AOS 103

Study Aid Slides: Final

Some important stuff to know for the final…but not totally comprehensive

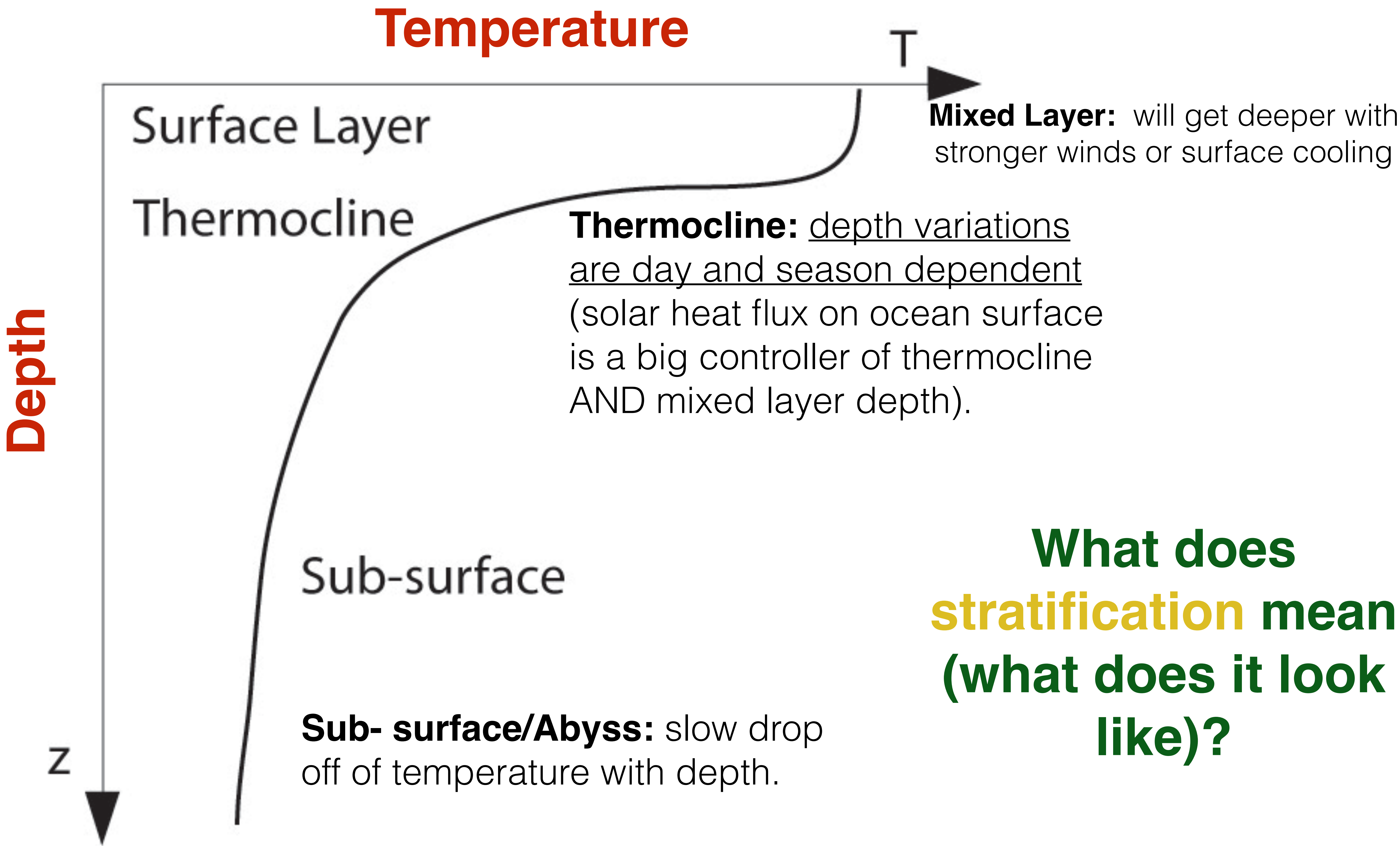
USE THIS AS A REFERENCE FOR CONCEPTS YOU MAY NOT UNDERSTAND BY LOOKING AT THE LECTURE SLIDES/HW

DO NOT JUST TRY TO MEMORIZE THESE OR THE LECTURE SLIDES

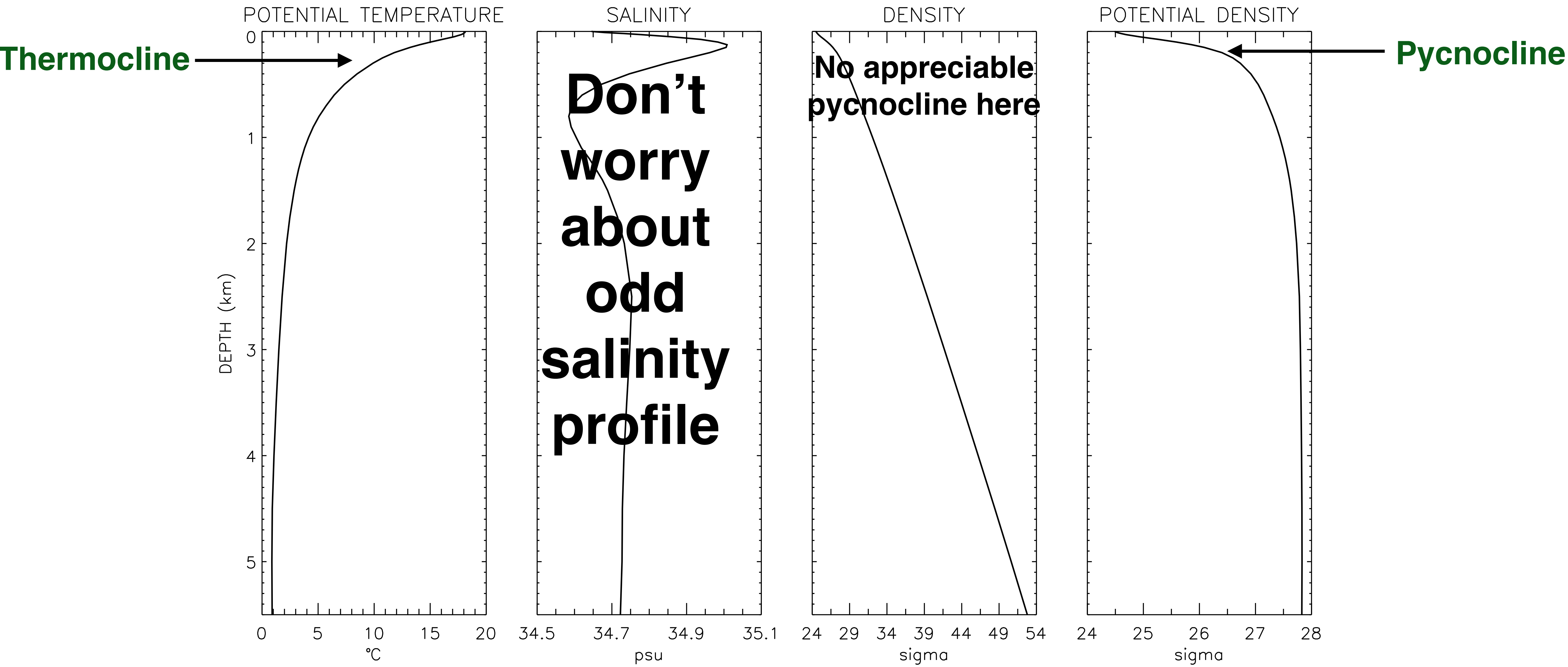
Topics you should know/understand and <u>be able to apply</u>

- Ocean geography
  - sea floor topography, name of oceans, major currents
- Temperature, salinity, density
  - equation of state
  - gravitational stability (stratified vs unstratified)
  - potential vs in situ (for temperature and density)
  - Global patterns and what controls them
- Surface heat fluxes
  - sensible, latent, radiative
- Conservation laws
  - IN = OUT of anything
- Barotropic vs baroclinic
- Pressure
- Coriolis Force
- Hydrostatic Balance
- Geostrophic Balance
- Ekman Balance
- Relative and planetary vorticity (cyclonic vs anticylonic)
- Potential Vorticity
  - what kinds of flows are due to PV conservation
- Gyre circulation
  - Ekman + Geostrophy + PV
  - Western boundary currents
- Water masses
  - formation, location, materially conserved tracers, transformation between water masses
  - Water mass geography
- ACC
  - role of Ekman and geostrophy in the ACC
  - ACC fronts
- Waves
  - Characterizing waves via dispersion relation
  - surface, internal, Kelvin, Rossby
    - Generation, what medium they propagate on, restoring force
  - Stokes Drift/transport due to waves
- Observations and modeling
  - Types of observations
  - application and limitations of both (observations and models)
  - Aliasing
- Mesoscale eddies
  - instabilities that cause to eddies
  - force balance of eddies
  - types of eddies
  - effects of eddies
- Tides
  - Tidal producing forces (tidal bulge)
  - Amphidromic points
  - Bill O'Reilly's thoughts on tides
  - Kelvin (tidal) wave propagation
- Coastal Ocean
  - Geography of coastal ocean (shelf, slope, canyons)
  - Slope Currents
  - Topographic Rossby waves
  - Shelf vertical profile of T,S,density
  - Surf zones: longshore and rip currents due to waves
  - Wave refraction
  - Tsunamis
- El Nino/La Nina
  - equatorial view of winds, sea surface, thermocline and how it varies during ENSO phases
  - teleconnections
- Ocean and Climate

***This is a list of general topics, do not assume this is completely exhaustive (although it is close)



What does a vertical temperature profile look like during the day (strong surface heating) and night (strong surface cooling)?



- Increase in density with depth at large depths is not present in potential density
- **Pycnocline** present in potential density profile and **thermocline** present in potential temperature profile
- **Potential temperature and potential density are CONSERVED (as they follow the flow)**, which also makes these good quantities to trace water masses…

With the realization that compressibility (pressure influence on density) is negligible for the ocean currents we care about, we can form a more dynamically meaningful measure of density and temperature:

Potential Density

- Removes effect of compressibility

$$\rho_{pot} = \rho(S, \Theta, p_{atmosphere}) - 1000\text{kg/m}^3$$

$\rho_{pot} = \text{potential density}$

$\text{S} = \text{salinity}, \ \Theta = \text{potential temperature}$

$p_{atmosphere} = \text{pressure of atmosphere}$

Potential Temperature

- **Compression by pressure** can change density —> changing the density changes the mass, which changes the internal energy, which can lead to a change in temperature

$$E = mC_pT$$

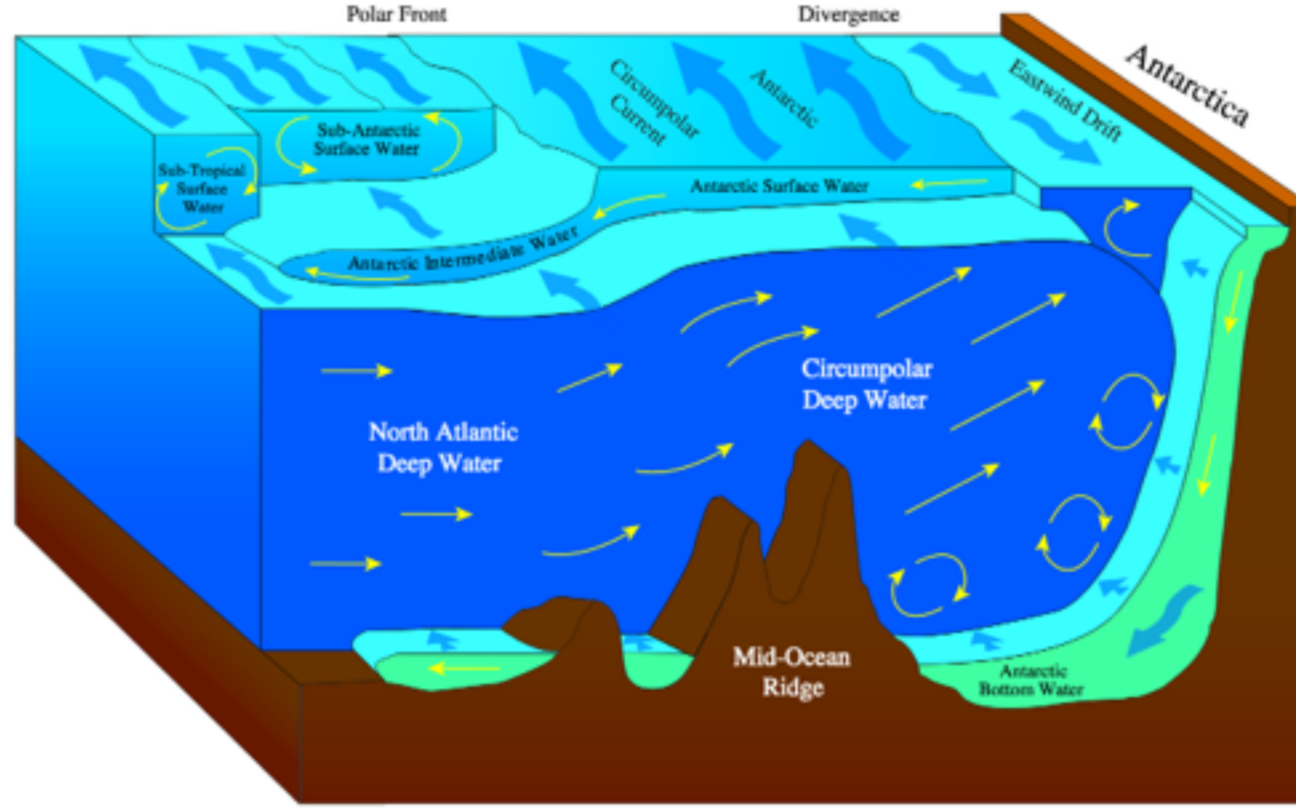
- Potential temperature **removes effect of compressibility**

Both potential density and potential temperature lead to simpler measures of water column stability!

Water Masses

- Observing (taking measurements of) the entire ocean (all of its horizontal and vertical expanse) is essentially impossible.

