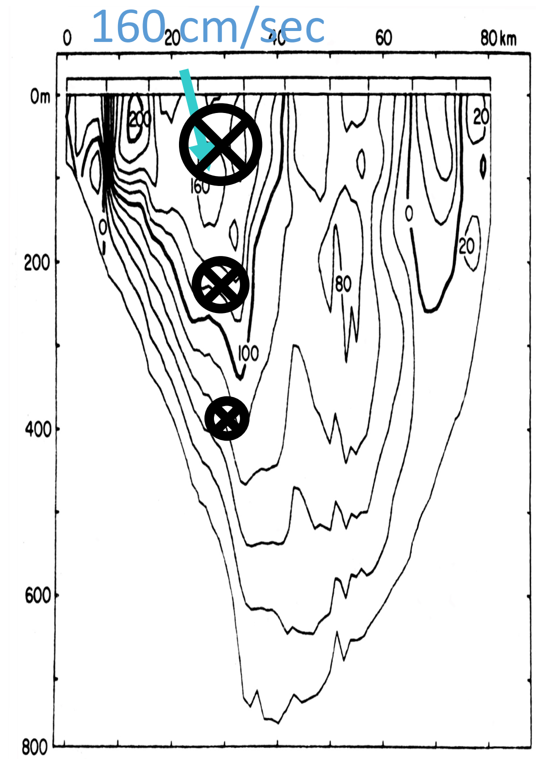
Gulf Stream vertical section of density and geostrophic velocity (west on left)



Surface dynamic height (meters) (similar to surface height).



Potential density vertical section across Gulf Stream



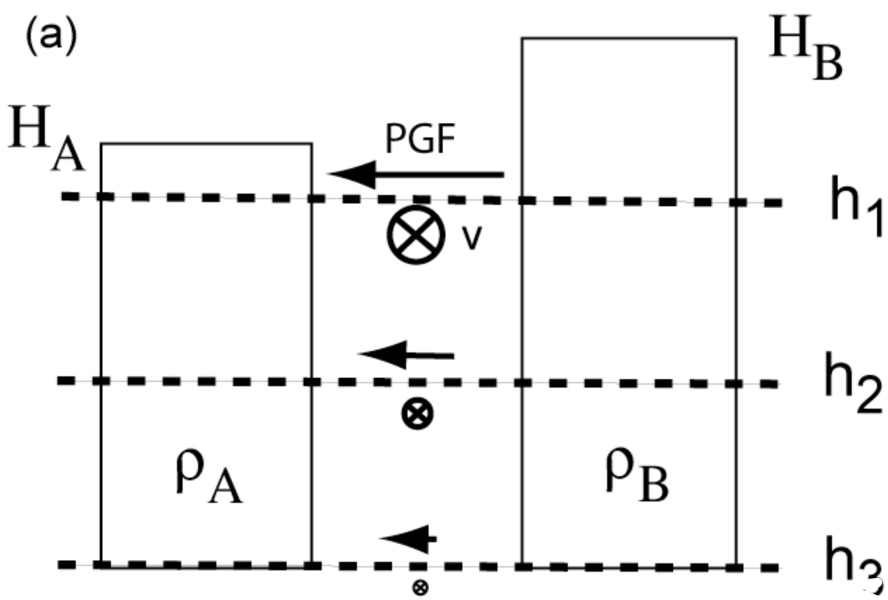
Northward velocity in the Gulf Stream

Roemmich, 1983

Thermal wind ("geostrophic method"):

How does the geostrophic flow change with depth (below the sea surface)?

Example 1: 2 columns of different density and different height



For this example: density at A is higher than density at B

$\rho_A > \rho_B$

Near the sea surface (at h_1), there is more mass at B than at A, so there is higher pressure at B than at A, so there is a westward PGF and northward flow (northern hemisphere).

Farther down (at h_2), the difference in mass above h_2 at B and A is smaller since the density at B is lower than an A. So the pgf is smaller and the current is weaker.

Even farther down (at h_3), we can have equal mass (equal pressure, hence NO pgf) since total mass at B and A is the SAME.

DPO Fig. S7.20

Thermal wind ("geostrophic method"):

Example 2: continuous density variation and uneven height

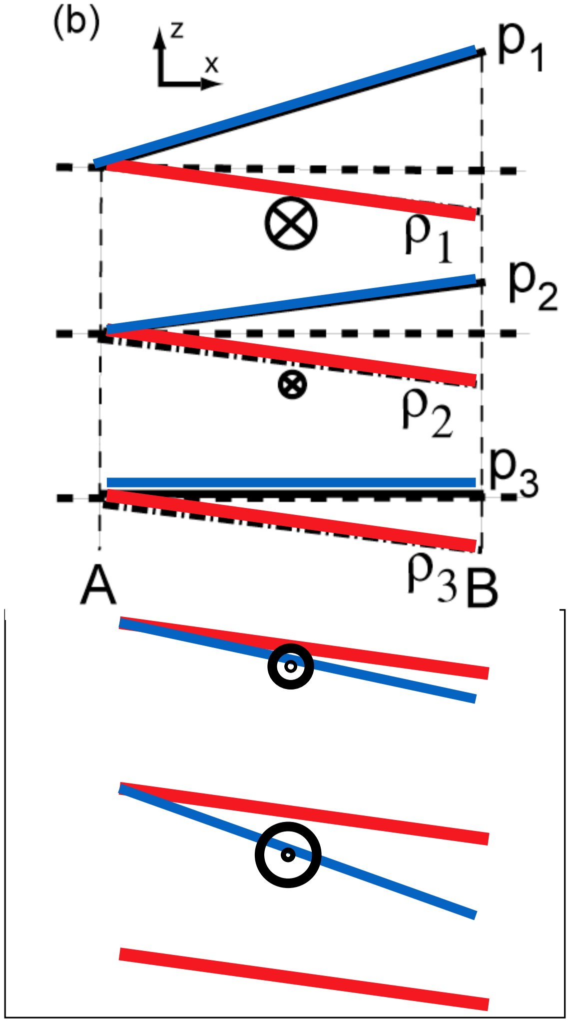
We measure density (RED lines).

Here we assume (or measure) that the pgf and therefore the velocity is 0 at depth 3 ('level of no motion'). Therefore contour p_3 (BLUE) must be flat there.

We use hydrostatic balance to calculate pressure (BLUE lines) at all other depths relative to level 3.

