SIOC 210 Final examination **Name:__________________**
Wednesday, December 11, 2019
11:30-2:30 PM

Please put your initials or name on each page, especially if you pull pages apart.

Turn off all phones, iPods, etc. and put them away.
This is a **closed book exam**.
You may use **two pages** of notes, both sides, written or printed.
You may use a non-communicating calculator.

Check which you prefer regarding the return of this exam and other graded materials
_______I will pick up the exam (after Jan. 5)
_______Return the exam etc to me via campus mail (or full address)
Mailcode___________________________

Possibly useful expressions and values; you will not need most of these.
ρ: use 1025 kg/m^3 for generic calculations
c_p = 4000 J/kg°C
$\rho\ c_p\ T$
1 PW = 10^{15} W = 10^{15} J/sec
Earth's radius: 6371 km
$V_{Ek} = -\tau^{(x)}/(\rho f)$
$f = 2\Omega \sin(\text{latitude})$
$\Omega = 0.73 \times 10^{-4}$/sec
U/fL, 1/fT
sin (30°) = 0.5
sin(50°) = 0.77
1° latitude = 111 km
1 Sv = 1×10^6 m^3/sec
g = 9.8 m/sec^2
Force balance (momentum equation):
acceleration + advection + Coriolis force =
pressure gradient force + gravity + friction

Multiple choice or short answer (**2 points each; 14 points total**)
For each multiple choice problem, **circle ONE CORRECT answer**.

1. The California Current
(a) is driven by Ekman downwelling in the subtropical gyre
(b) is pushed directly downwind by alongshore winds
(c) is a boundary current that reaches the ocean bottom (several kilometers deep)
(d) is driven by upwelling due to offshore Ekman transport

2. The restoring force in a Rossby wave, which makes the water return back to an equilibrium location, is
(a) the variation of Coriolis parameter with latitude
(b) gravity
(c) potential vorticity
(d) the discontinuity in density between the air and the sea

3. The Kuroshio
(a) differs from other subtropical western boundary currents by including a so-called large meander before it separates from the coast
(b) has a transport on the order of 10 Sv
(c) is the western boundary current of the South Pacific
(d) carries subpolar water to the coast of Japan

4. The speed of a shallow water wave
(a) depends on wavelength of the wave
(b) increases as the bottom depth decreases (becomes shallower)
(c) depends on water depth
(d) depends on what caused it, for instance a storm or an underwater earthquake

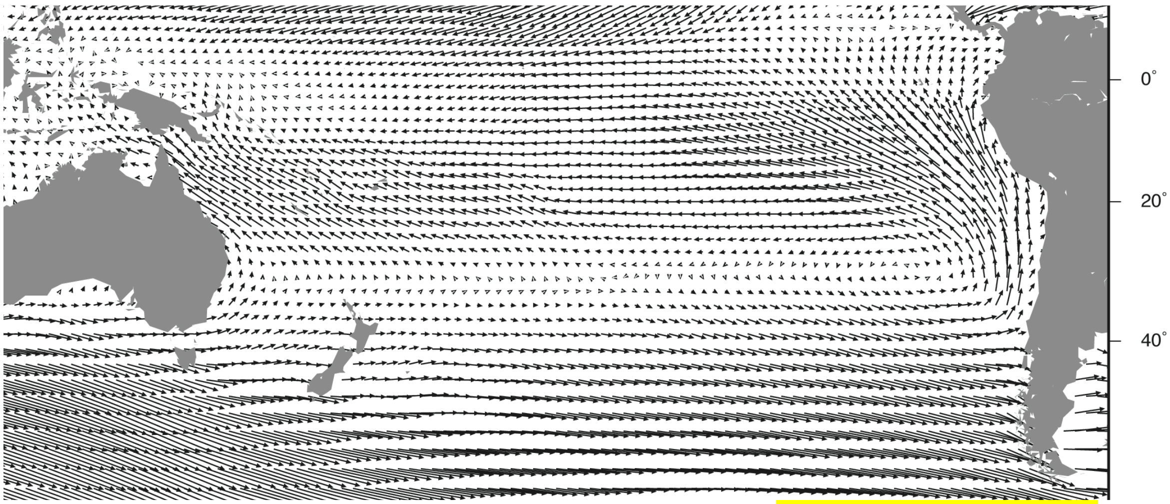
5. A neap tide occurs
(a) during full moon (brightest)
(b) during new moon (darkest)
(c) when the moon is in the equatorial plane of the Earth
(d) during half moon

6. Which of the following is NOT TRUE about ENSO (El Nino/Southern Oscillation)
(a) Characteristic period is 3-7 years
(b) Decreases the sea surface temperature of the Eastern Tropical Pacific
(c) Is associated with decreases in fisheries catches along the western coast of South America
(d) Alters the zonal structure of the tropical oceanic heat flux to the atmosphere

7. For the global overturning circulation:
(a) Surface sources of deep water in the North Pacific contribute to the global overturning circulation.
(b) The net overturning transport associated with North Atlantic Deep Water formation is approximately 2 Sv.
(c) Inflow to the Nordic Seas occurs through the branches of the North Atlantic Current.
(d) The Sverdrup balance results in Deep Western Boundary Currents.