- Water masses provide a way of geographically defining the ocean with limited observation



Things to care about for a water mass

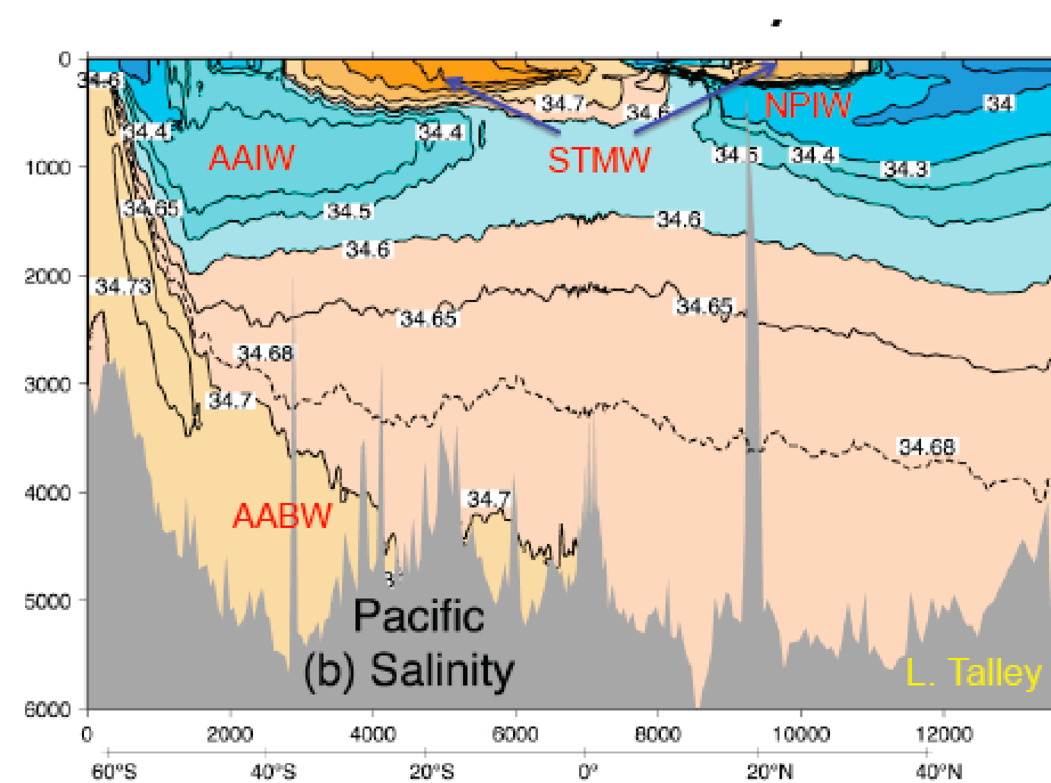
1) Where it is formed (**origin**)

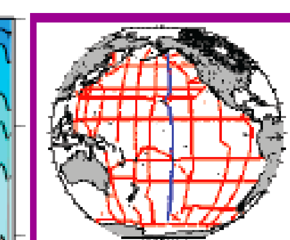
2) How it is formed (**mechanism**)

3) What properties are conserved as they flow with the water mass (**tracers**)

4) What depths does it travel through (**depth: surface, intermediate, bottom**)

5) Where does it end up (**destination**)





STMW=Subtropical Mode Water

NPIW=North Pacific Intermediate Water

AAIW=Antarctic Intermediate Water

AABW=Antarctic Bottom Water

Planetary Geostrophic Momentum Equations

(F = ma) / volume $\rho_0 = \text{constant}$

$$\frac{\partial p}{\partial x} = \rho_0 f v$$

x-direction balance

Pressure gradients in x-direction and **Coriolis force** drive currents in y-direction (v)

$$\frac{\partial p}{\partial y} = -\rho_0 f u$$

y-direction balance

Pressure gradients in y-direction and **Coriolis force** drive currents in x-direction (u)

$$\frac{\partial p}{\partial z} = -\rho g$$

z-direction balance

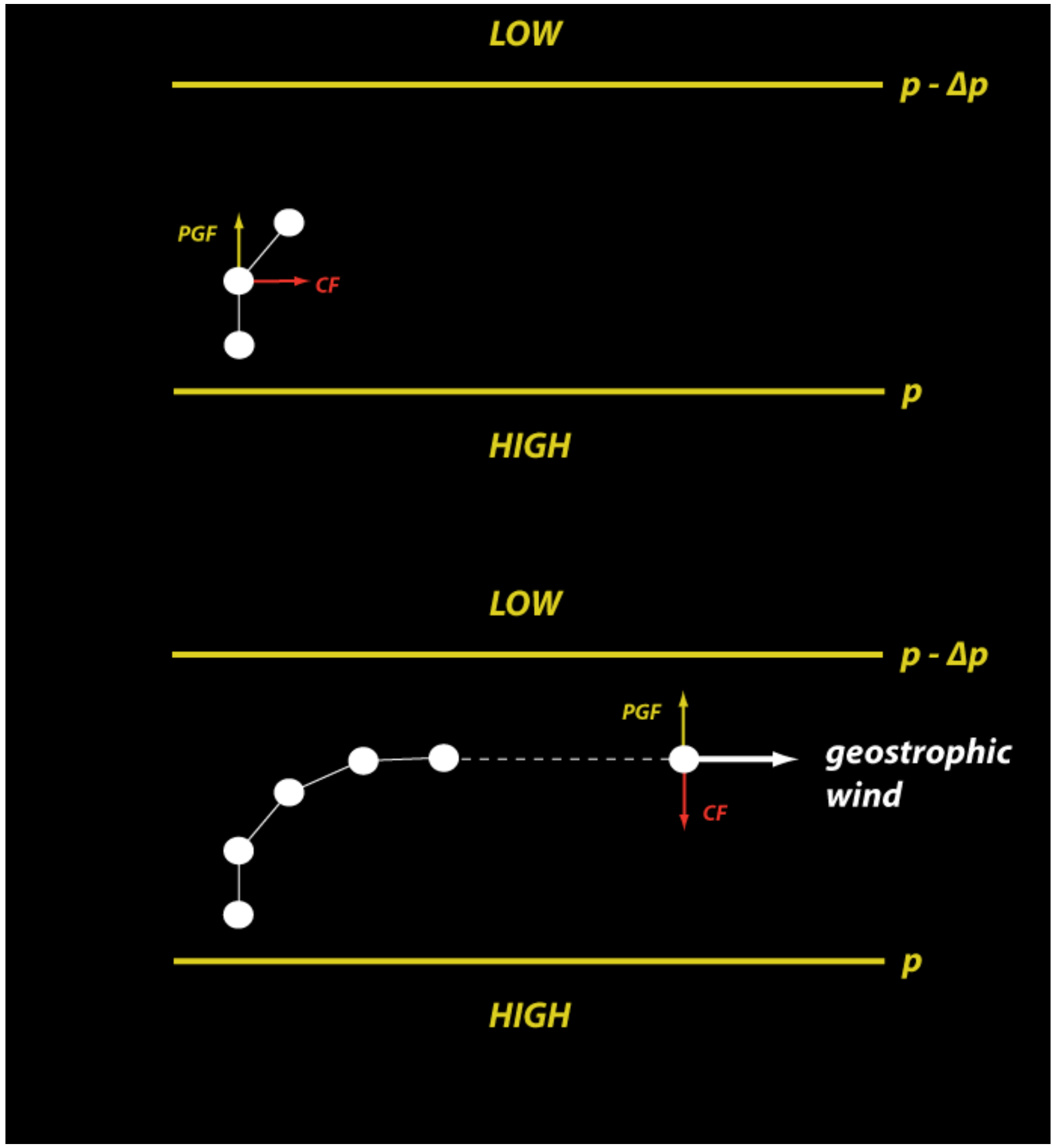
Pressure at any depth is equal to the weight of the fluid above it

"Hydrostatic"

"hydro" = water; "static" = not moving up or down

These equations mean nothing without a physical interpretation…

Geostrophic System (North Hemi)



An air (or water) parcel in this system is being acted on by 2 forces

1) **Pressure gradient force (PGF)**
2) **Coriolis force (CF)**

- **The PGF wants to push the parcel from the HIGH to LOW pressure bars (bottom to top)**
- **The CF wants to make the air parcel deflect to the RIGHT (we're in the NH) of its flow at any point**
- **Once the parcel adjusts to both forces, it ends up flowing in between the lines of constant pressure (this is geostrophic flow)**

Geostrophy is a BALANCE (PGF = CF), so the air parcel ends up flowing IN BETWEEN the lines of constant pressure

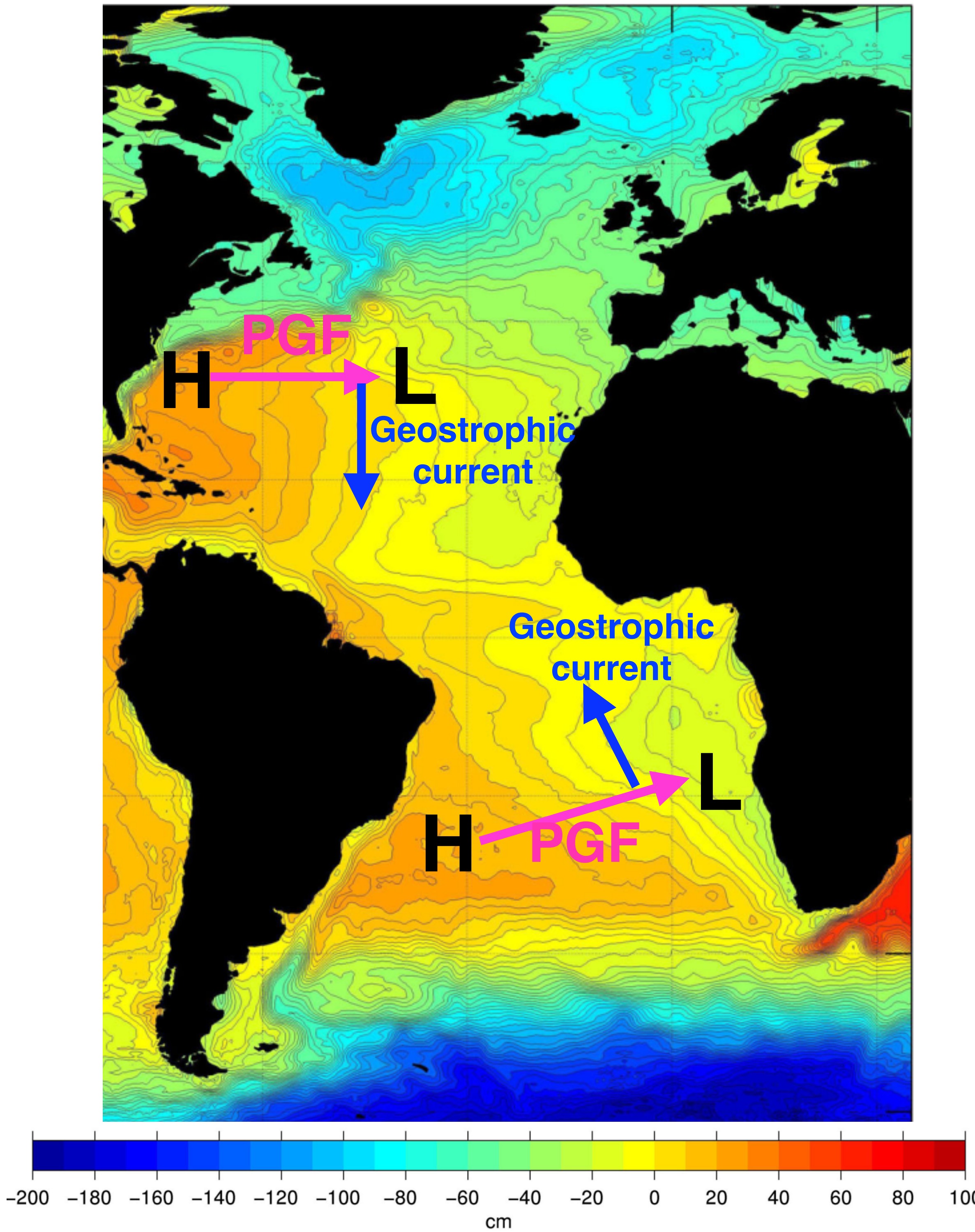
***We say geostrophic flows run "parallel to isobars" (isobar = line of constant pressure)**

***Geostrophic rule of thumb: in NH with geostrophic wind at your back, low pressure is to your LEFT (in SH, low pressure is to your right)**

Inferring geostrophic velocity

1) Sea surface height map (x,y)

- Determine what direction the pressure gradients vectors are pointing (the PGF arrows point from HIGH pressure to LOW pressure = HIGH sea surface elevation to LOW sea surface elevation (red to blue))
- Draw your PGF arrow that points from HIGH to LOW pressure
- If you are in the NH, the geostrophic current is an vector directed to the RIGHT of your PGF arrow(vector)
- If you are in the SH, the geostrophic current is a vector directed to the LEFT of your PGF arrow(vector)



Time-averaged sea surface elevation [cm]

Rules of Thumb

KNOW THESE FOR EXAM!

Northern Hemisphere

-Coriolis force deflects flows to the **RIGHT**

-Geostrophic flow is to the **RIGHT** of an arrow pointing from high to low pressure (i.e. the direction the water wants to flow due to the pressure gradient force)

-Ekman transport is to the **RIGHT** of surface wind stress

Southern Hemisphere

-Coriolis force deflects flows to the **LEFT**

-Geostrophic flow is to the **LEFT** of an arrow pointing from high to low pressure (i.e. the direction the water wants to flow due to the pressure gradient force)

-Ekman transport is to the **LEFT** of surface wind stress

Terminology

Pressure gradient: points from low to high pressure
Pressure gradient force: points from high to low pressure

Advice to not confuse yourself: when thinking of geostrophic velocities draw/think of arrows pointing in the direction of the pressure gradient FORCE (HIGH to LOW)…this will make it more intuitive to deduce geostrophic velocity from that

North Hemi: geostrophic velocity will flow to the RIGHT of the pressure gradient force (HIGH TO LOW arrow)

Thermal Wind: How do geostrophic velocities vary with depth??

$$\frac{\partial v}{\partial z} = \frac{-g}{\rho_0 f}\frac{\partial \rho}{\partial x}$$

Vertical variation (shear) of geostrophic velocity in the y-direction

Horizontal gradient of density in the x-direction

x-component

Thermal wind relates horizontal density gradients to vertical changes in the geostrophic velocity (which is a horizontal flow)

$$\frac{\partial u}{\partial z} = \frac{g}{\rho_0 f}\frac{\partial \rho}{\partial y}$$

Vertical variation (shear) of geostrophic velocity in the x-direction

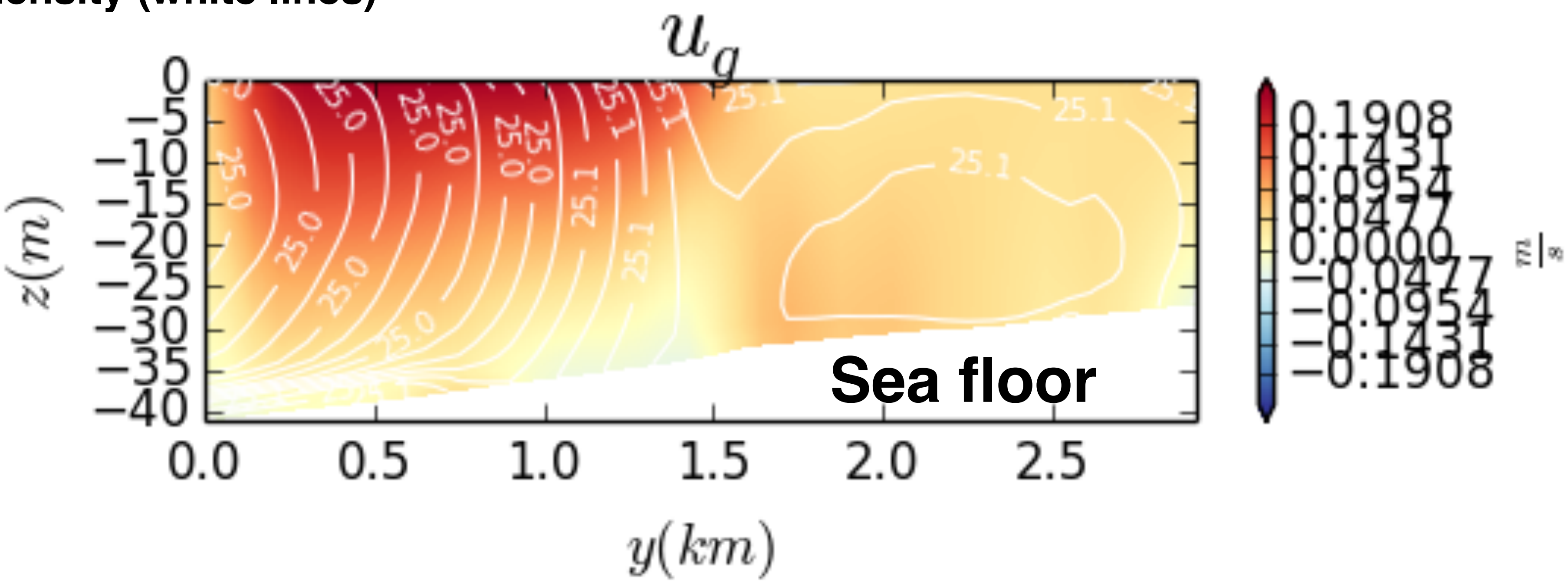
Horizontal gradient of density in the y-direction

y-component

You DO need to understand this relationship for the exam!!!