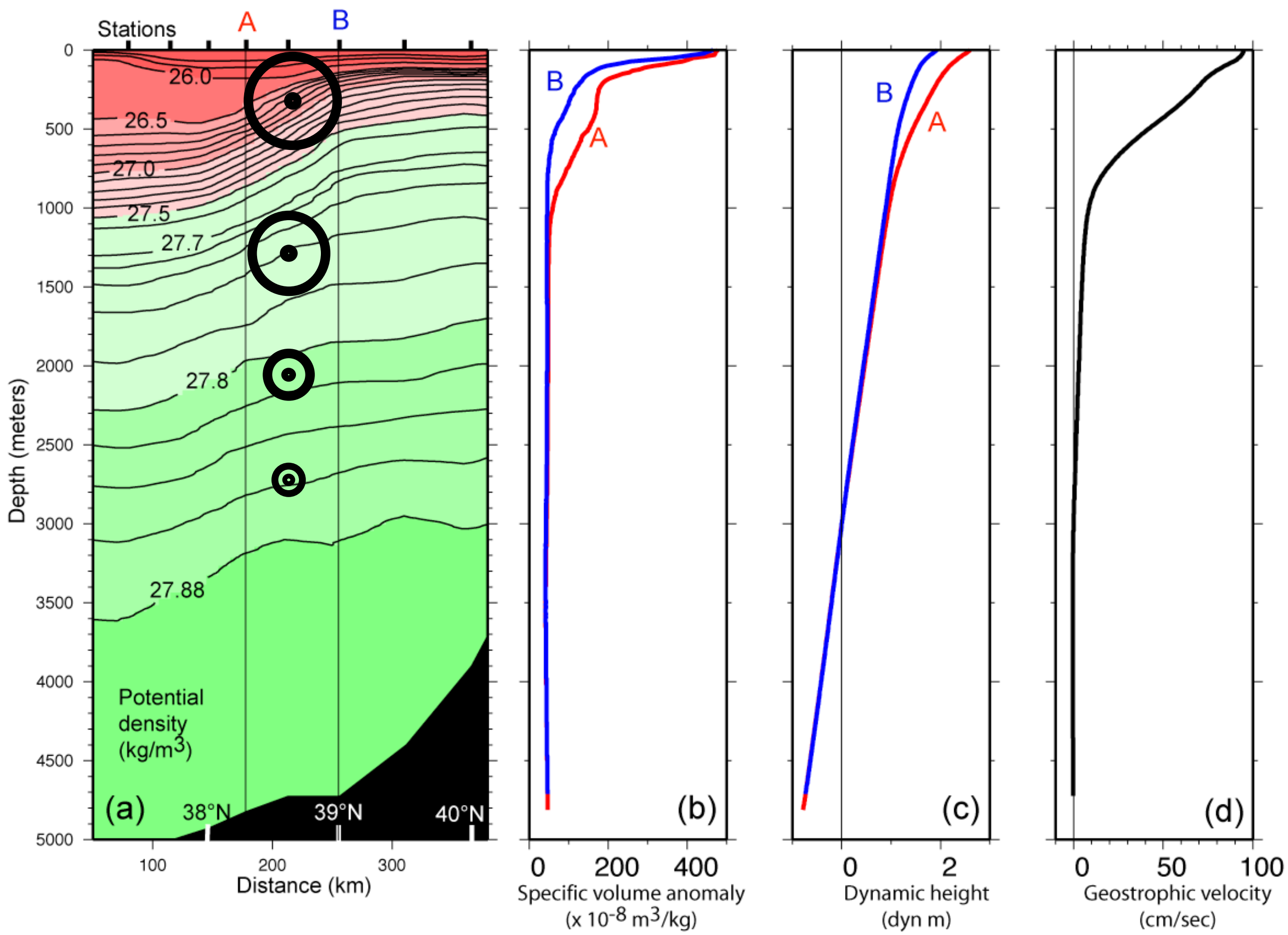
Water is less dense at B than at A, so isobars are higher there, above level 3, than at A. Sea surface is therefore higher at B than at A.

(And below level 3, the flow would start going back the other way, out of the page)



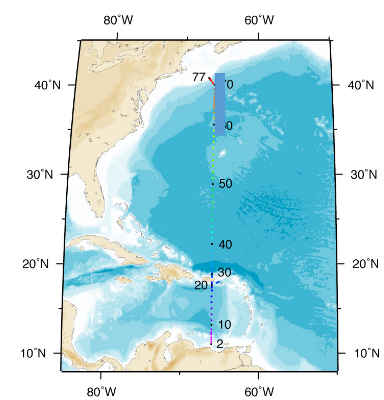
DPO Fig. 7.10

Gulf Stream density, dynamic height and geostrophic velocity



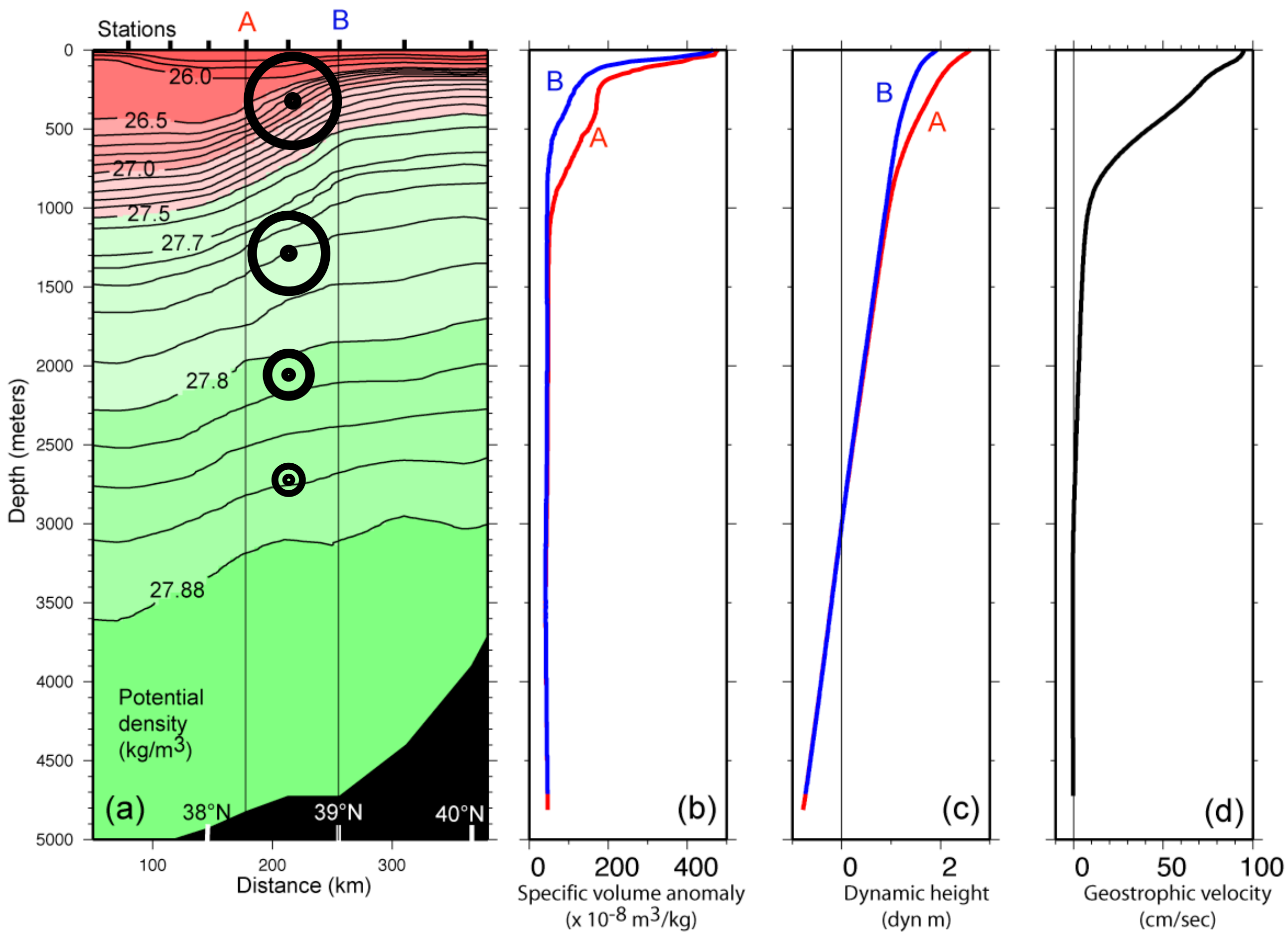
In this example, compute geostrophic velocities relative to 0 cm/sec at 3000 dbar.