Problems

8) (10 points) (2,1,1,1,3,2)
The mean wind stress (in N/m^2) in the eastern and central **South** Pacific is shown in the figure.



(a) Indicate on the figure where coastal upwelling is found. Along S. American coast between 35S and equator.
Sketch the direction of the Ekman transport at this location. To left of wind, so offshore
What is the name of the current system where this occurs?_Peru-Chile Current, or Humboldt Current

(b) Mark the regions of the Westerlies and Trades in mid-South Pacific (subtropical region). Westerlies are south of about 35S in this figure. Trades are from about 30S and north of that.

(c) Sketch the direction of Ekman transport relative to these Westerlies and Trades.
To left of wind, so northward in the Westerlies, and southward in the Trades (in Southern Hemisphere). (Map goes across equator, so if you put in the Ekman transport in the Northern Hemisphere, it would be northward. I didn't ask for this, but if you do it anyway and indicate it incorrectly I'll have to deduct a point.)

(d) Is there Ekman CONVERGENCE or DIVERGENCE in this open-ocean region? (Circle answer.)

(e) Sketch the direction of the Sverdrup transport in the same region as you marked in (c) and (d). Northward.
Explain very briefly the dynamics that result in this direction for the Sverdrup transport.
Use potential vorticity conservation, $Q = f/H$. Ekman convergence results in column squashing (H decreases). So magnitude of f also has to decrease which requires

equatorward flow (northward). f is negative in S.H., but that doesn't matter – Q is a negative quantity, and reducing H means that the negative f has to get smaller as well.

(f) What is the name of the western boundary current is associated with (e)? _East Australian Current_______
Mark its approximate location on the map. Along eastern coast of Australia. If you are being really accurate you will also show it extending across the Tasman Sea and coming south along the North Island of New Zealand, but I won't require that level of detail.

9) (10 points) (1, 2,1, 1, 1, 2, 2)
The attached map of surface geostrophic streamfunction from Reid is meant to assist you with a visual map where you can mark some of your answers. The wind map in problem 8 should also be useful.

(a) During "normal" years in the tropical Pacific, which direction do the large-scale winds blow?_westward_____
What do we usually call these winds?__Trade Winds. You can also answer with Walker Circulation________

(b) What is the distribution of atmospheric pressure at the sea surface in the tropics which drives these winds? That is, where is the pressure high and where is it low? High in the eastern equatorial Pacific and low in the western equatorial Pacific.

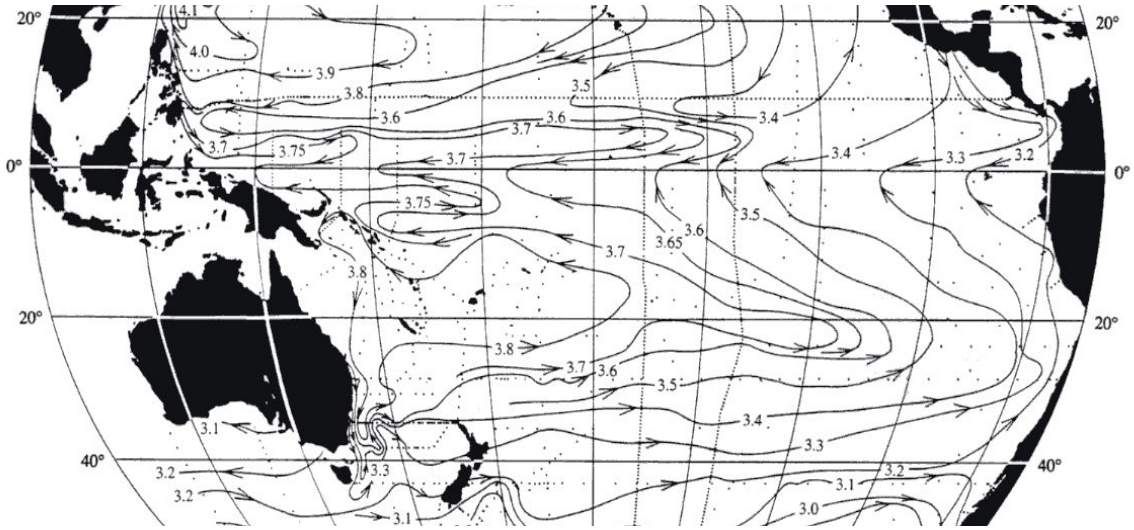
(c) In the region of low surface atmospheric pressure, is it RAINY or DRY? (Circle answer.)