Thermal Wind: Interpreting Data/Plots

This plot shows a ‘cross-section’ of geostrophic velocity (colors) and density (white lines)



****This is an example of a baroclinic current b/c it has vertical variation (i.e. the velocity is not constant with depth)

$$\frac{\partial u}{\partial z} = \frac{g}{\rho_0 f}\frac{\partial \rho}{\partial y}$$

$u_g \longrightarrow$ geostrophic velocity in or out of page (red means out of page, blue means into page), its the same as “u” in the equation above

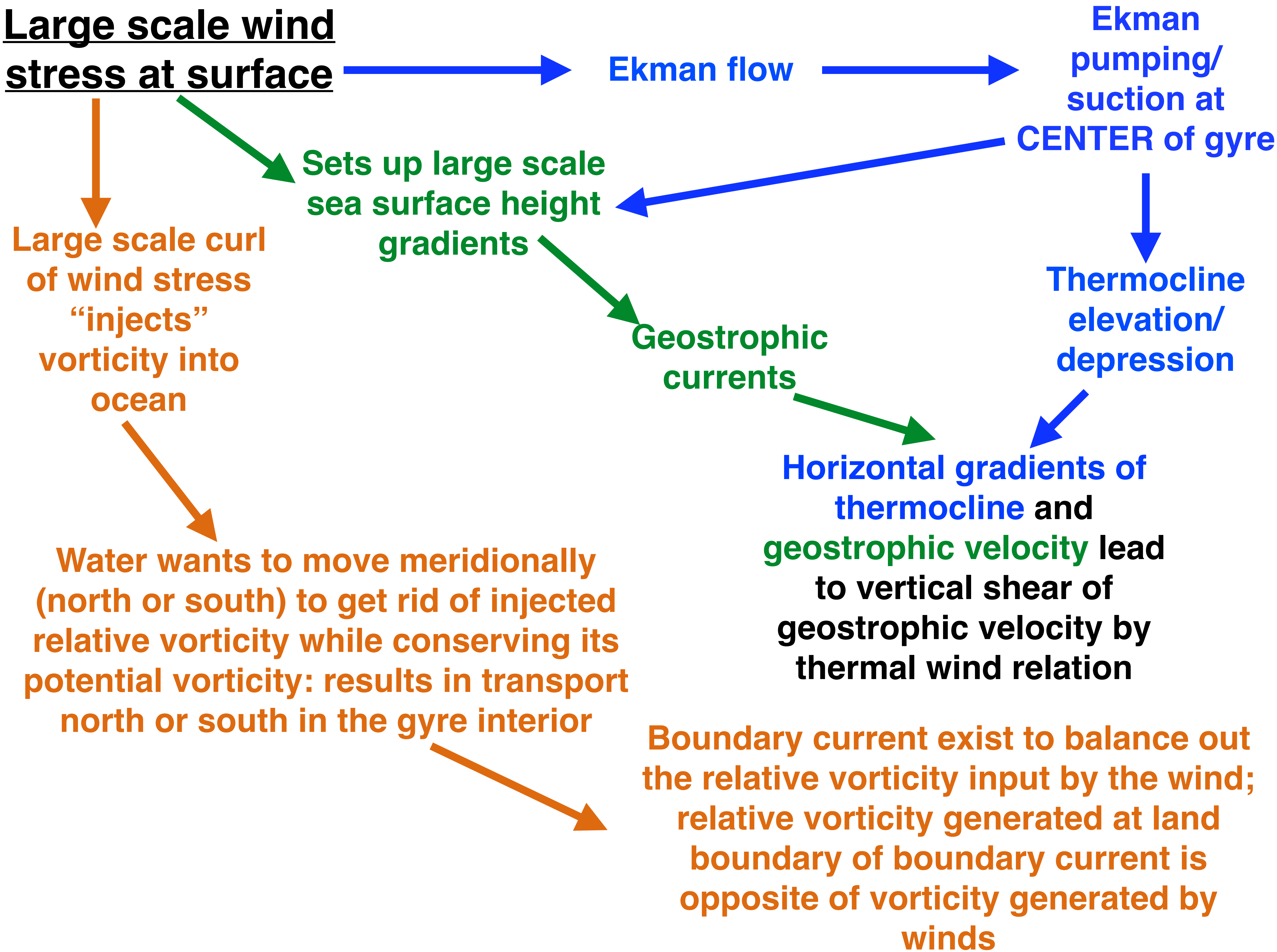
- Because there is a horizontal density gradient along the y-axis, the geostrophic velocity (that goes in or out of the page) has vertical shear (i.e. it increases or decreases with depth)
-In this case, the geostrophic velocity DECREASES with depth on the left half of the plotted domain

******The reason why the velocity is stronger (and the shear more pronounced) on the left side of the plot is because the horizontal density gradient is stronger there…the white lines are vertical and close together, so if you were to step from left to right along the y-axis, density would be changing very rapidly from y=0 to y=1.5km; but from y=1.5km to y=3.0km (the right side), the density gradient is pretty small, so the geostrophic velocity and subsequent vertical shear of geostrophic velocity is relatively smaller and less noticeable there.

Gyres

There are 3 main types of dynamics going on in gyres that can all be traced back to the wind stress (in conjunction with Coriolis force):

1) Ekman dynamics (Ekman flow/transport and Ekman pumping/suction)
2) Geostrophic currents due to sea surface height gradients
3) North/south transport in center of gyre and at land boundaries due to potential vorticity conservation



Large scale wind stress at surface
Ekman flow
Ekman pumping/ suction at CENTER of gyre
Sets up large scale sea surface height gradients
Large scale curl of wind stress “injects” vorticity into ocean
Thermocline elevation/ depression
Geostrophic currents
Horizontal gradients of thermocline and geostrophic velocity lead to vertical shear of geostrophic velocity by thermal wind relation
Water wants to move meridionally (north or south) to get rid of injected relative vorticity while conserving its potential vorticity: results in transport north or south in the gyre interior
Boundary current exist to balance out the relative vorticity input by the wind; relative vorticity generated at land boundary of boundary current is opposite of vorticity generated by winds

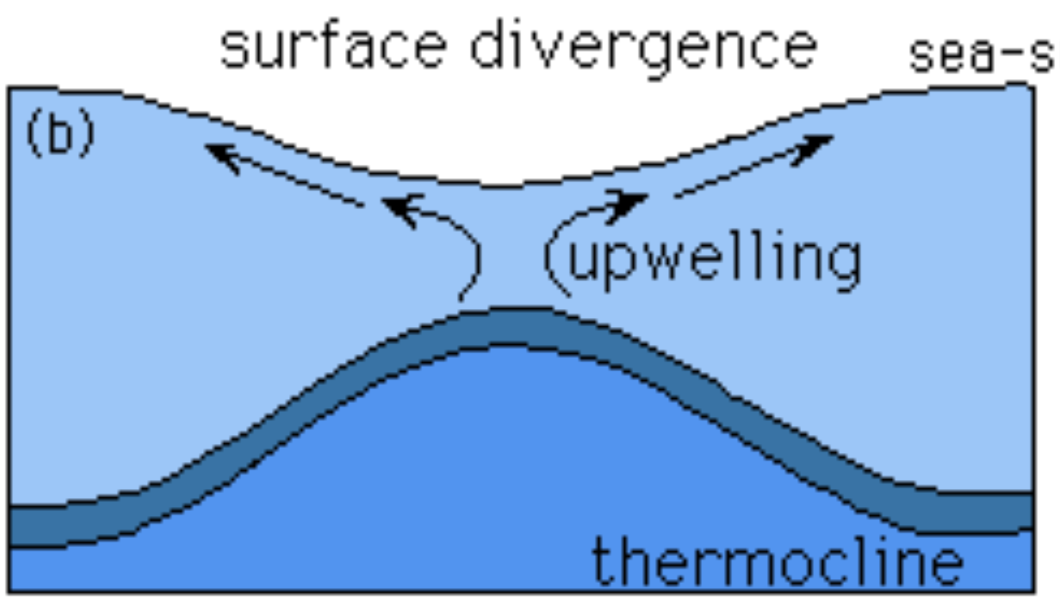
For any gyre:

- **Start with the large scale atmospheric pressure**
- **Deduce the geostrophic atmospheric wind from this pressure**
- **Use the wind pattern to infer Ekman transport (it will go into our out of the gyre radially)**
- **Use the direction of Ekman transport to infer whether there is upwelling (suction) or downwelling (pumping) at the center of the gyre**
    - **Essentially answer this question: is there convergence or divergence of water at the center of the gyre?**
- **Use this behavior at the center of the gyre to infer what the thermocline and sea surface height are doing**
- **Use the sea surface height to infer which way the surface pressure gradient forces want to push water**
- **Use these pressure gradient forces to infer a geostrophic current**
- **The horizontal variation of the thermocline combined with a geostrophic current will mean that the geostrophic current will have vertical shear (increase or decrease) with depth due to the thermal wind balance**
- **The final piece of the gyre story is the boundary current…figure out the sign of vorticity that the wind is inputting to the gyre and what type of boundary current would be needed to balance that out**

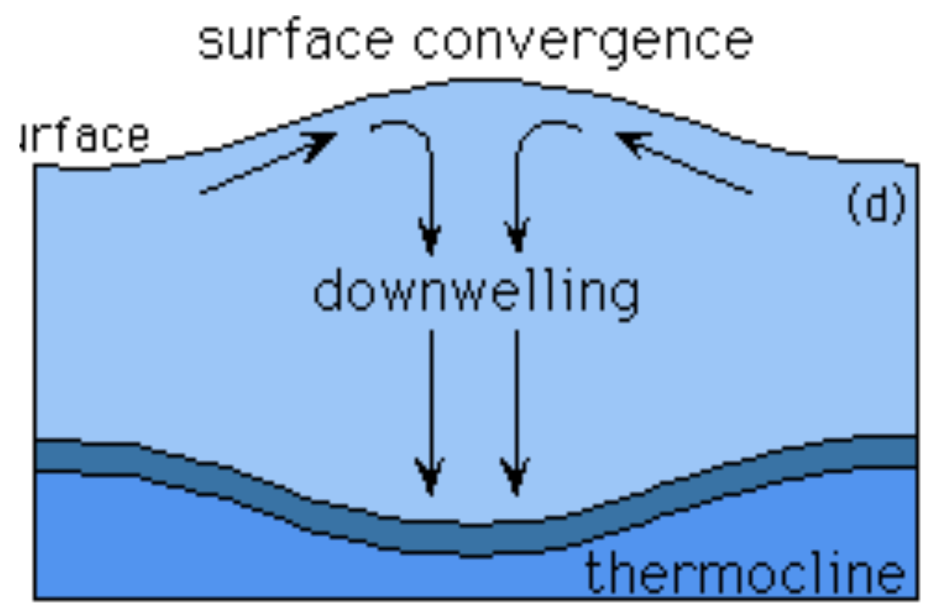
Thermocline and sea surface height response to Ekman pumping/suction

Upwelling (due to surface divergence) = SUCTION
- thermocline raised up
- sea surface depressed

Downwelling (due to surface convergence) = PUMPING
- thermocline depressed
- sea surface raised up



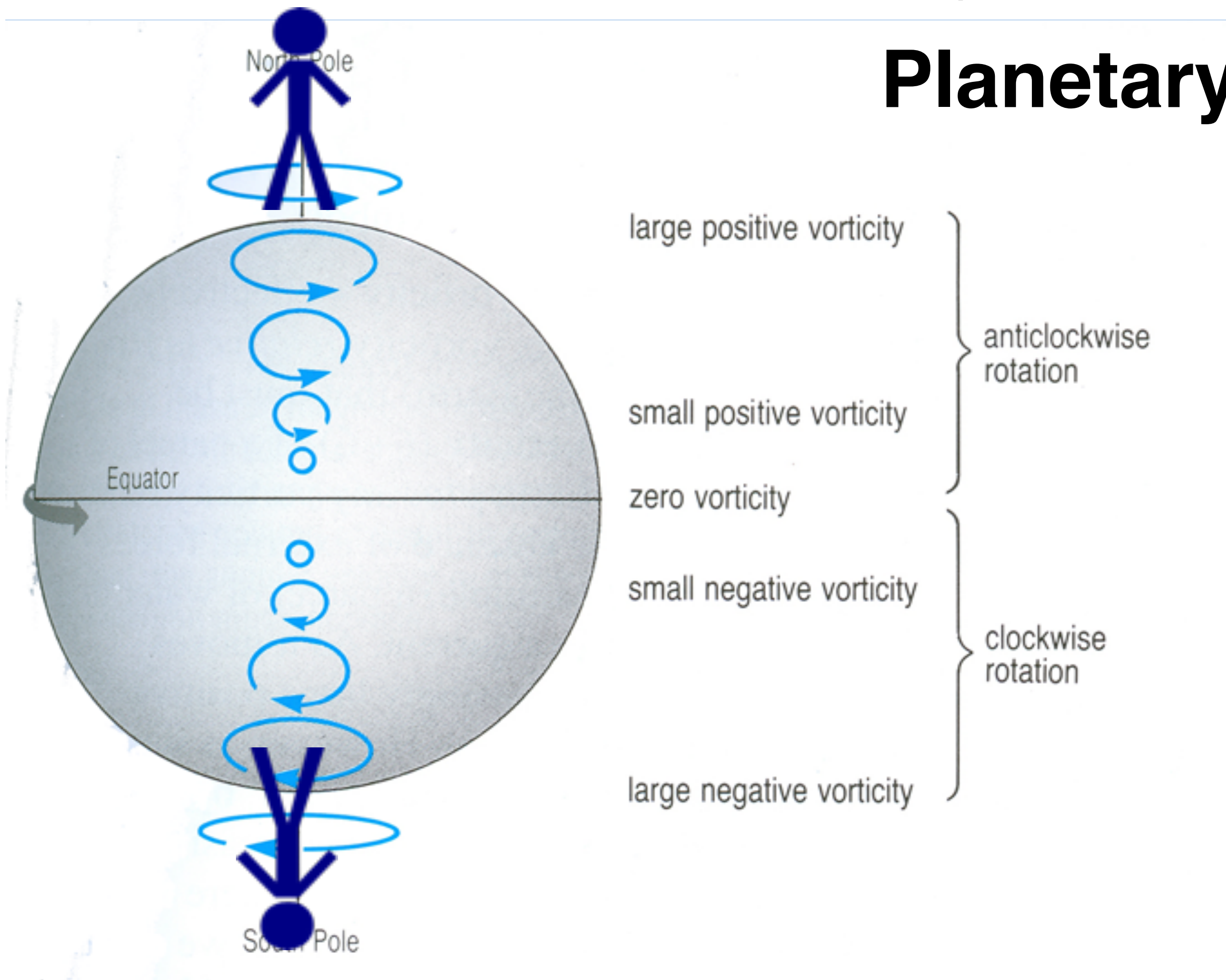
What's the geostrophic velocity?
(pick a hemisphere)



What's the geostrophic velocity?
(pick a hemisphere)

Planetary Vorticity

Because the Earth is always rotating, everything in it always has some vorticity. We call this vorticity "planetary vorticity", simply b/c it is due to the planet's own rotation.



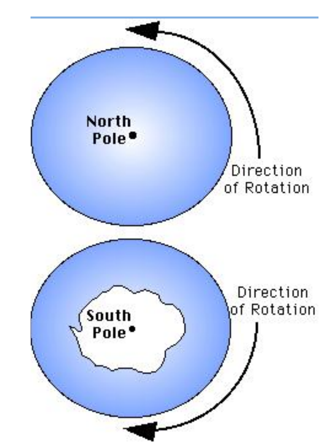
Planetary vorticity = Coriolis parameter = f

Units: [1/s]

NH - counterclockwise = cyclonic

SH - clockwise = cyclonic

"Cyclonic" always refers to having the same sense of planetary rotation. The "sense" of planetary rotation is opposite in each hemisphere. Thus cyclonic refers to counterclockwise rotation in the Northern Hemishphere (NH) and clockwise rotation in the Southern Hemisphere (SH)



Relative Vorticity

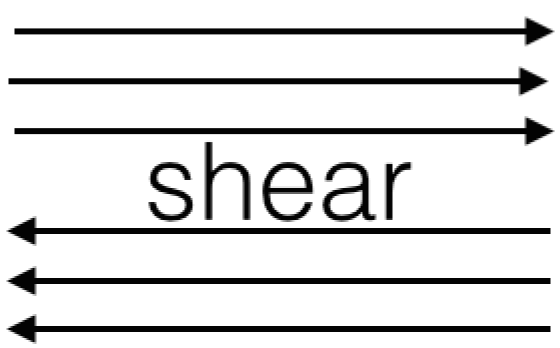
Relative Vorticity $\zeta = (\nabla \times \mathbf{v}) \cdot \hat{\mathbf{k}} = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$

Vertical component of curl of 3D velocity

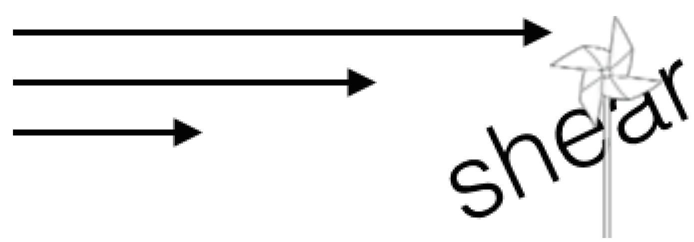
Just tells us how much rotation or shear a fluid is exhibiting in its horizontal velocities

Units: [1/s]

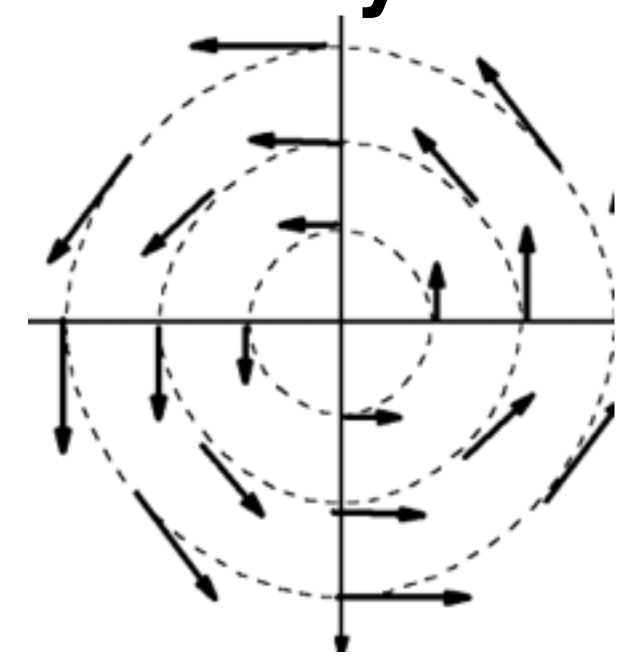
All 3 of these flow profiles have vorticity.