If we MEASURE v at 3000 dbar, then just add it to the whole profile

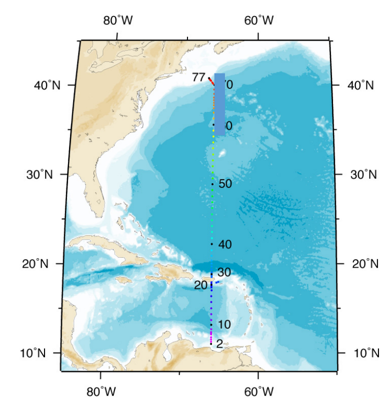


DPO Fig. 7.11

Gulf Stream density, dynamic height and geostrophic velocity



Northern hemisphere:
Tilted isopycnals up towards right give us flow out of page, decreasing with depth



DPO Fig. 7.11

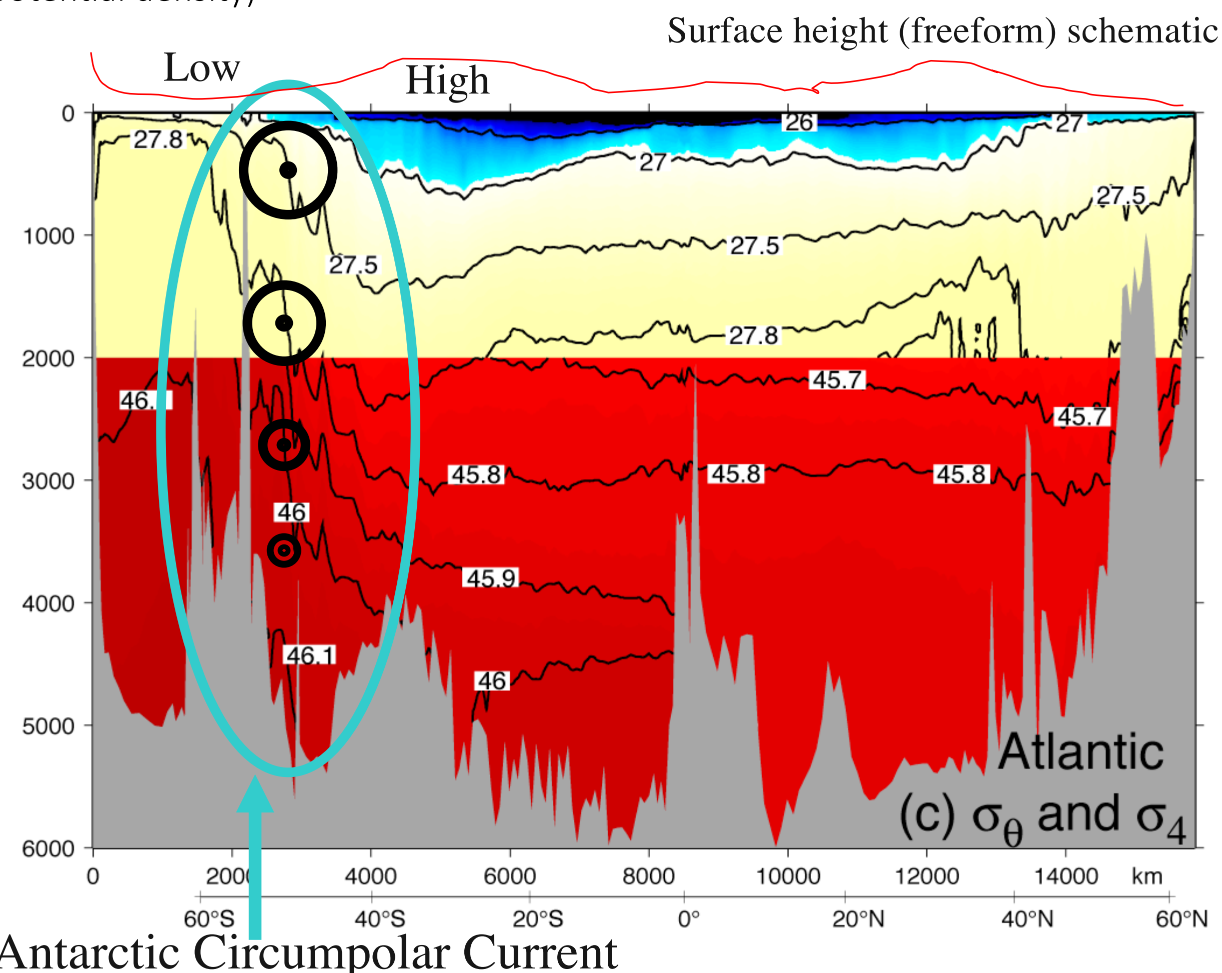
Vertical structure of the circulation

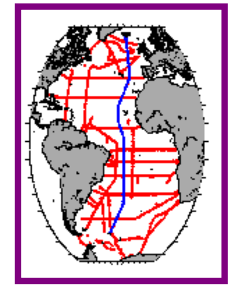
(Atlantic section of potential density)

Southern hemisphere:

Geostrophic flow is to the left of the pgf

Tilted isopycnals DOWN towards right give us flow out of page, decreasing with depth





DPO Fig. 4.10

Thermal wind (formal expressions)

The vertical shear in geostrophic velocity is proportional to the horizontal density derivative.