(d) What direction is surface velocity at the equator in a normal year?_westward_______

(e) Is the surface velocity at the equator geostrophic? YES or NO
(No for many reasons – Coriolis is zero, and also it is frictional, so even if this were at non-zero latitude, it would not be geostrophic.)

(f) What are the depth, direction and typical speed of the Equatorial Undercurrent? EUC is centered at about 150 to 100 m depth depending on longitude. Direction is eastward. Maximum typical speed can be 150 cm/sec.

(g) During an El Nino event, does the surface pressure in northern Australia increase or decrease compared with the surface pressure in the central Pacific? It increases because the Walker circulation is much weaker, and shifts eastward.


20°
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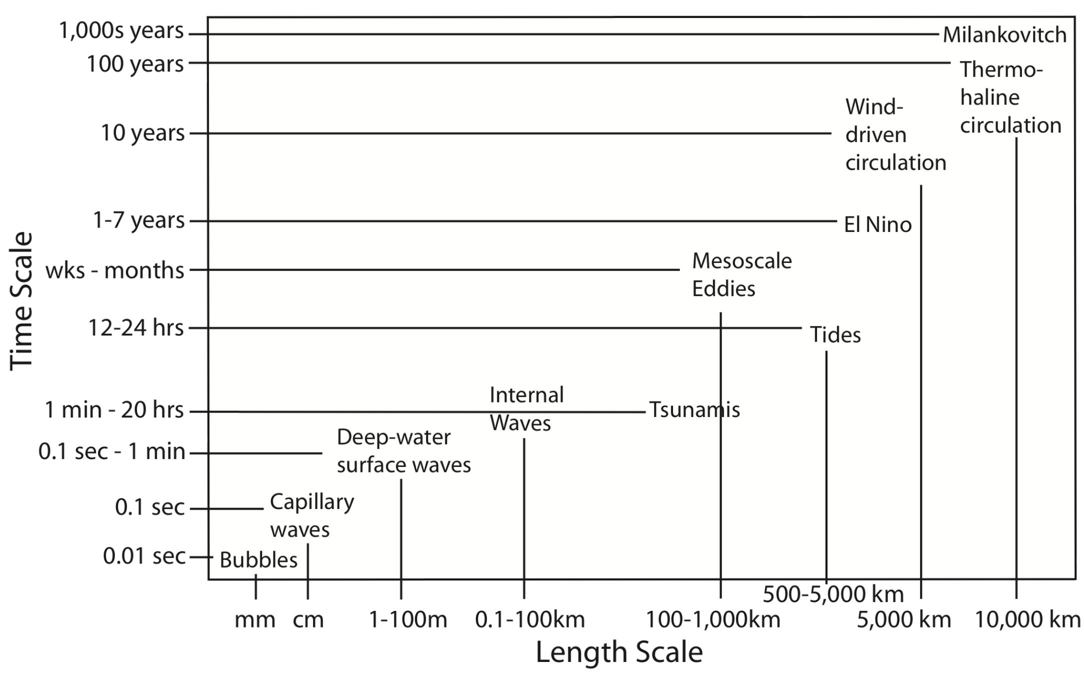
10) (5 points) (2, 1, 2)
(a) Which phenomena in this next diagram are affected by Coriolis force? You can simply circle parts of the diagram and label. Circle everything over 24 hours. If you are more of an expert, you might include the internal waves and tides because both have frequencies that are low enough (not really shown on diagram) to be affected by Earth's rotation.

(b) If you compute a Rossby number for these phenomena, which ones have small Rossby number and which ones have large Rossby number? Small Rossby number are the those affected by Coriolis, so circled in (a).

(c) What is the Rossby number? (Give an expression for it, and explain what it is in words and why it matters.) The expression is actually given on the front page. It can be written as either 1/fT or U/fL, where T is the time scale of the motion. When 1/fT is small, that means the time scale is much longer than Earth's rotation time scale, so the motion is affected by Coriolis.