Clockwise



Clockwise



Counterclockwise

When we talk about vorticity we use the convention of saying whether or not the flow is "spinning" in a clockwise or counterclockwise manner…just imagine a pinwheel in the parts of the flow where there is shear and the way that pinwheel rotates.

For the North Hemi, what should the pressure in the center of this velocity field be if this were a geostrophic wind or current (high or low pressure)?

Absolute and Potential Vorticity (PV)

Absolute Vorticity: combine planetary and relative vorticity

$$\zeta_{relative} = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} = \zeta$$

$$\zeta_{planetary} = 2\Omega \sin(\phi) = f$$

$$\zeta_{absolute} = \zeta_{planetary} + \zeta_{relative} = f + \zeta$$

Potential Vorticity (PV)

But in the ocean we like to think about "water columns" that have depth…

We also know that if we have a "fluid column", we can change its vorticity by "stretching" it due to conservation of angular momentum…if we "stretch" out the column by making it taller, but more thin in diameter the vorticity will increase

So we need to incorporate this dependence of column height(depth) into our vorticity.

We include a depth-dependence with potential vorticity

Absolute vorticity

$$q = \frac{f + \zeta}{H}$$

Water column thickness (depth)

Cyclonic and Anticyclonic

	North Hemi	South Hemi
Cyclonic	Counterclockwise	Clockwise
Antiyclonic	Clockwise	Counterclockwise

Easiest way to remember: just memorize that the NH's cyclonic rotation is counterclockwise….if you remember that, you can remember all the other ones by knowing that the SH is the opposite for cyclonic and anticyclonic is just the opposite of cyclonic in each hemisphere

YOU NEED TO KNOW THIS FOR THE EXAM!

Best way to get familiar with it is to give yourself multiple examples: put a high or low pressure center in a hemisphere and draw the geostrophic wind around it and then say whether its cyclonic or anticyclonic for that hemisphere

PV Thinking/Deductions

The way these questions *will probably be worded* (ask Prof Stewart in Lecture tomorrow) is as follows:**

Case 1:

The winds (or something else) tend to increase the vorticity of the ocean and thereby increase its potential vorticity ($q \sim f/H$). In which which direction does this cause water columns to move (if H is constant)

Answer Case 1:

If q is being increased, then f must increase and this will cause northward movement

Case 2:

The winds (or something else) tend to decrease the vorticity of the ocean and thereby decrease its potential vorticity ($q \sim f/H$). In which which direction does this cause water columns to move (if H is constant)

Answer Case 2:

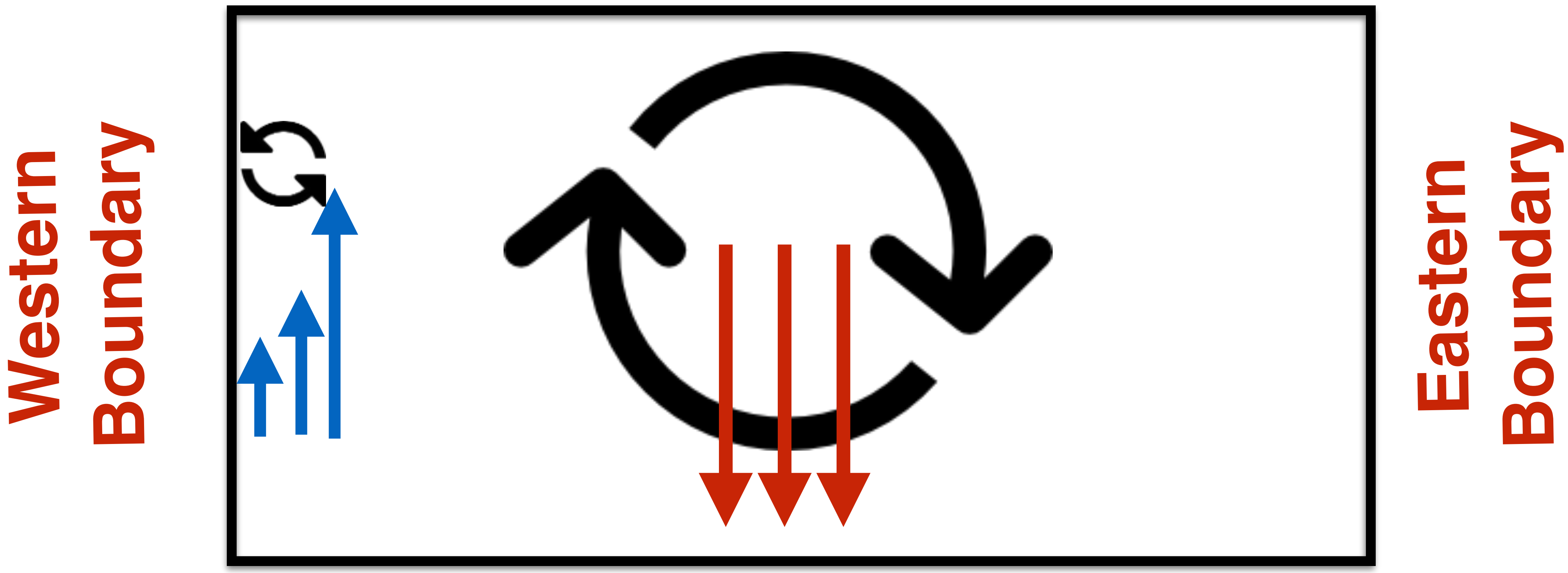
If q is being decreased, then f must decrease and this will cause southward movement

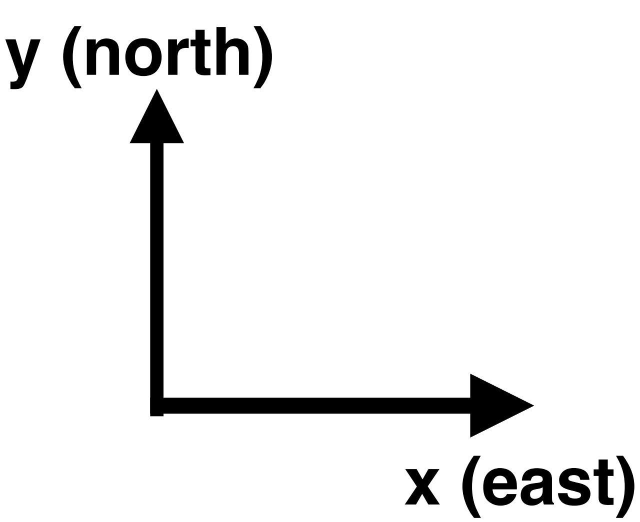
GETTING TO BOUNDARY CURRENTS FROM VORTICITY (RELATIVE AND POTENTIAL)

To balance out the negative vorticity input by the wind, the boundary current must create(supply) positive vorticity.

The western boundary current supplies this positive vorticity

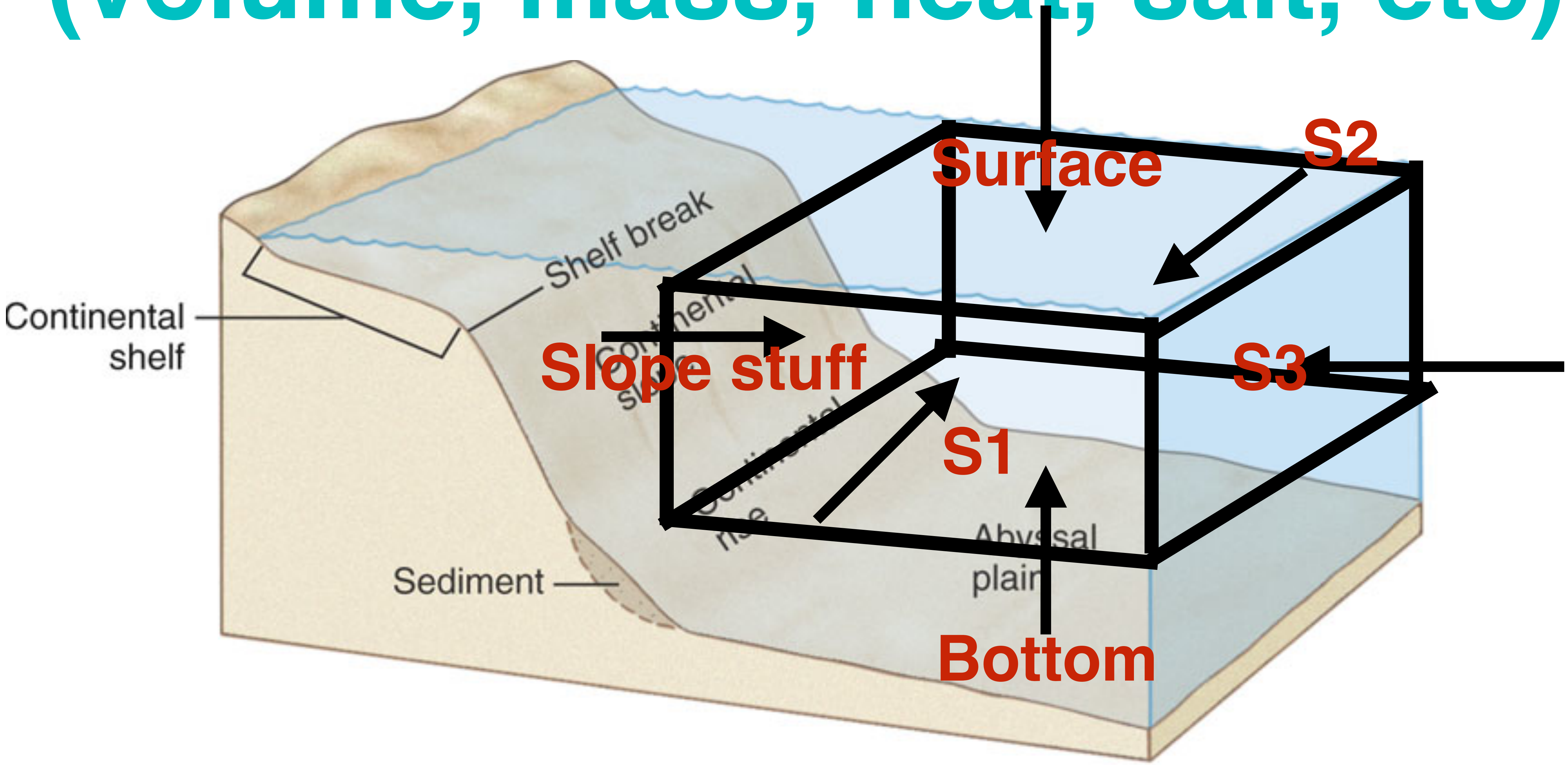
It exists to 1) conserve mass and 2) balance out the vorticity input by the wind





Interior transport: caused by Case 2 scenario on last slide (winds act to *decrease* potential vorticity)

Conservation of any Flux (volume, mass, heat, salt, etc)

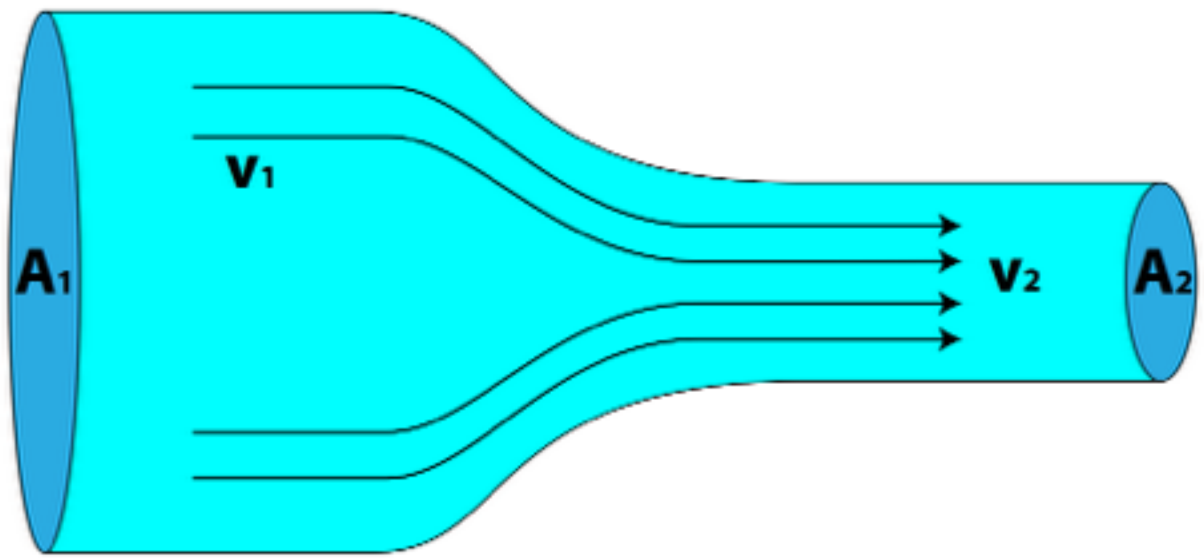


IN = OUT

ALL THE ARROWS NEED TO SUM TO ZERO

Conservation of Volume

We can use conservation of volume(or mass) to calculate the actual velocity of fluid going in and out of different areas (i.e. faces of a box), but you should ALWAYS FIRST be using this principle to give yourself an intuition of how a fluid flows in and out of different areas if it is conserving volume(mass)



IN = OUT

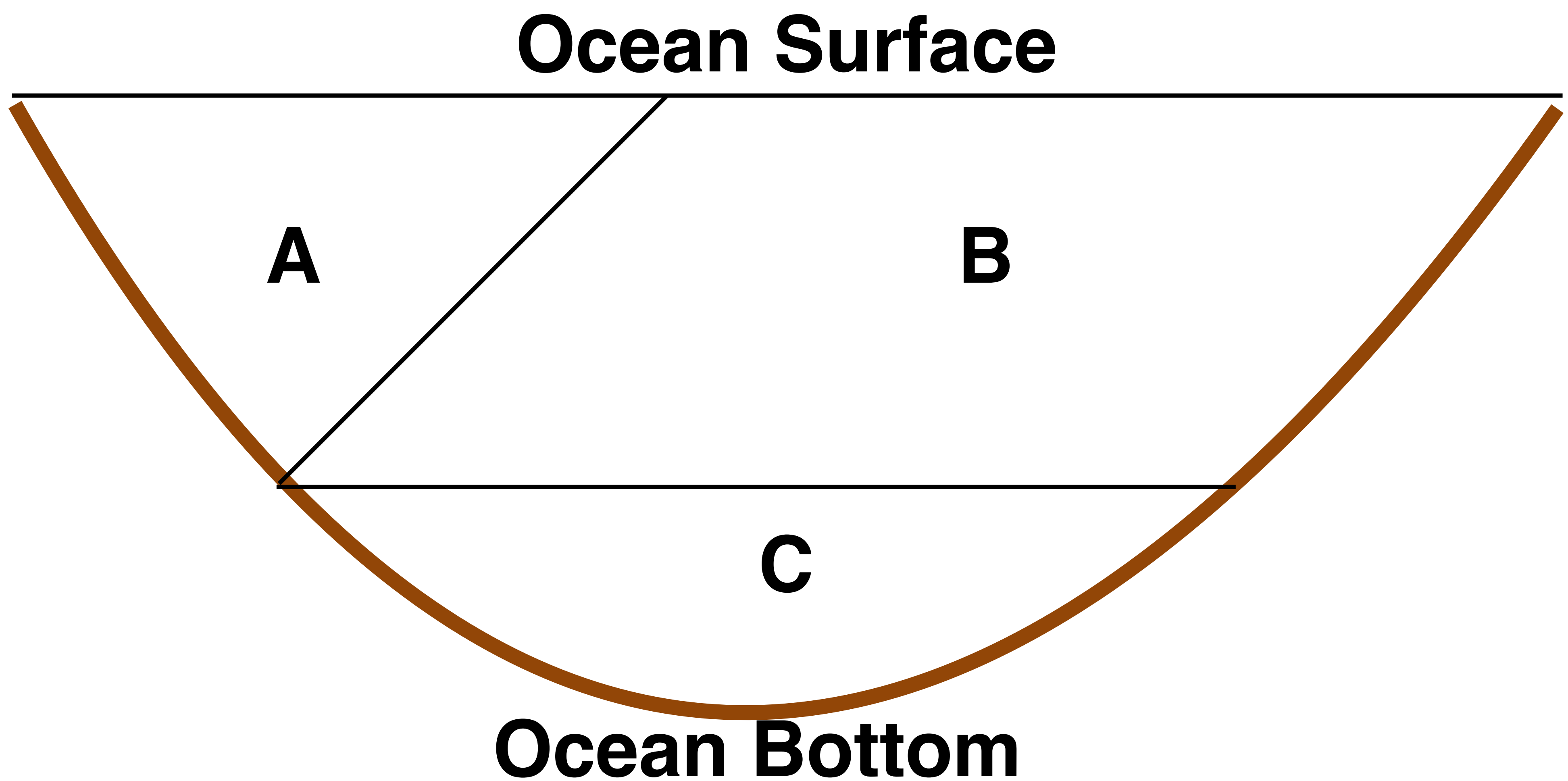
$$V_1 A_1 = V_2 A_2$$

1) **Do you expect V1 to be greater than or less than V2**
2) **Show why mathematically using the conservation of volume**