Formally:

$$-f\partial v/\partial z = (g/\rho_o)\partial\rho/\partial x$$
$$f\partial u/\partial z = (g/\rho_o)\partial\rho/\partial y$$

(For dynamics-based students: this is derived from the geostrophic x, y momentum balances (take the vertical derivative) and then substituting from hydrostatic balance for the vertical pressure derivative.

Notice that thermal wind gives only the vertical shear of the velocity.

To obtain velocity, integrate vertically.

Therefore must know the velocity at one depth (‘reference velocity’ at a ‘level of known motion’) in order to construct absolute velocity profile.

Reference velocity for thermal wind balance

The pgf is calculated as the difference of pressure between two stations at a given depth (flat surface relative to the geoid).

a) If the velocity is known at a given depth, then the pgf at that depth is also known (from geostrophy)

b) From the measured density profiles at the two stations, we can calculate how the pgf changes with depth, which tells us the velocity change with depth. (This is through the thermal wind relation.)

c) Using the known velocity from (a), which we call the reference velocity, and knowing how velocity changes with depth from (b), we can compute velocity at every depth.

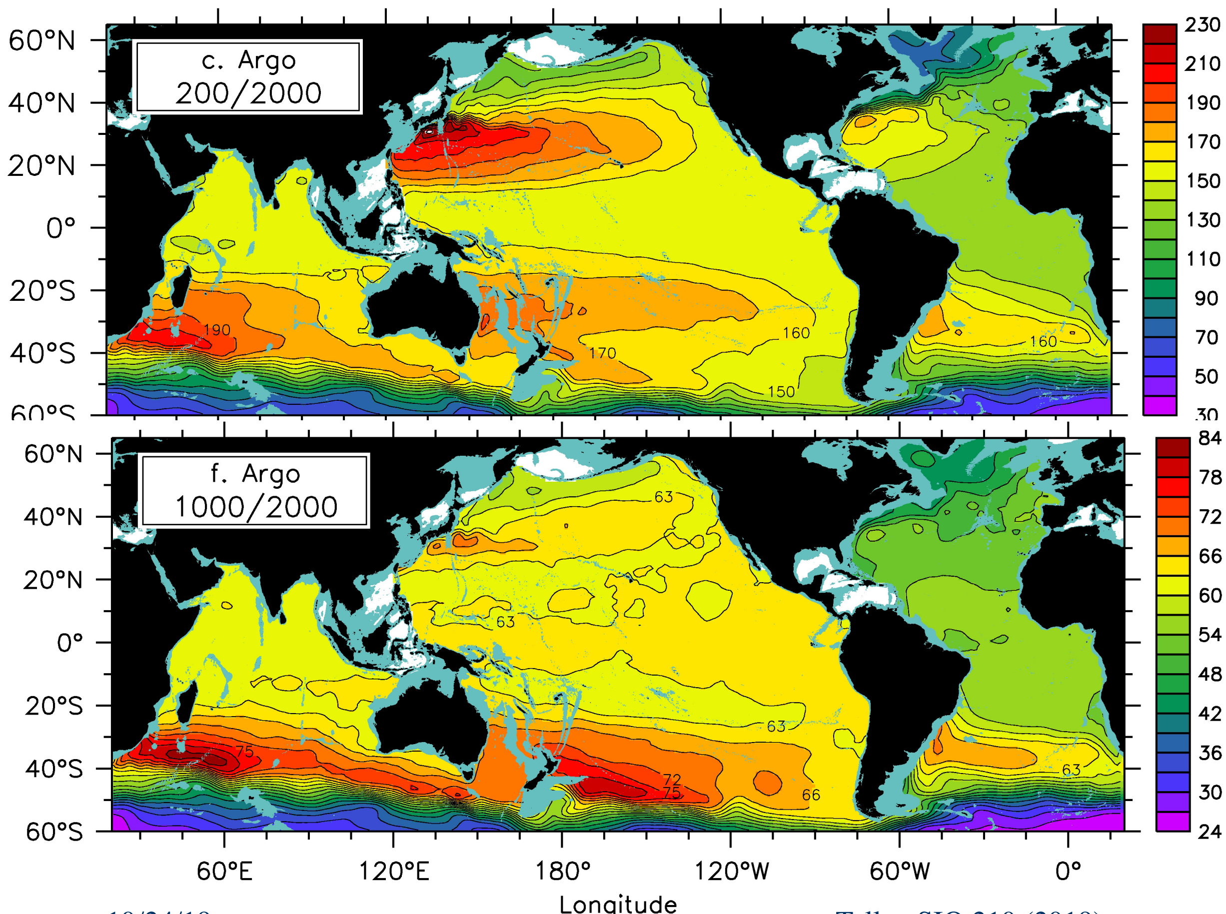
Reference velocity for thermal wind balance

Reference velocities for vertically sheared geostrophic velocity profile:

Level of no motion: Old-fashioned - assume 0 velocity at some great depth, and compute velocities at all shallower depths. This is useful if you are focused on very energetic upper ocean flows, but not useful if you want to look at weak deep flows.

Level of known motion: Much better - observe or determine through external means (use of tracers, mass balance, etc) a good guess at the velocity at some depth. This is essential if you want to study deep circulation.