11) (10 points) (2, 3, 1, 1, 1, 2)
(a) Define potential temperature. Potential temperature is the temperature a water parcel (or air parcel if in the atmosphere) has when moved adiabatically to the sea surface. (It can also be defined relative to any pressure, which is necessary for definition of potential density relative to a pressure other than 0 dbar.)

(b) For a parcel of water at 3000 m, is its potential temperature HIGHER or LOWER than its measured temperature? (Assume that potential temperature is computed relative to the sea surface.) (Circle the correct answer)

Explain why. If a parcel starts at 3000 m and our thought experiment is to move it to the sea surface, where the pressure is much lower, it will expand. When a parcel expands adiabatically its temperature decreases.

(c) Is the freezing point of seawater HIGHER or LOWER than the freezing point of freshwater? (Circle the correct answer)

(d) What is the approximate freezing point of seawater? (in °C) I'll accept any answers between -1.5°C and -2 °C. Most likely is around -1.7°C; it depends on salinity and a bit on pressure.

(e) Is sea ice formed from seawater FRESHER or SALTIER than the seawater? (Circle the correct answer)

(f) How does your answer to (e) relate to the formation of Antarctic Bottom Water along the continental shelves of Antarctica? Formation of sea ice from seawater releases salt (brine) into the water column, which is much denser than the ambient seawater. It is also at the freezing point, so it is quite dense, and is denser than other water near the freezing point but without the brine. So if it is salty enough, it will sink. This is the main process for formation of AABW.

12) (6 points) (1,1,1,1,2)
We quantify the amount of water and properties moving through the ocean using transports. Calculate the approximate **volume transport** of a simplified Gulf Stream.

(a) What is the typical surface speed of the Gulf Stream? 100 cm/sec = 1 m/sec

(b) What is the typical bottom speed of the Gulf Stream? About 5 to 10 cm/sec

(c) What is the typical width across the Gulf Stream? About 100 km= 10^5 m

(d) What is the typical depth of ocean in the Gulf Stream? About 4 to 5 km = 4 to 5 x 10^3 m.

(e) Use these quantities, from a, b, c, d and calculate the volume transport of the Gulf Stream. Assume that the velocity of the Gulf Stream is the average of the surface and bottom speed. (Is this likely an overestimate or underestimate?)
Mean speed: call it 60 cm/sec = 0.6 m/sec.
Volume transport = v * width * depth = (0.6 m/sec)(10^5 m) (5 x 10^3 m) = 3 x 10^8 m^3/sec = 300 x 106 m3/sec = 300 Sv.

This is quite a large overestimate, as the G. Stream transport varies from about 30 to 150 Sv. It's an overestimate because the surface velocity I chose would be the maximum at the core of the current, so the velocity decreases to each side, and because I chose a linear vertical shear, whereas the Gulf Stream high velocities are concentrated in the upper 1000 m (upper kilometer).

13) (9 points) (1,1,1, 2,4)
Oxygen is an important tracer of water masses. It is subject to physical, chemical and biological processes.

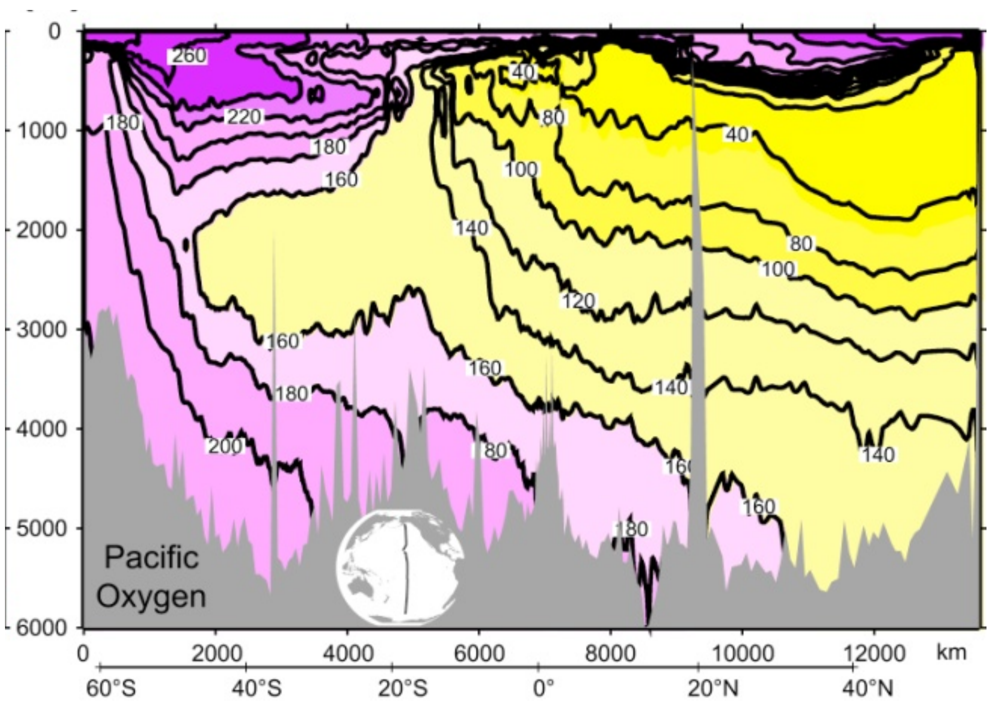
(a) What process creates highest oxygen content? Physical process of air-sea gas exchange saturates the surface waters. (If you know more biology than is taught in this class, there can also be input of oxygen from photosynthesis in the euphotic zone, which can increase oxygen content/saturation above what the atmosphere puts in.