****So for any time you have a problem that has stuff (water, mass, etc) fluxing in and out of boxes, basins, any old shape…you will probably be able to figure out flow or transport using conservation of volume**

Conservation of Volume

Cross-section example to deduce direction of a flow



ψ **Volume transport**

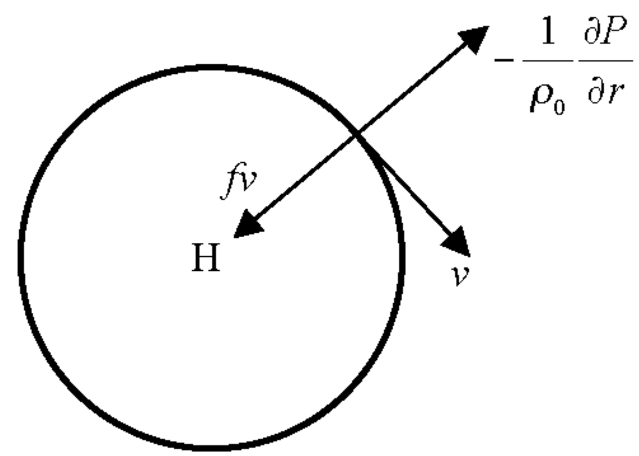
$\psi_A + \psi_B + \psi_C = 0$ **Conservation of Volume**

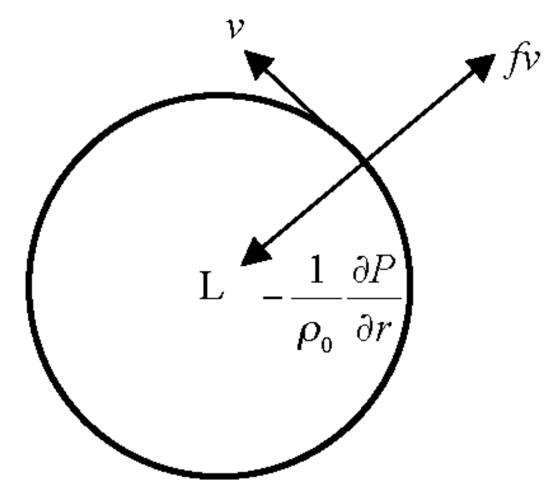
If we knew the direction of A and B, we could deduce the direction of C based on conservation of volume (e.g., if A and B were out of the page, C would have to be into the page).

Eddies

-Coherent vortices in the ocean that are approximately in geostrophic balance (PGF = CF)

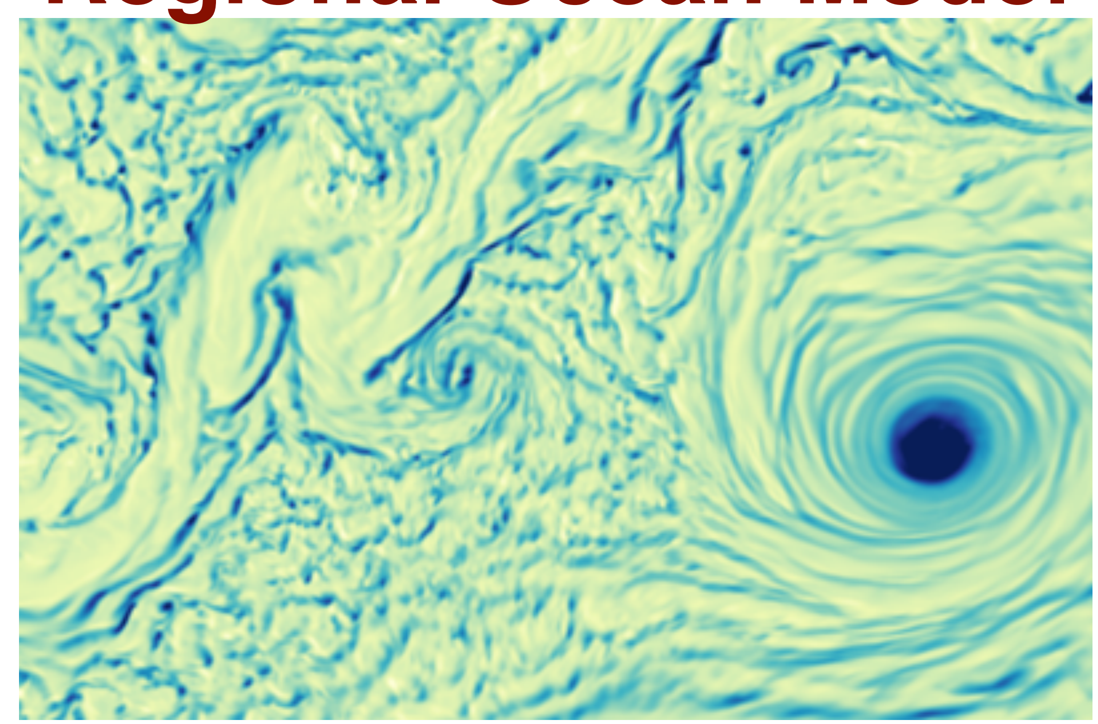
Study aid: convince yourself of these geostrophic flows





Real World

Regional Ocean Model



Can you tell if this North Hemi eddy is cyclonic or anticyclonic?

Eddy and Mean Components (mathematical definition)

Take a field and decompose it into 2 components:

1) Mean (average)
2) Fluctuations about the mean ("eddy")

$$v = < v > + v'$$

Field (for this example, velocity)

Mean (time or space)

Eddy component (deviation from the mean)

$$< v' > = 0$$

By definition, the mean(average) of a fluctuation (eddy) is zero

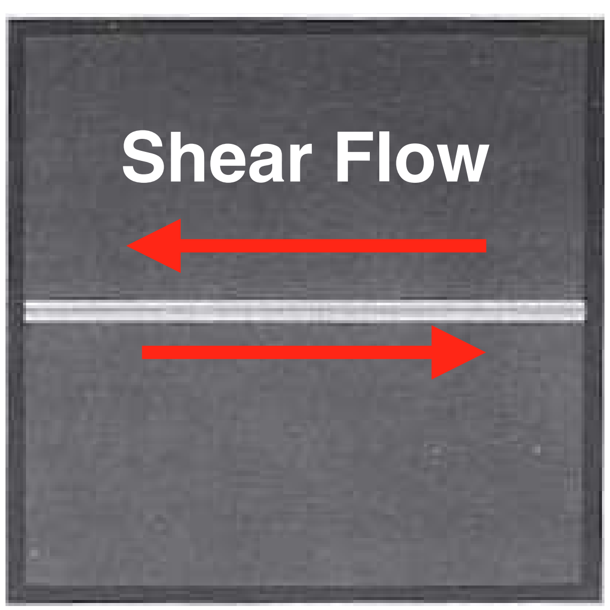
Barotropic Instability → horizontal shear is energy source for the eddy

-BAROTROPIC: this implies that there is no depth-dependence (i.e. we are in a horizontal 2D system)

-Barotropic instability occurs when there is a 2D (x,y) shear flow

-Perturbations (i.e. something that will disrupt the state of the flow) can amplify exponentially and lead to eddy (vortex) formation by ‘rolling up’ of the shear layer

(x,y) system with a shear flow



Step forward in time →

Step forward in time →

Vortex emergence due to barotropic instability

Baroclinic Instability → vertical shear and horizontal density(buoyancy) gradient are energy source for eddy

-2D instability but it has a DEPTH-DEPDENCE (that's what "baroclinic" means), so one of the dimensions must be depth (z-axis)

Vertical shear

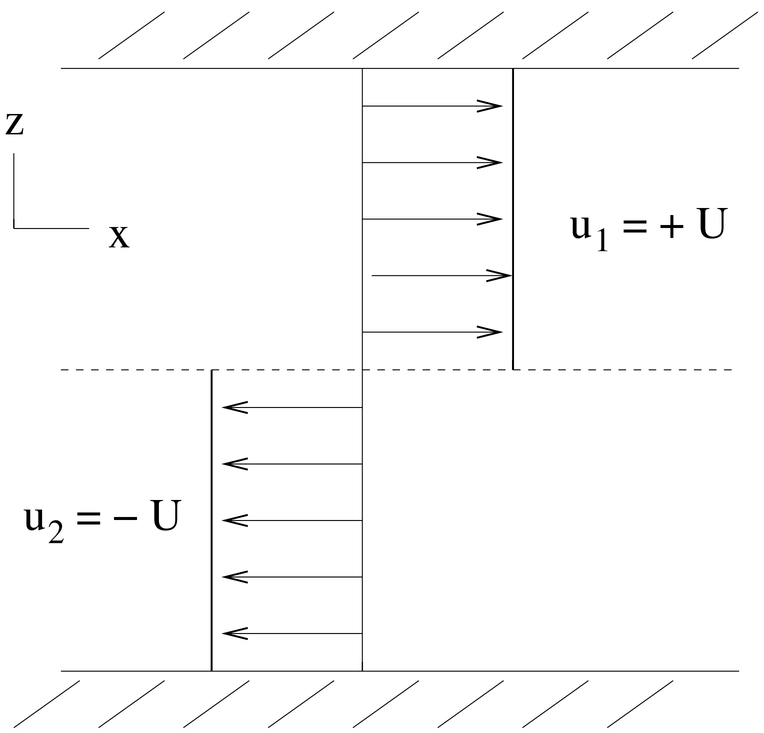
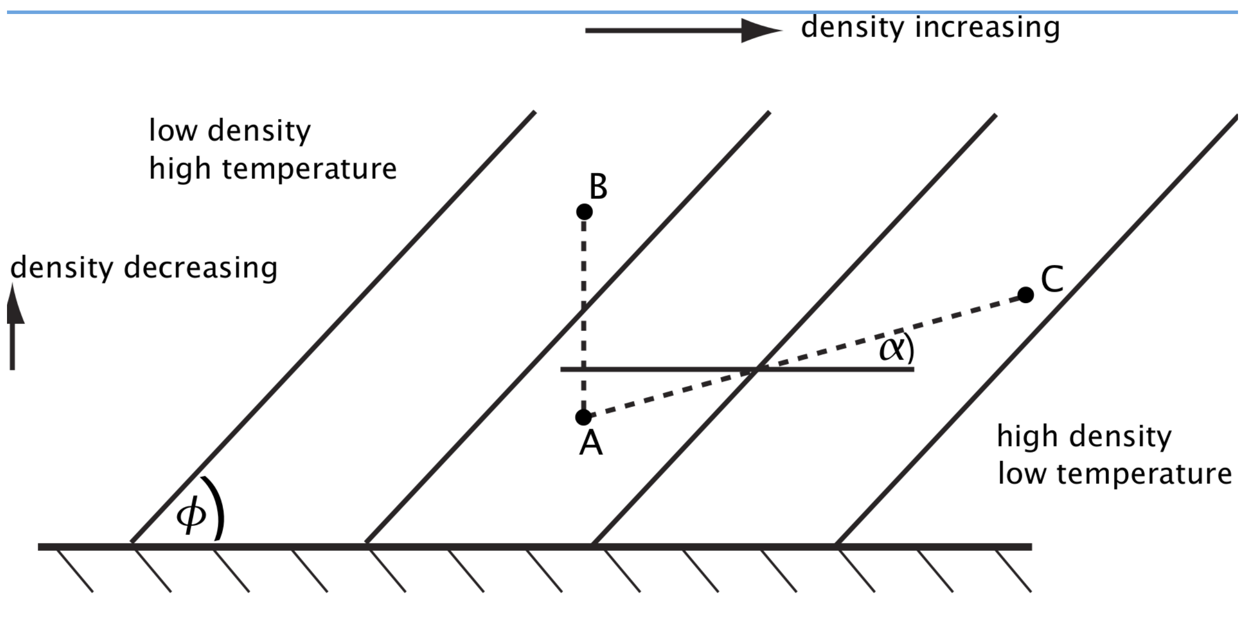


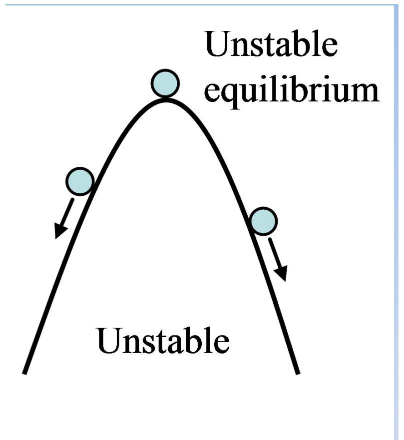
Fig. 5.4. Mean zonal baroclinic flow in a 2-layer fluid.