Geostrophic circulation at 200 and 1000 dbar relative to 2000 dbar



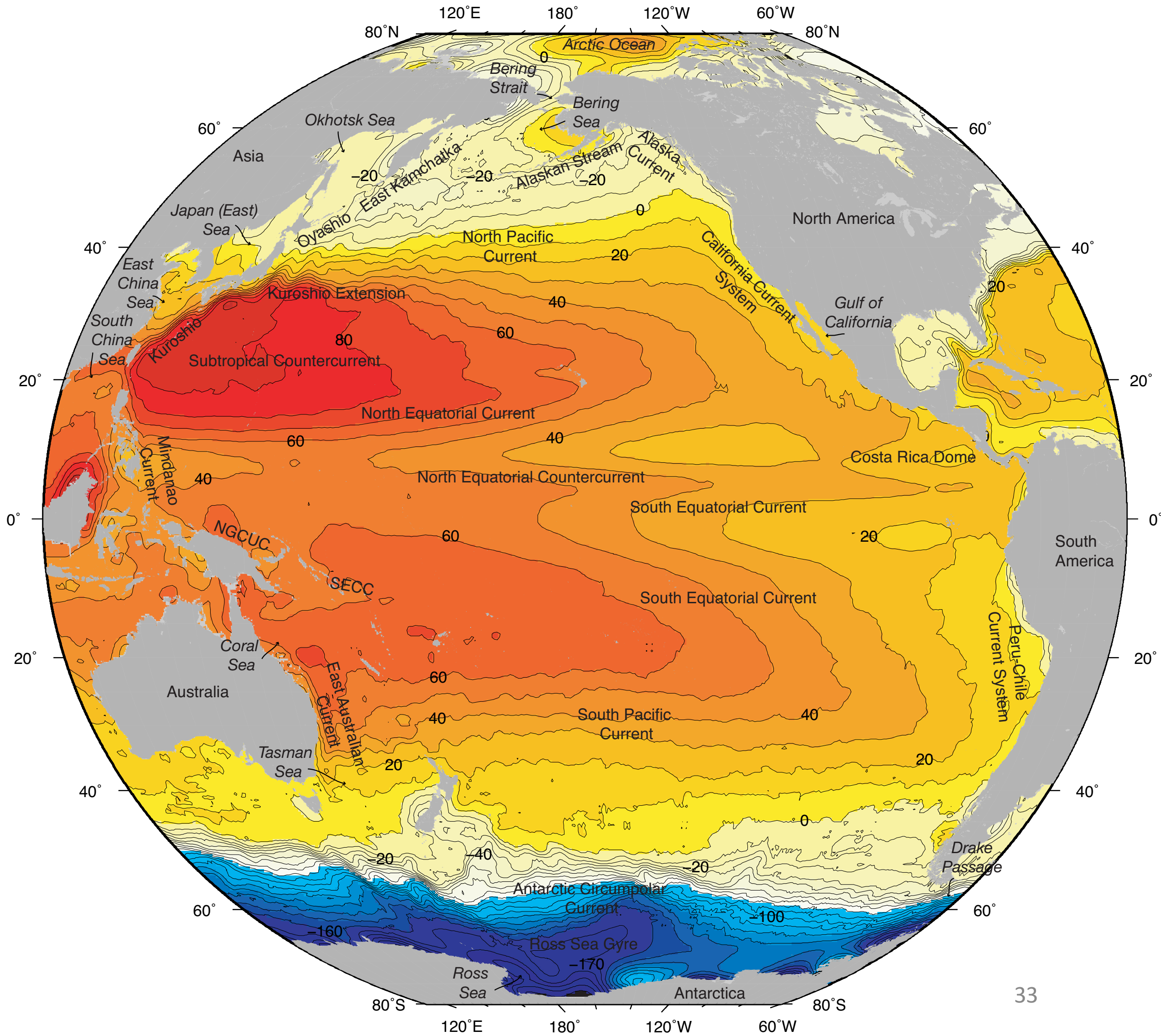
Shrinkage of strong part of ST gyres to west and pole (into the WBC)

This would be the actual circulation at 200 and 1000 dbar if the flow at 2000 dbar = 0. (It is not 0; but it is weaker than at shallower depths, so these are good depictions of the circulation.)

Roemmich and Gilson, 2009
DPO Fig. 14.3

Sea surface height in the Pacific.

(Using Niiler et al., 2003, surface heights based on drifters)

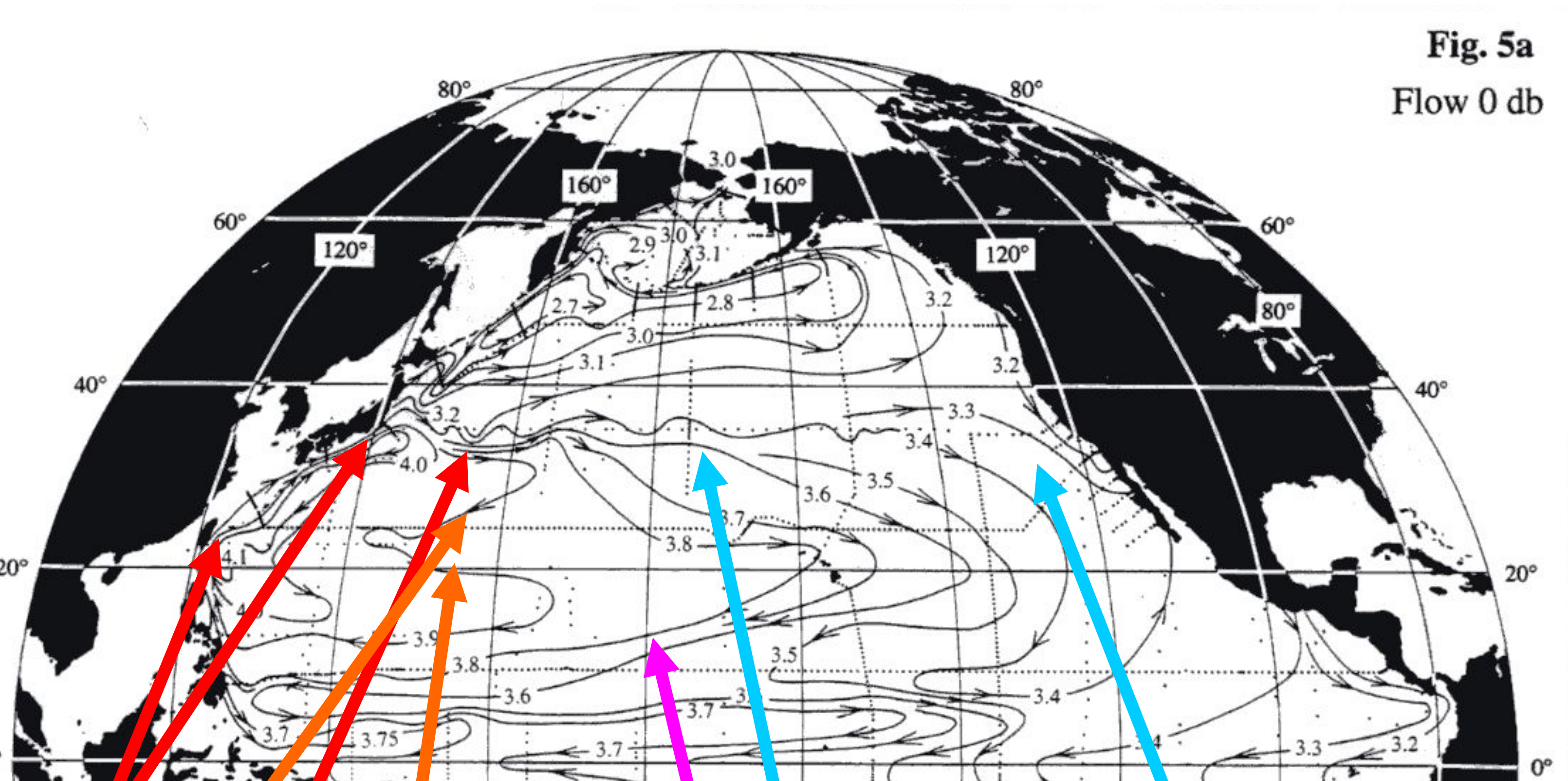


DPO Fig. S10.1

N. Pacific surface steric height

(Reid, 1997)