Horizontal density gradient



Potential Energy → $E_{pot} = \rho g z$

Let's relate this diagram for how unstable equilibrium works to the figure above on the right… →

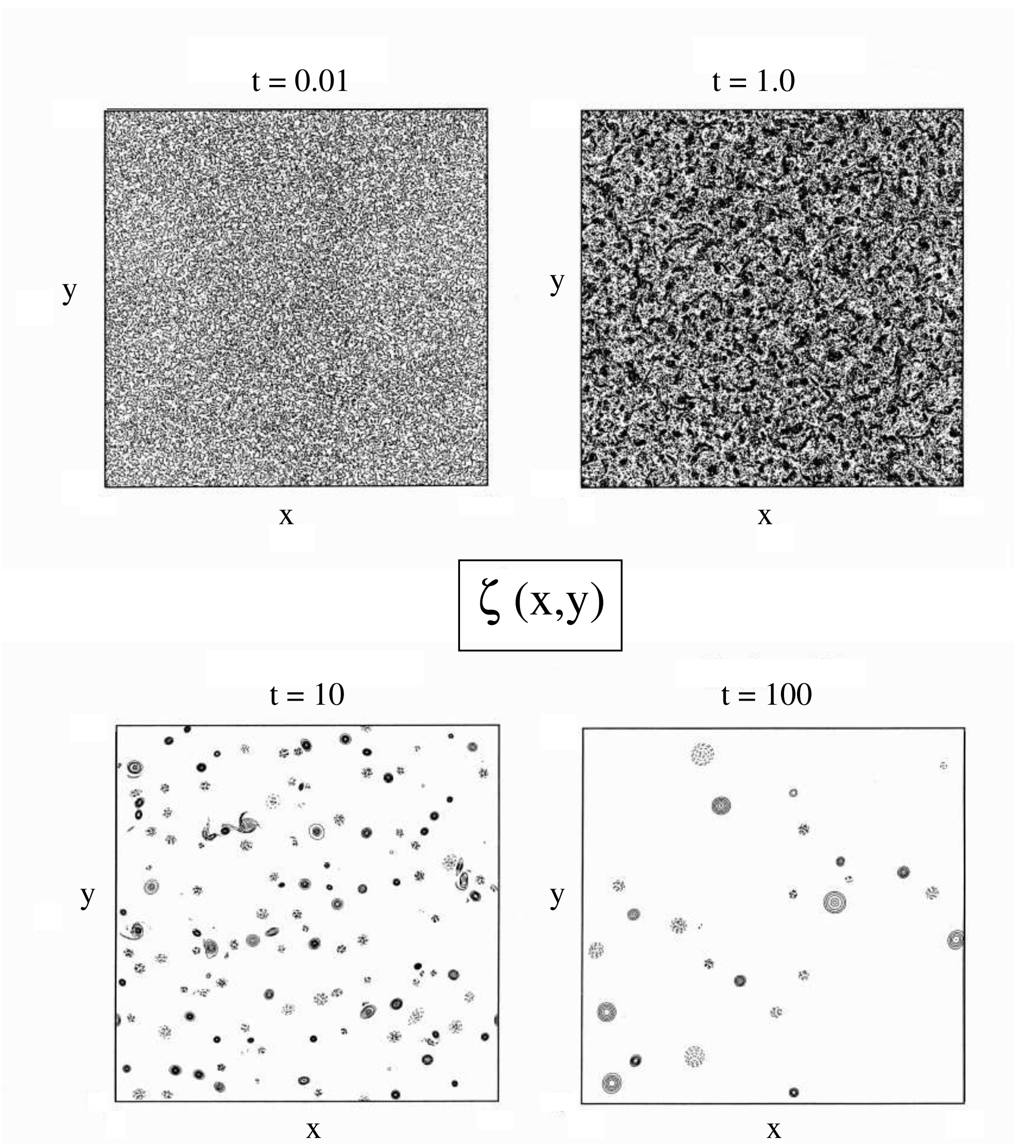


Turbulent Cascades of Energy

2D turbulence

Inverse energy cascade

- 2D(barotropic) turbulence has energy that is transferred to larger and larger scales as time goes on
- An initial state of small scale vorticity (many vortices) will ultimately end up as fewer, larger vortices



3D turbulence

Forward energy cascade

- 3D stirring leads to smaller and smaller scales of tracer gradients
- The transfer of energy is to smaller and smaller scales

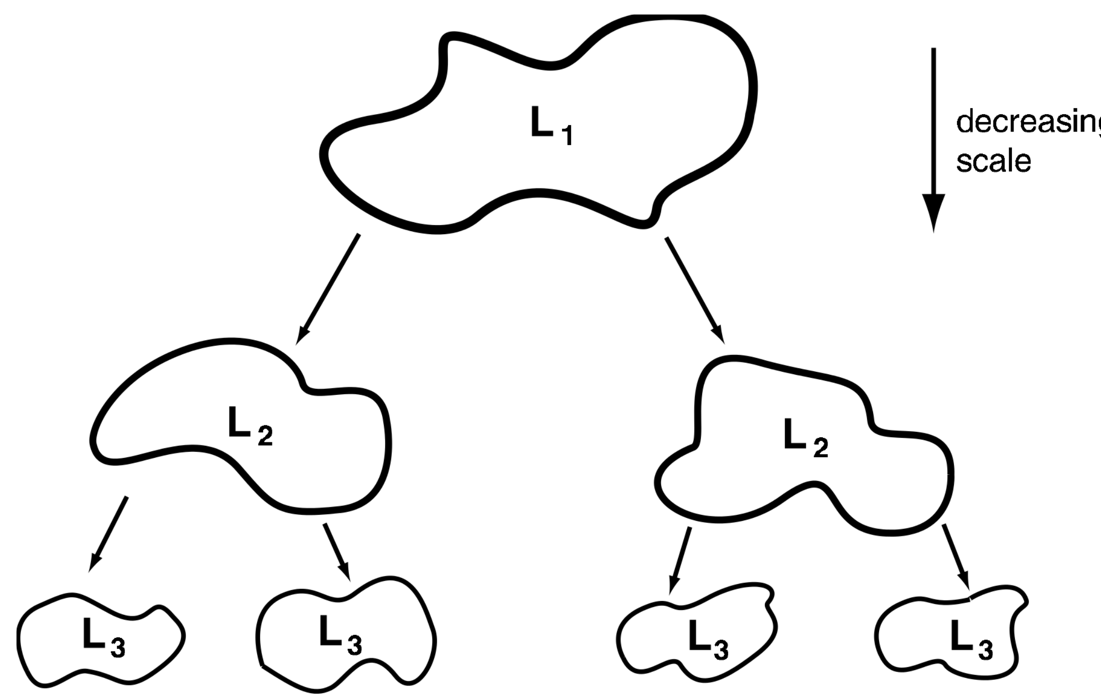


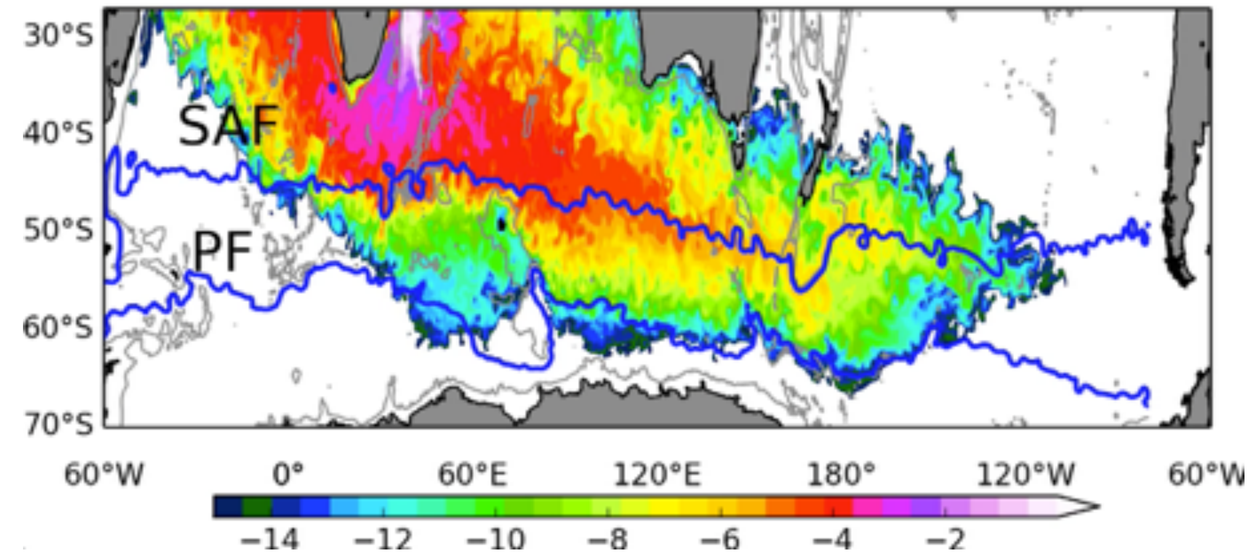
Fig. 8.2 Schema of the passage of energy to smaller scales: eddies at a large scale break up into smaller scale eddies, thereby transferring energy to smaller scales. If the passage occurs between eddies of similar sizes (i.e., if it is spectrally local) the transfer is said to be a cascade. The eddies in reality are embedded within each other

Effects of Eddies

1) Eddy diffusion of tracers

-eddies transport tracers from places of high concentration to places of low concentration
-in the ACC, heat transport to the south is primarily done by this eddy diffusion process

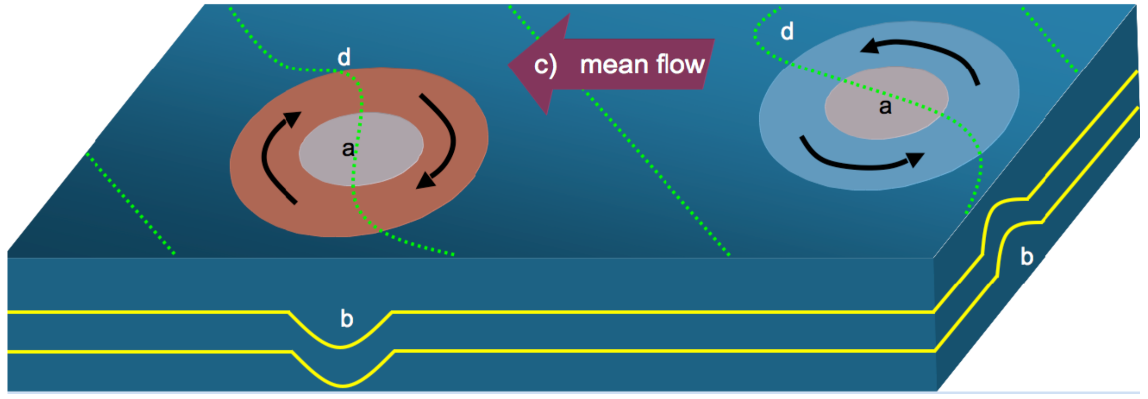
(1)



2) Bolus Transport

- eddy induced contraction of isopycnals causes transport through the isopycnal surfaces

(2)

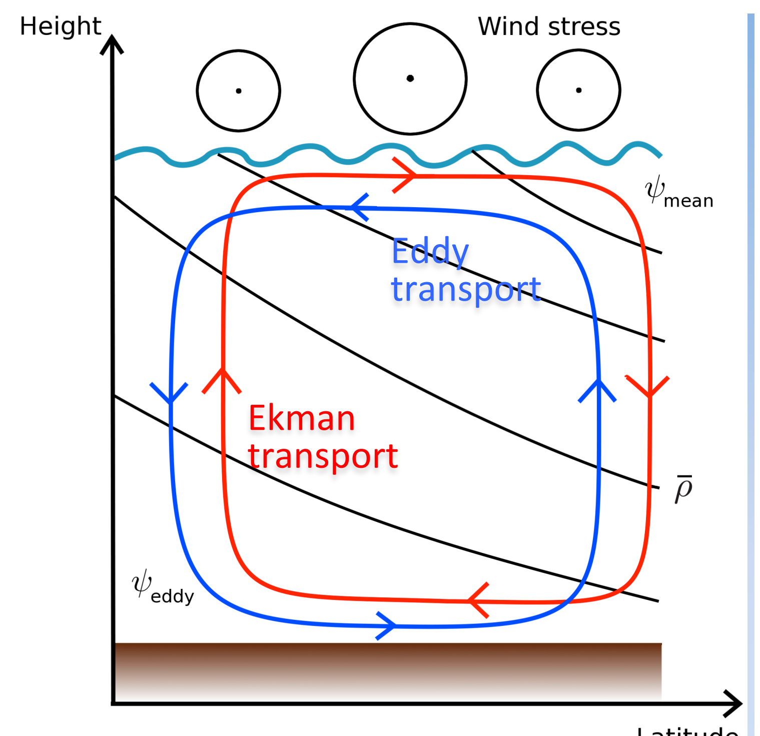


3) Isopycnal un-steepening

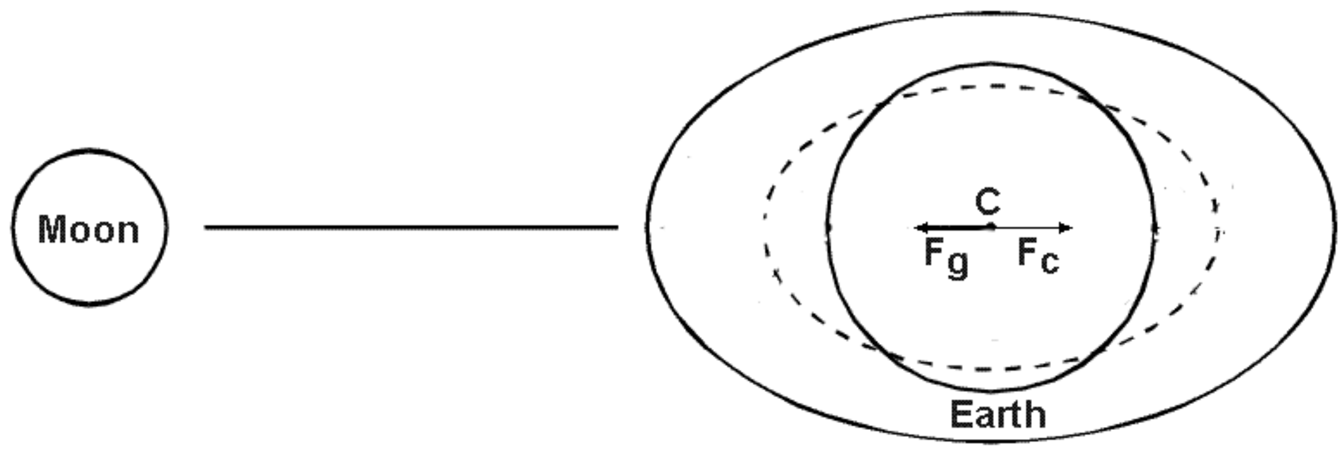
-potential energy is released due to eddies 'un-steepening' isopycnals (i.e. force the isopycnals to become more flat in the horizontal)

ACC: eddies act to flatten the isopycnals, ekman transport acts to steepen the isopycnals—-> the balance between the 2 determines how baroclinic the ACC is

(3)



Tides due to gravitational forces: moon and sun pulling on the Earth



$$F_g = \text{gravitational force}$$

$$F_c = \text{centrifugal force}$$

$$\text{Net Force} = \mathrm{F_g} - \mathrm{F_c}$$

$$F_g = \frac{G \times M_{moon} \times M_{earth}}{R^2}$$

How does the gravitational force behave with distance to the moon?

At center of mass of Earth:

$$F_g = F_c \longrightarrow \text{Net Force} = 0$$

At surface of Earth (closest to Moon):

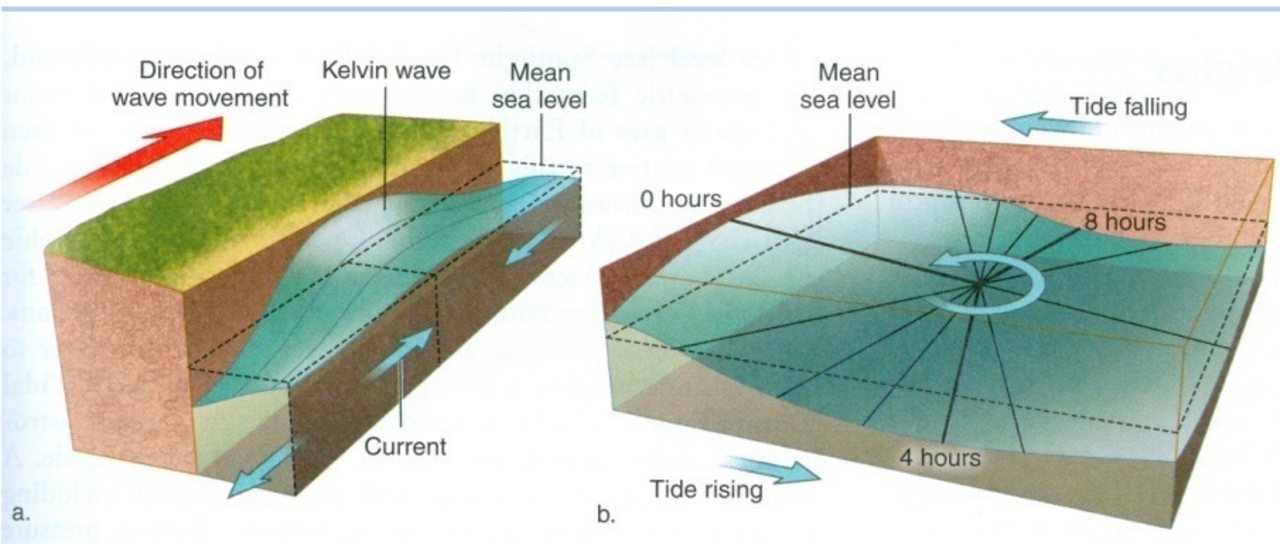
$$F_g > F_c \longrightarrow \text{Net Force} > 0$$

Net force that is non-zero causes the earth to bulge towards the moon (or sun)… this causes tides

Coastal Kelvin Wave: a tidal signature that propagates along the coast

Ingredients for a coastal Kelvin wave: Coriolis force, pressure gradient, topographic boundary (i.e. a coast, that we call a 'coastal waveguide')

**A 'wave' here can be considered a sea surface elevation that propagates (like waves you see at the beach, but here they are of much bigger scale and for our purposes, we will say that there is no wave breaking)