DPO FIGURE 10.2



Kuroshio and K. Extension

North Pacific Current

California Current

Recirculation, C-shape

North Equatorial Current

Kuroshio and Kuroshio Extension

Features that are similar to all subtropical western boundary currents:

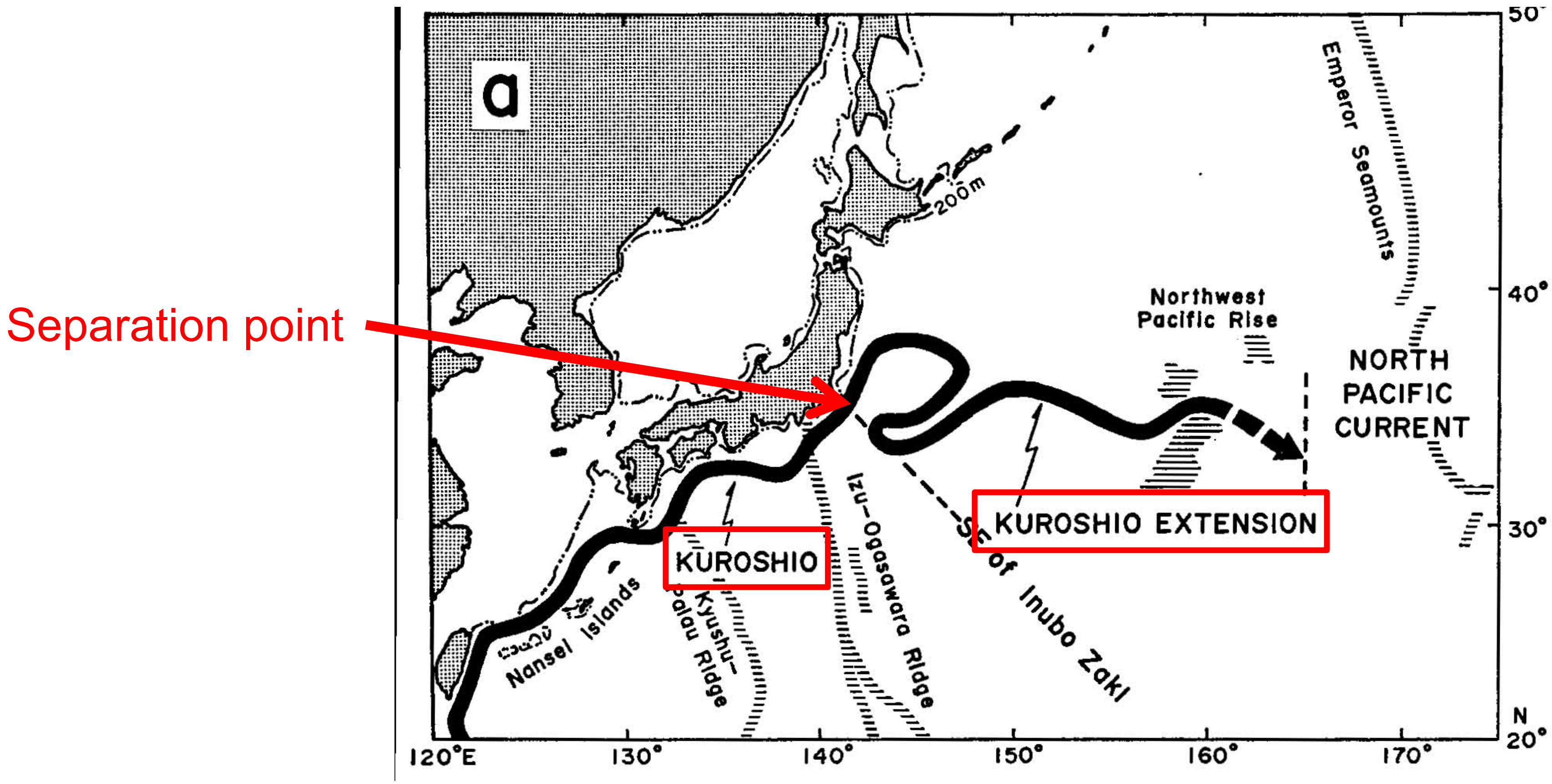
1. High surface velocities > 100 cm/sec
2. Extends to the ocean bottom (weak velocity)
3. 'Separates' from western boundary
4. Extends far eastward into the gyre ("Kuroshio Extension")
5. Kuroshio meanders (time dependence)
6. Kuroshio has "recirculations" in opposite direction on both sides of the current. Biggest "recirculation" is on south side of Kuroshio Extension - "C - shape" of gyre.

Special feature of Kuroshio, not similar to other WBCs:

7. Large meander state of Kuroshio

Kuroshio nomenclature

(Kawai, 1972)



Kuroshio Extension meandering

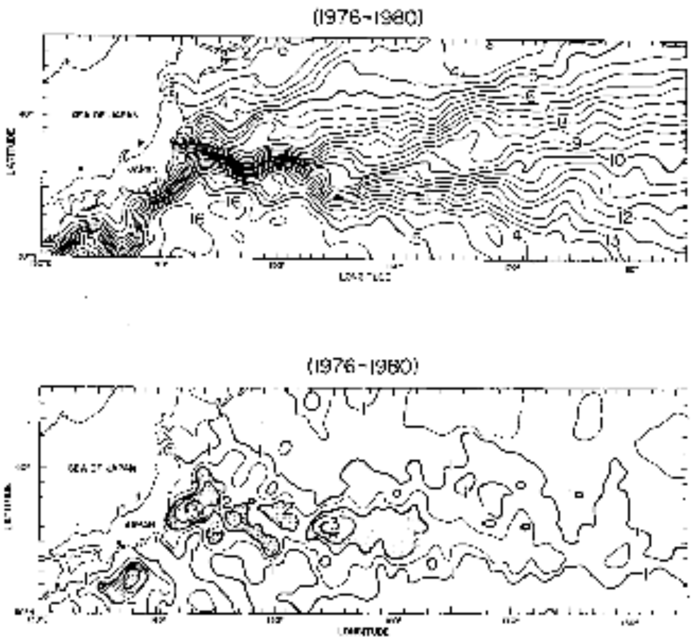
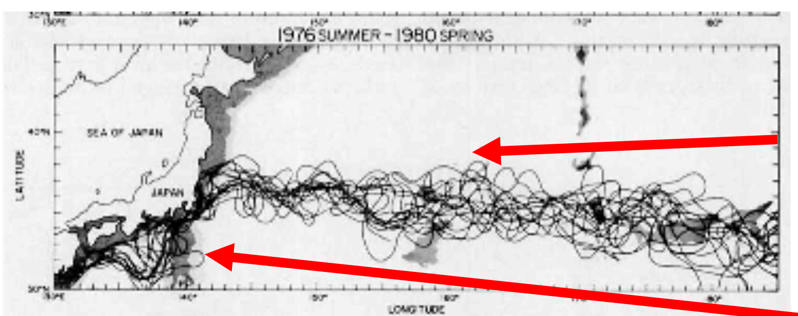


FIG. 3. Long-term annual mean and total rms differences of temperature (°C) at 300 m estimated from maps contained in Fig. 2. The contour interval is 0.5°C on both maps. Regions where rms differences exceed 2°C are shaded.

Mean

Mizuno and White (1983)

Variability (rms temperature)



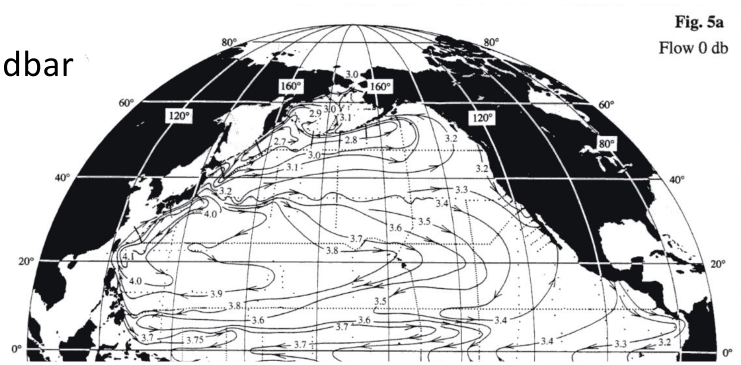
Individual Kuroshio tracks

Normal meanders

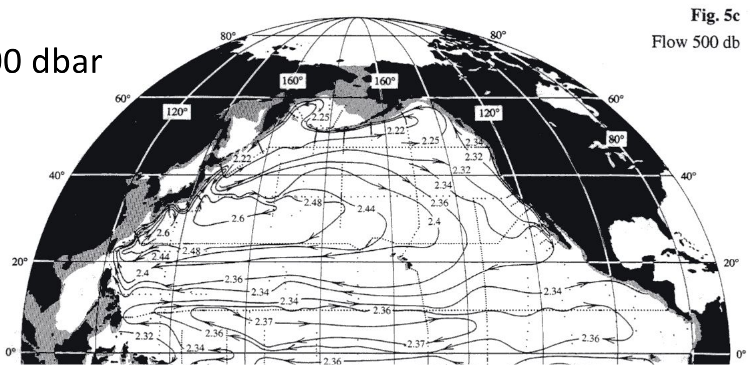
"Large meander" (before separation point)

Vertical structure of the Kuroshio subtropical gyre: 0, 500, 1000 dbar

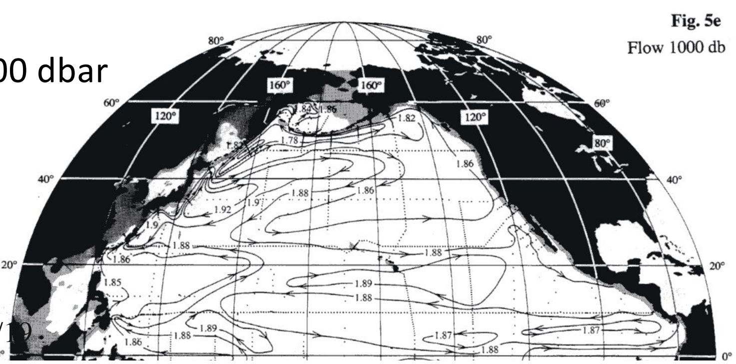
0 dbar



500 dbar



1000 dbar



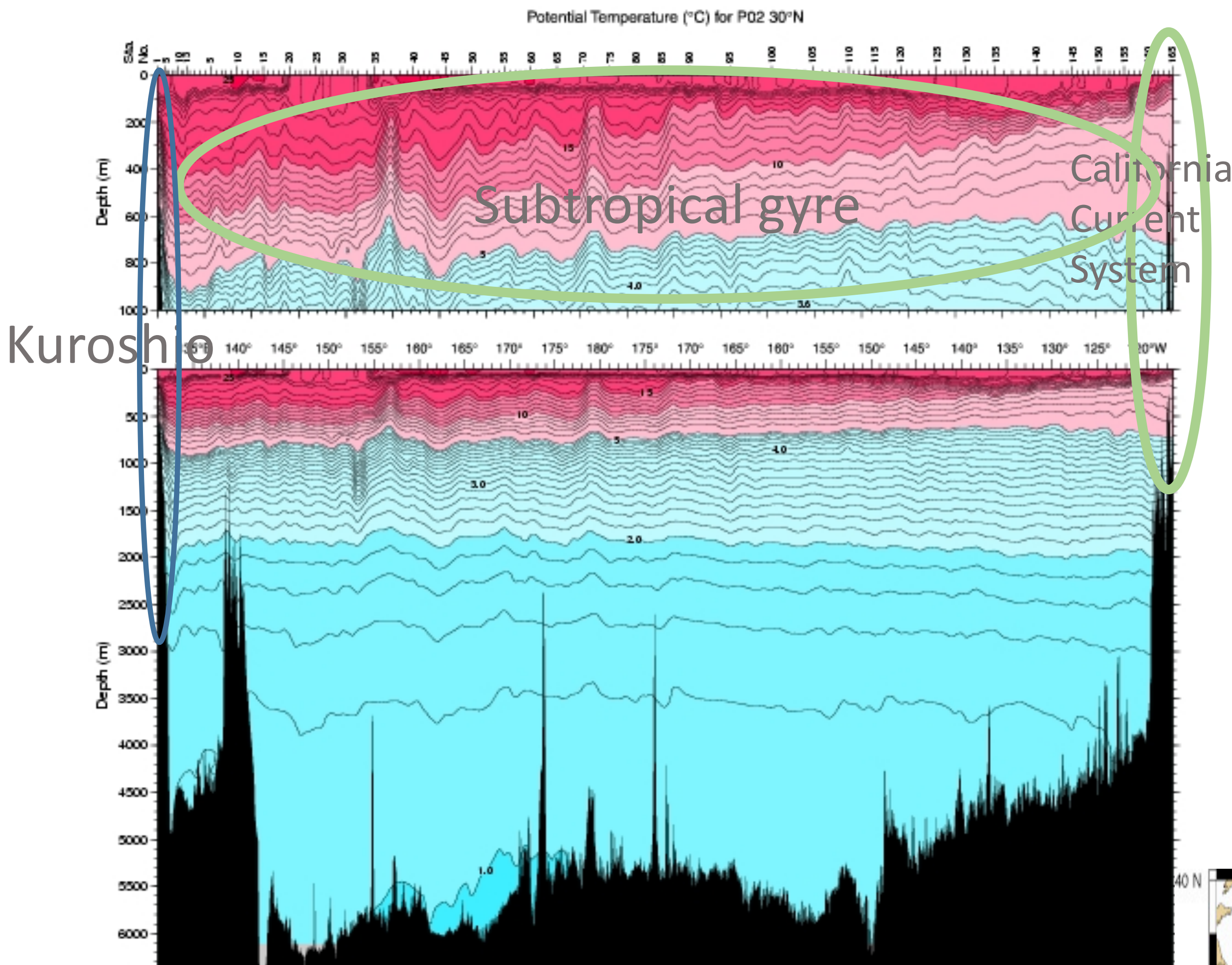
Shift in subtropical gyre with increasing depth:

- Gyre shrinks towards northern side and towards west
- C-shape disappears

At 1000 dbar, even Kuroshio not clear

DPO FIGURE 10.2 and 10.10

Reid (1997)



From WHP Pacific Atlas (Talley, 2007)

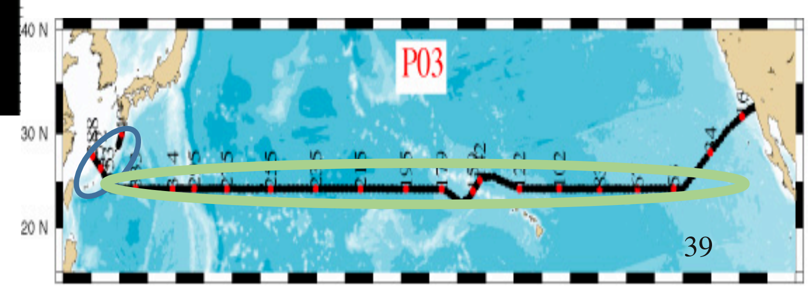
http://www-pord.ucsd.edu/whp_atlas

Vertical structure of the geostrophic subtropical gyre circulation (thermal wind)

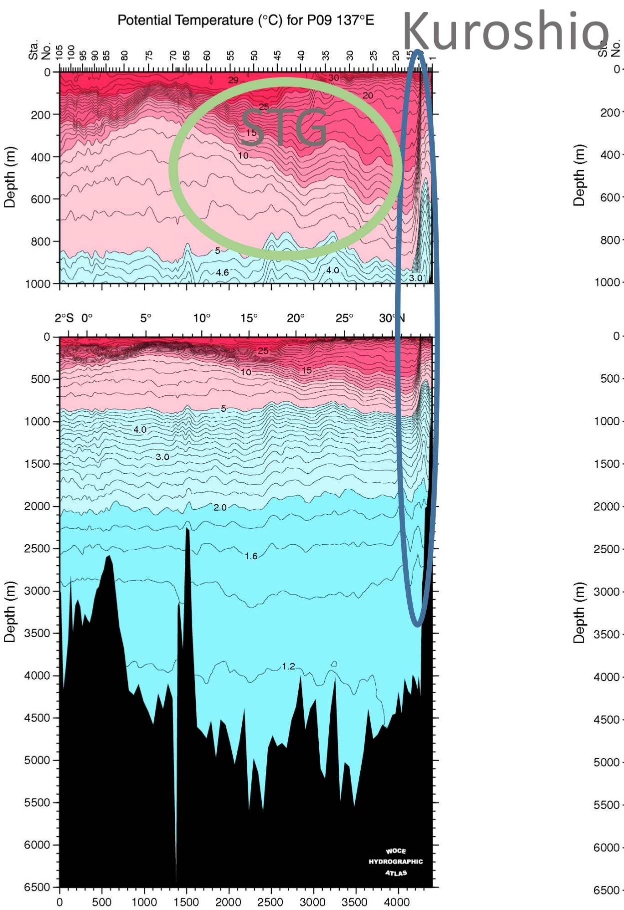
Zonal section

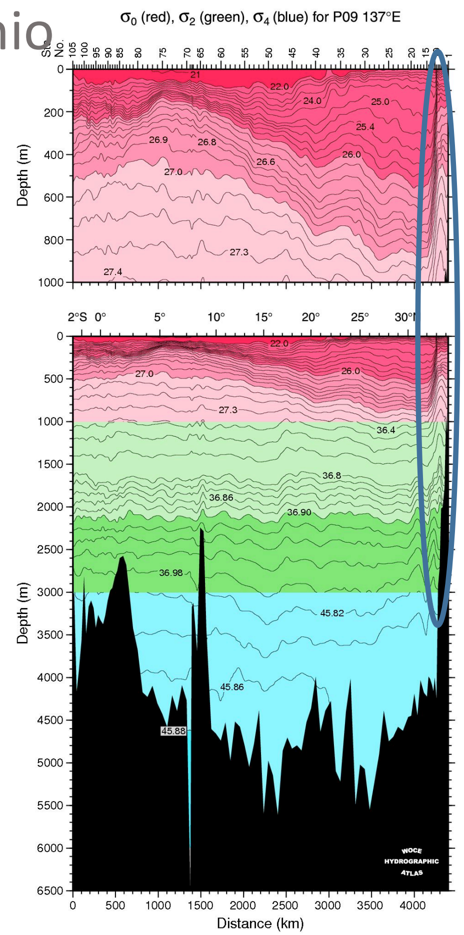
Kuroshio: very narrow downward isotherm tilt at western boundary. (northward)

Subtropical gyre (upper 800 m): isotherms tilt generally upwards towards the east. (southward)



Vertical structure: thermal wind (geostrophic shear)





Meridional section

Kuroshio: steep isotherm tilt at northern boundary. (eastward)

Subtropical gyre (upper 800 m): isotherms tilt generally upwards towards the south. (westward)