North Hemi example

-a Kelvin wave propagates northward along the coast,
-the Coriolis force wants to deflect this wave to the RIGHT
-BUT, there is a coastal boundary, so water piles up at the coast
-This pile of up of water is manifested in a sea surface elevation, which we know causes pressure gradients
-The pressure gradient force leads to a geostrophic current (PGF = CF)

$$c^2 = gH$$

$$c = \sqrt{gH} = \text{wave speed}$$

g = gravity
H = depth (water column thickness)

Rule of thumb: Kelvin waves propagate with the coast to the right in the NH (so to the left in the SH)

Waves: Mathematical Description

$$\eta = a\cos(kx - \omega t)$$ **Linear wave equation**

$$k = \frac{2\pi}{\lambda}$$ **Wavenumber**

*Note: wavenumber is inversely proportional to wavelength

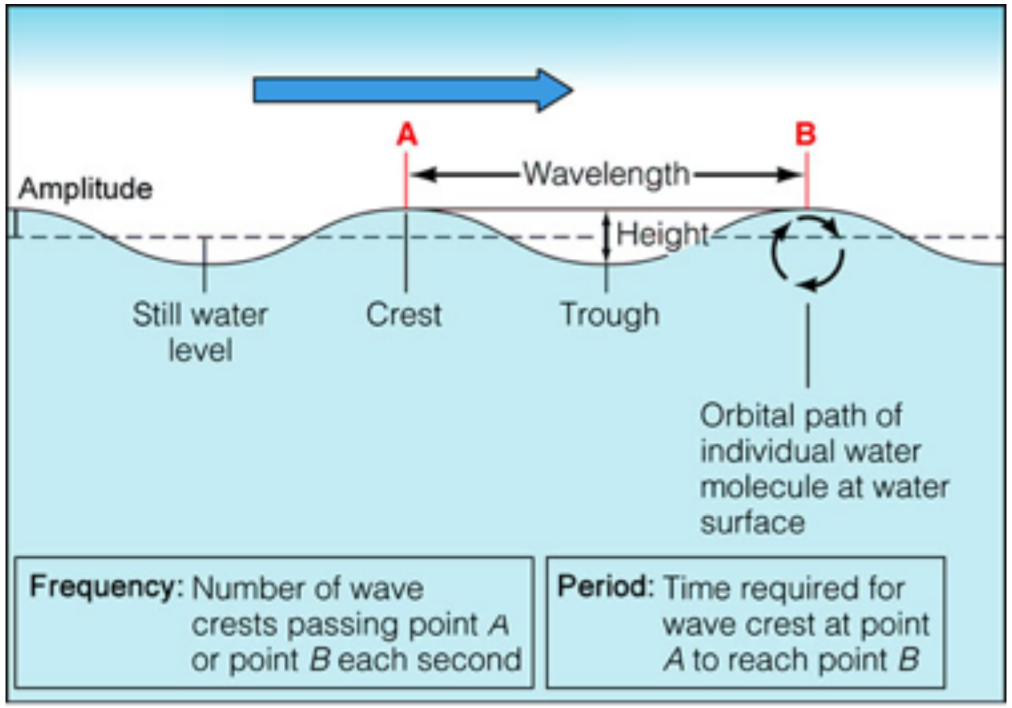
$$\omega = c_p k = \frac{2\pi}{T}$$ **Frequency**

*Note: frequency is a function of wavenumber $\omega = \omega(k)$

$$c_p = \frac{\omega}{k} = \frac{2\pi}{Tk}$$ **Phase Speed**

$$c_g = \frac{\partial \omega}{\partial k}$$ **Group Speed**

t: Time [s]	x, y, z: Space Coordinates [m]
λ: Wave length [m]	a: Amplitude [m]
T: Wave period [s]	k: Wave number [1/m]
ω: Frequency [1/s]	η: Sea Surface Height [m]
C_p: Phase Speed of Wave [m/s]	C_g: Group Speed of Wave [m/s]
H: Water Depth [m]	



Surface Wave: General Phase Speed

$$C_p = \frac{\omega}{k} = (g/k \tanh(kH))^{1/2}$$

***We can simplify (and categorize surface waves) via assumptions about the ratio of wavelength to depth**

Shallow Water Waves

$$\lambda > 20H$$

$$c_p = (gH)^{1/2}$$

$$\omega = C_p k = (gH)^{1/2} k$$

$$C_g = \frac{\partial \omega}{\partial k} = (gH)^{1/2}$$

Deep Water Waves

$$\lambda < 2H$$

$$c_p = \left(\frac{g}{k}\right)^{1/2}$$

$$\omega = C_p k = k \left(\frac{g}{k}\right)^{1/2} = (gk)^{1/2}$$

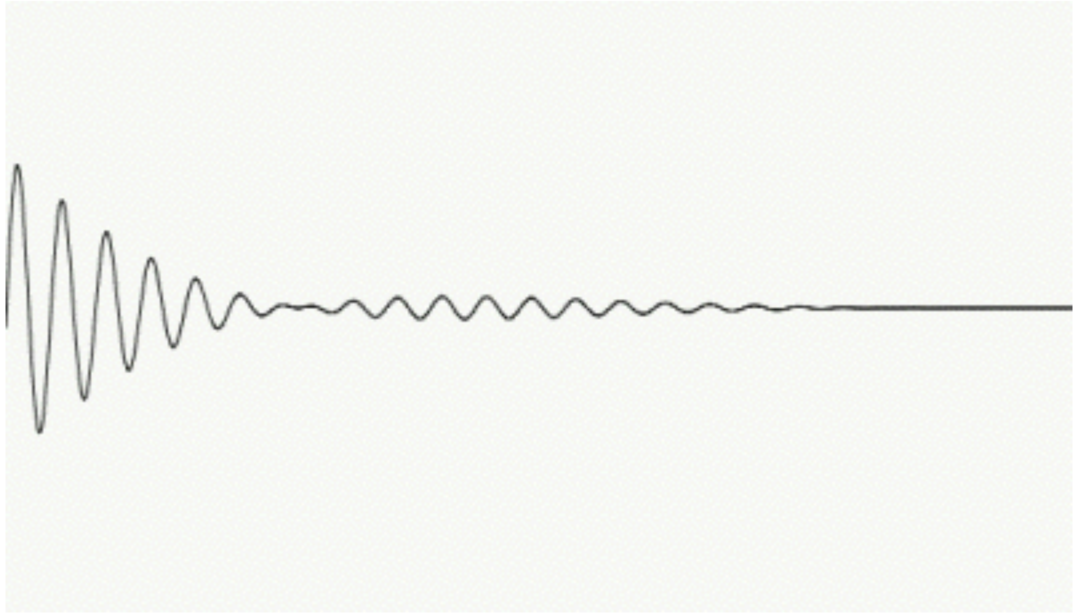
$$C_g = \frac{\partial \omega}{\partial k} = \left(\frac{g}{4k}\right)^{1/2}$$

Dispersive vs Non-dispersive

A wave is dispersive if the phase velocity DOES NOT equal the group velocity

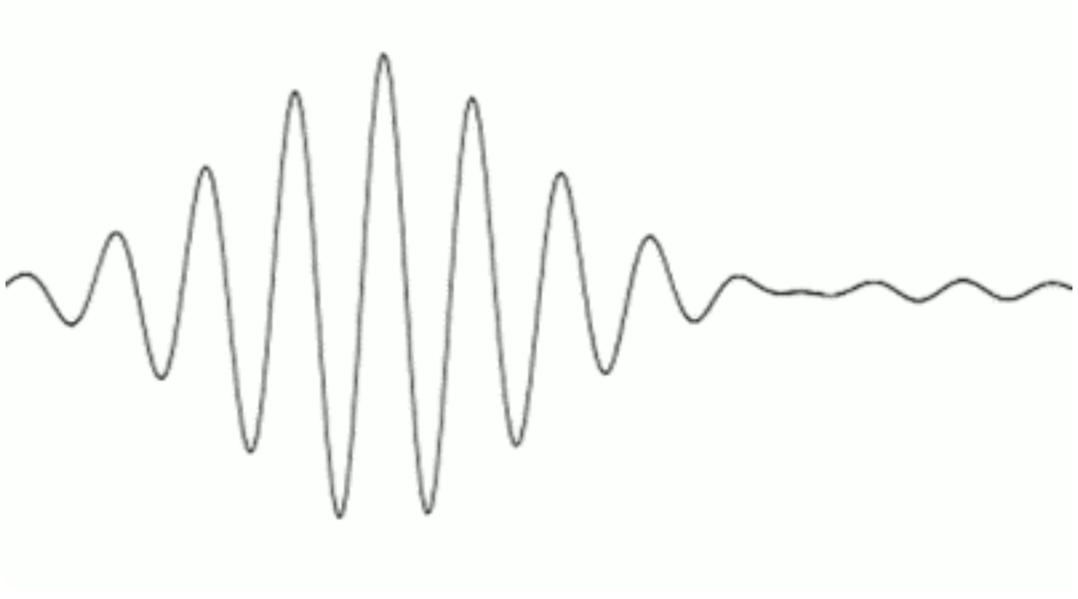
Non-dispersive wave packet (movie)

$$c_p = c_g$$



Dispersive wave packet (movie)

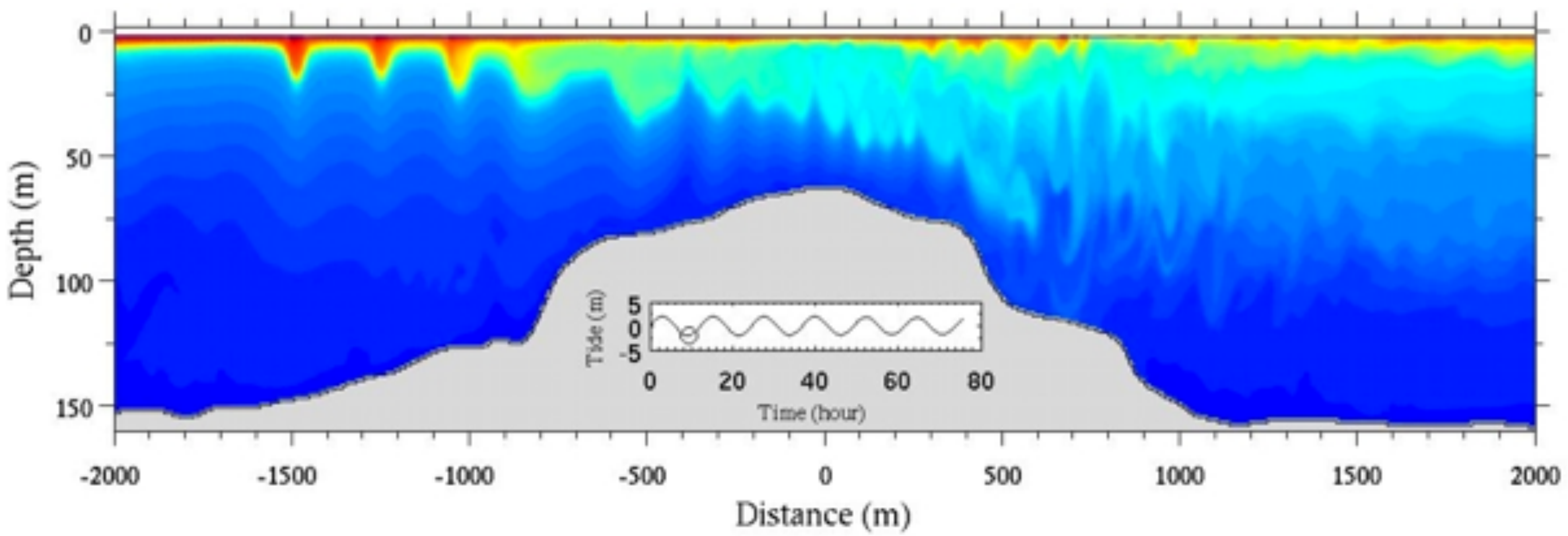
$$c_p \neq c_g$$



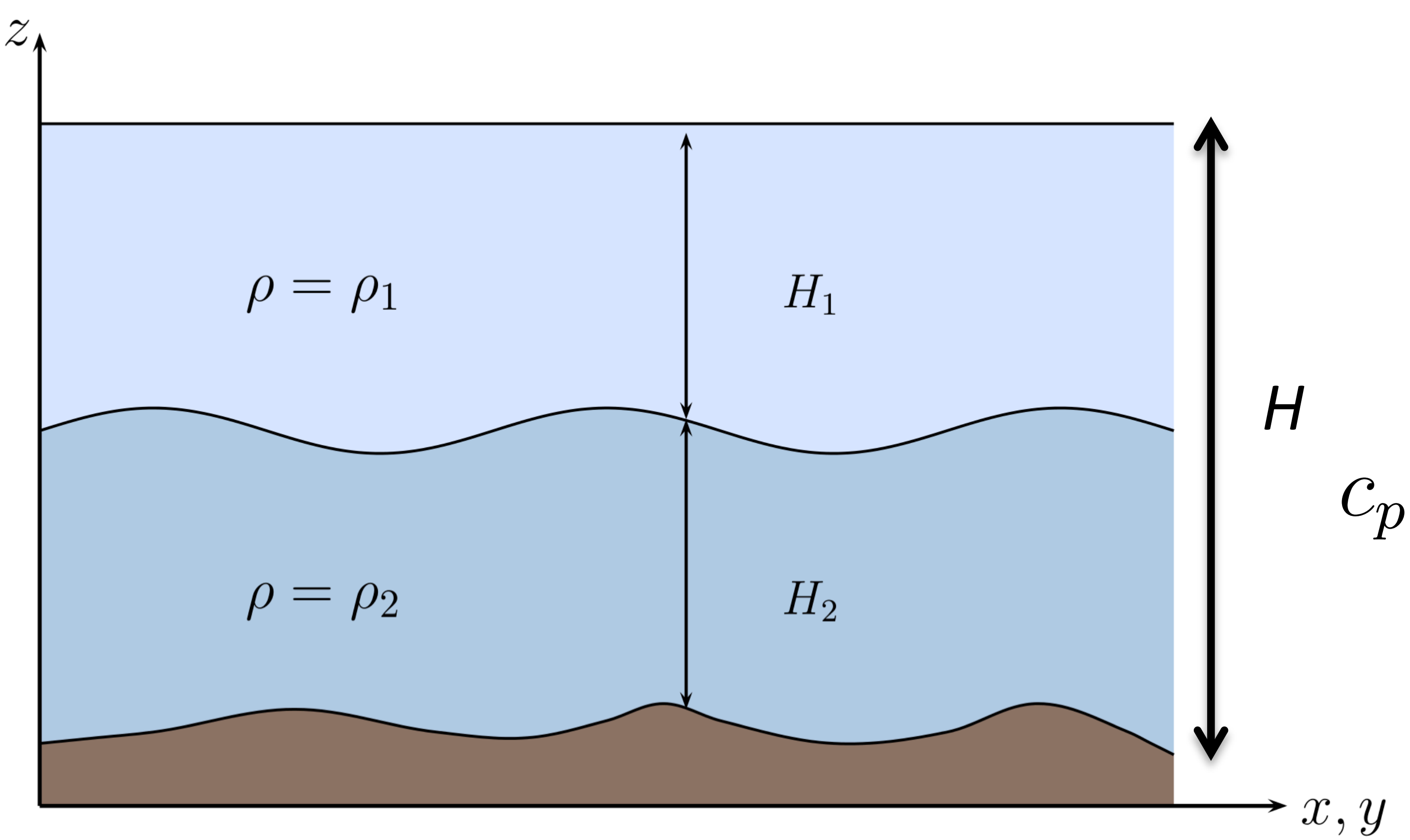
Google/wikipedia "wave dispersion" to see more movie examples

Internal Waves

(Distance,Depth) View



- **Propagate along isopycnal surfaces**
- **Subject to buoyant restoring force (reduced gravity)**
- **Generated by many processes including flow over variable topography**
- **When they break they can lead to mixing which is critical for closing out the Meridional Overturning Circulation (MOC)**

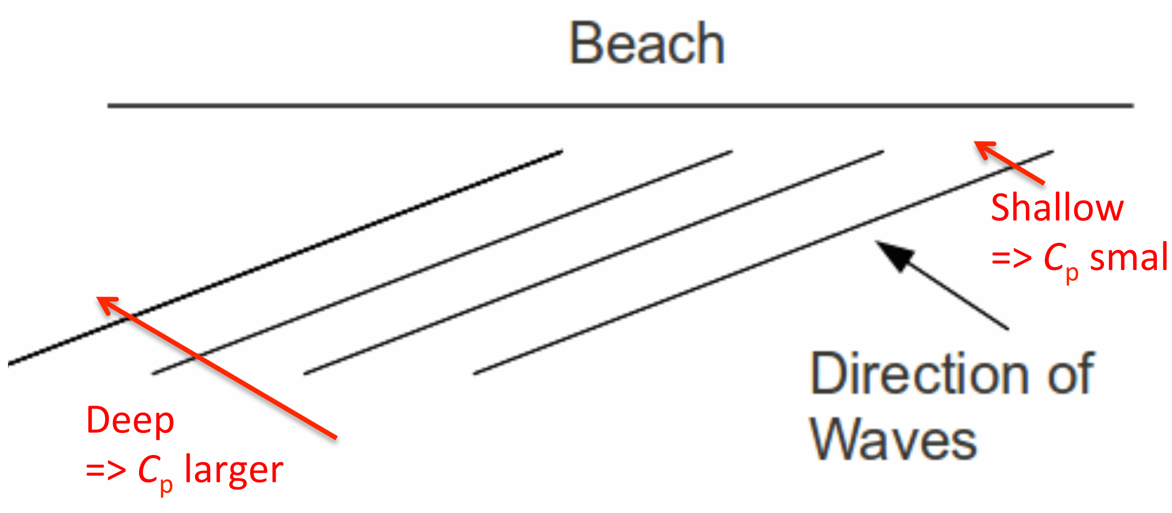


$$c_p = \sqrt{\frac{g' H_1 H_2}{H_1 + H_2}} \qquad g' = \frac{g\left(\rho_2 - \rho_1\right)}{\rho_2}$$

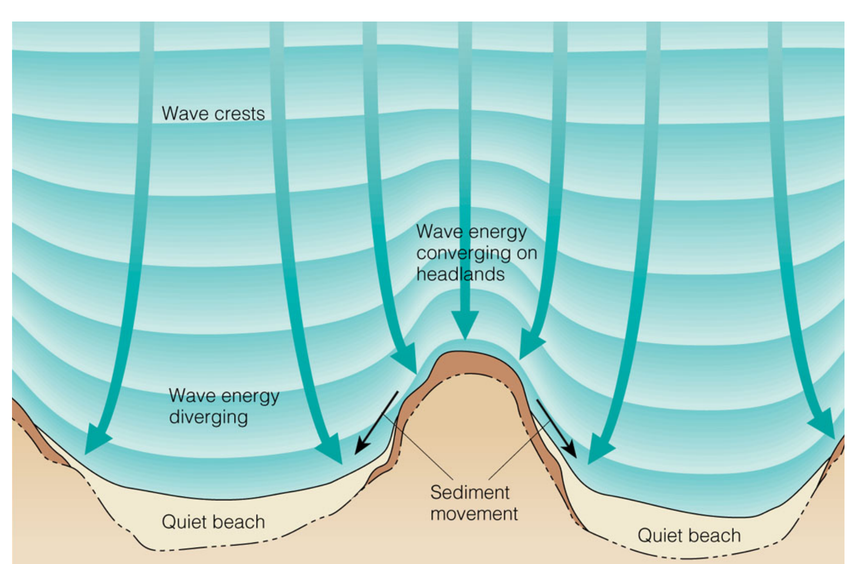
Coastal Waves: Wave Refraction

How do waves approaching a beach at an angle behave?

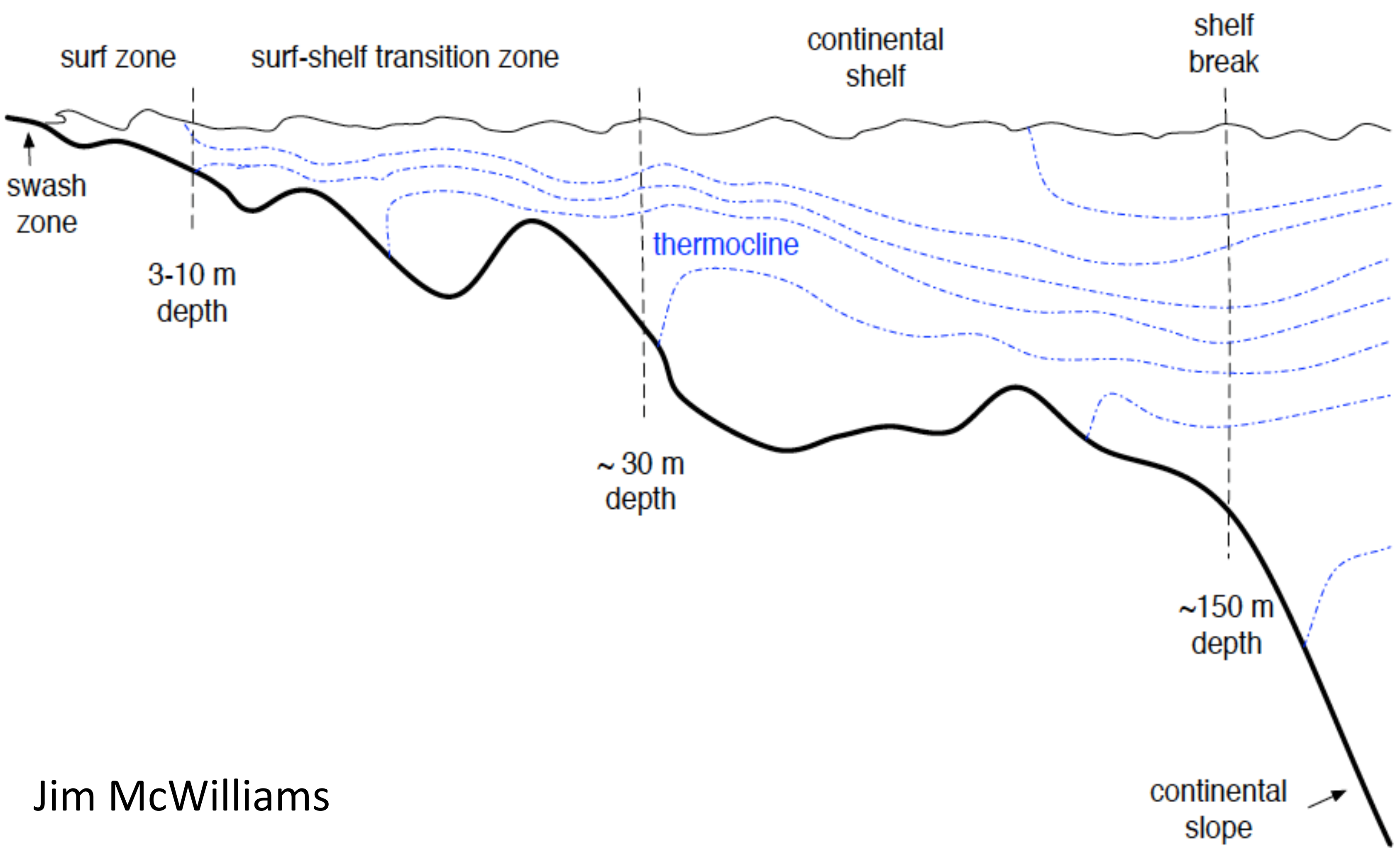
$$c_p = (gH)^{1/2}$$



Which region do you expect stronger wave activity: headlands or bays?



Continental Shelf



Jim McWilliams

Blue lines represent isopycnals (lines of constant density)

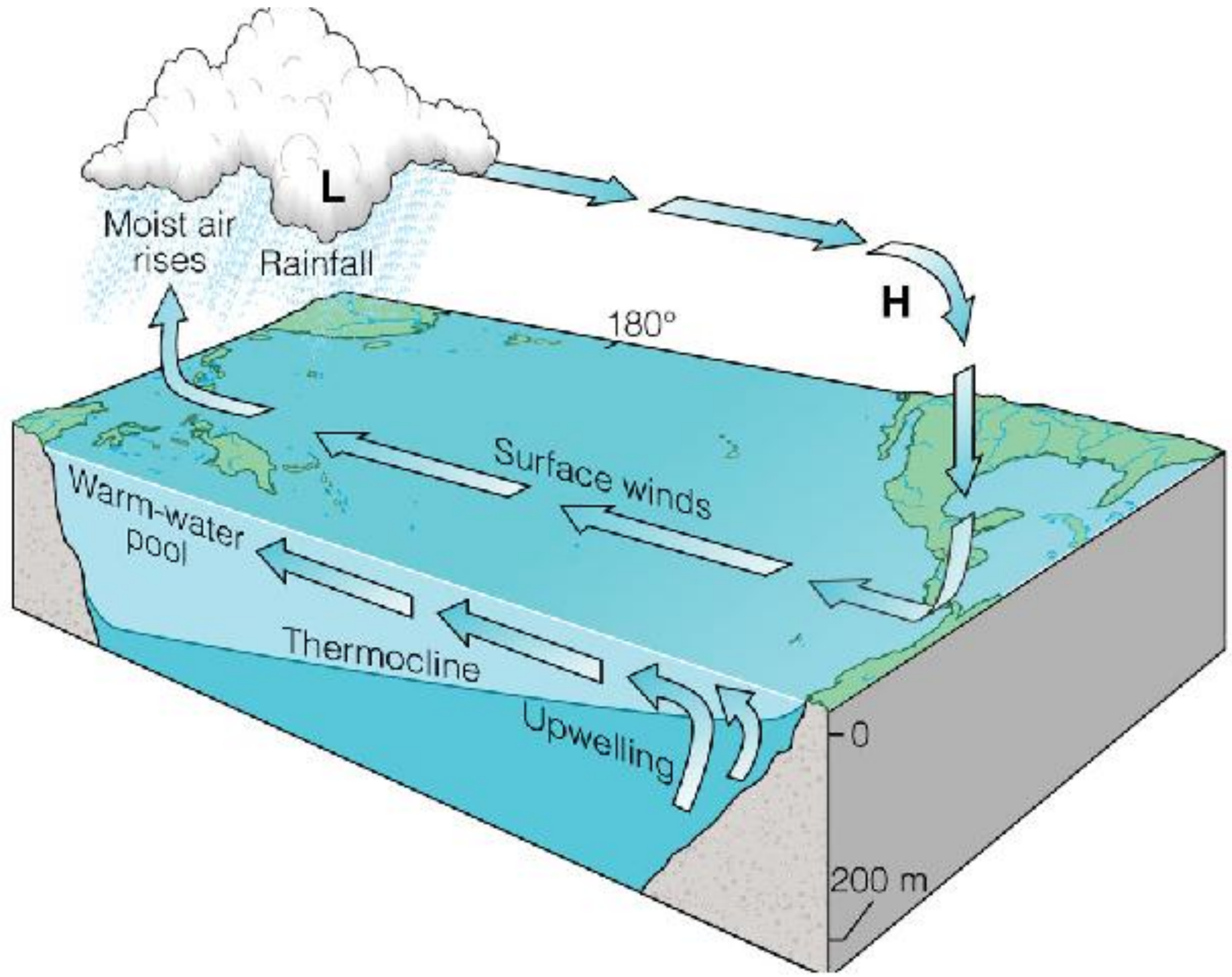
What does a vertical profile of density (or temperature) look like in the continental shelf?

Where are there <u>mixed layers</u> here?

Is there a thermocline?

Why would a slope current flow on the slope here?

The Equatorial "Bathtub"

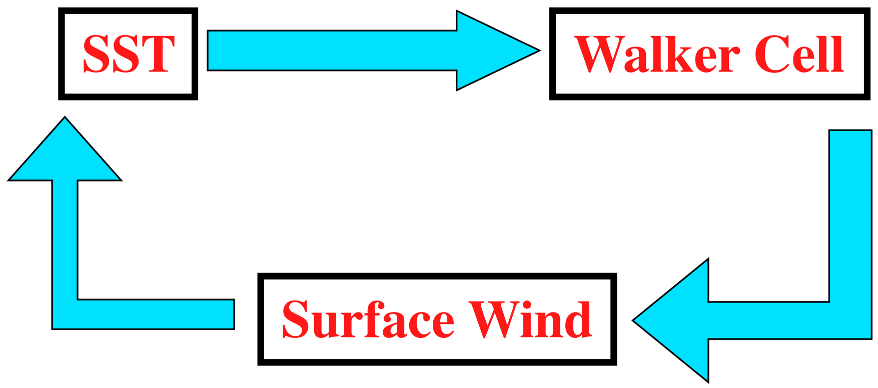


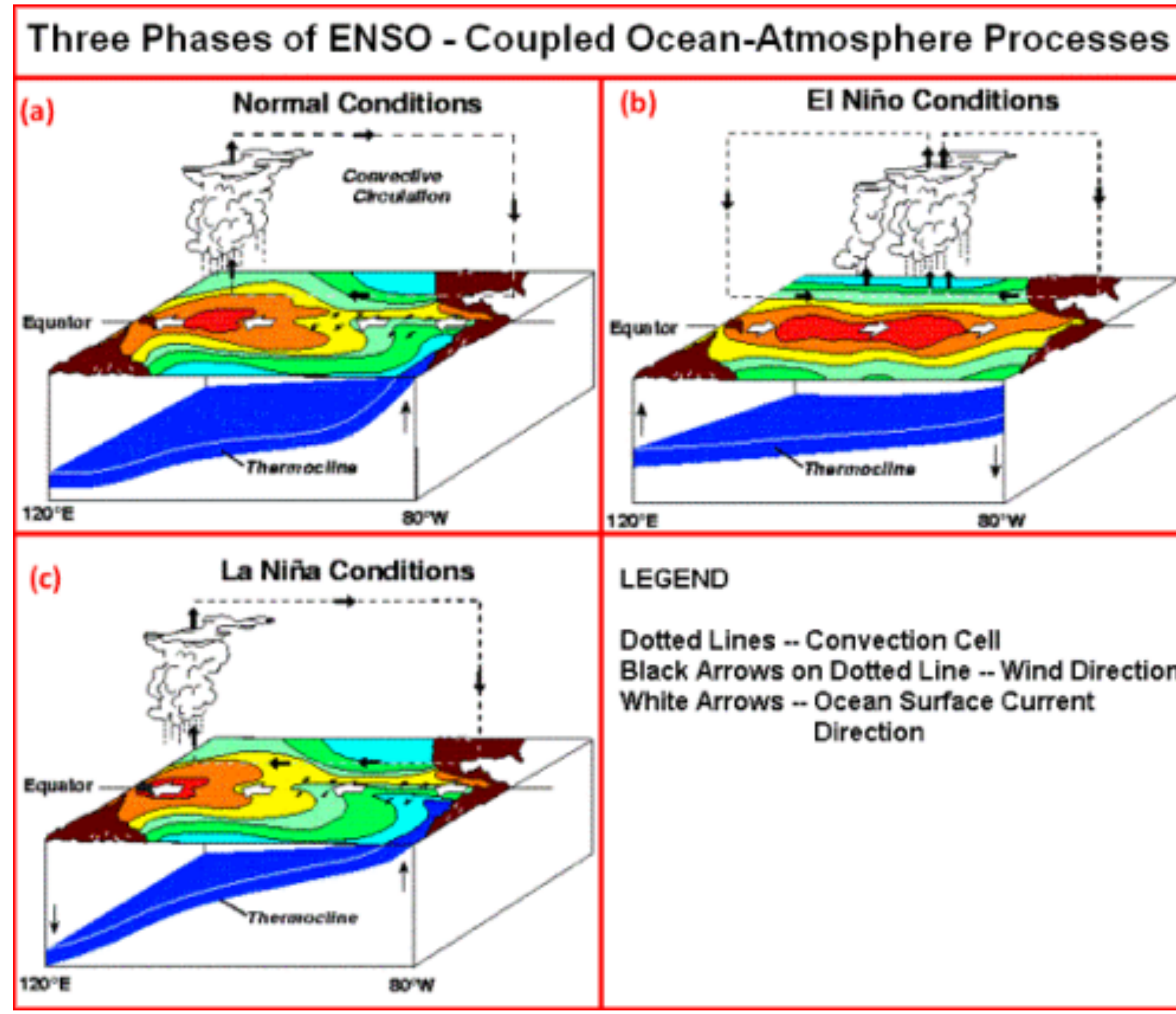
What does a raised thermocline near South America mean for near surface waters there?

Does it have an impact on the atmosphere near the surface of the ocean?

El Nino/La Nina

Ocean-atmosphere feedback system





El Nino is the result of a positive feedback between the ocean and atmosphere

How does the ocean transmit information across the equator to break this feedback?? → **Waves!**

El Nino/La Nina: Effects on Global Systems

How would you expect El Nino to affect the fishing off the coast of equatorial South America? Why?

ENSO events can have impacts across the entire globe via "teleconnections"

Jet Stream