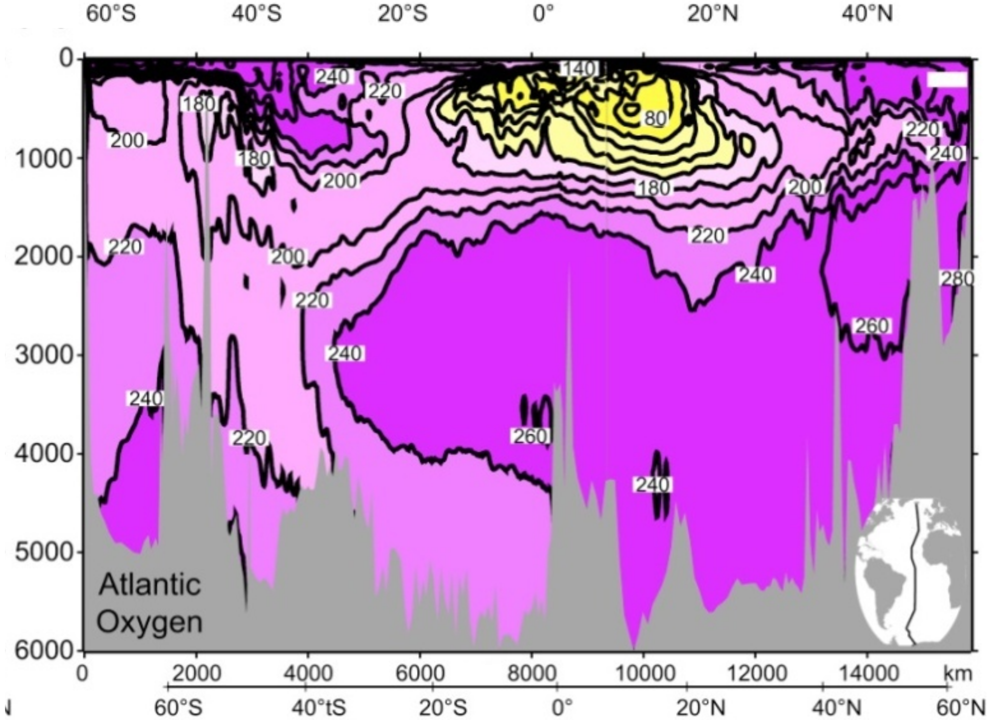
(b) What process creates lowest oxygen content? Biology – that is, respiration by bacteria.

(c) If oxygen is completely saturated (100%), is its concentration in μmol/kg HIGHER or LOWER where the water temperature is highest? (circle one)
I didn't ask for an explanation, but the simple one we give is that warmer water can hold less oxygen due to the kinetic energy of the molecules, so its oxygen (or any other gas) concentration is lower at 100% saturation than for cooler water.

(d) The plots are oxygen (μmol/kg) sections in the Pacific and Atlantic.
Mark the Pacific Deep Water (PDW). On Pacific section, it is the large yellow water mass at mid-depth – low oxygen.
Mark the North Atlantic Deep Water (NADW). On the Atlantic section, it is the large purple water mass at mid-depth – high oxygen.

(e) Using these oxygen plots, explain how deep water formation differs between the North Atlantic and North Pacific. That is,
What is the process of deep water formation in each ocean? In the North Atlantic, deep convection at various sites moves surface water to the deep ocean. Therefore it is new. In the North Pacific, there is no deep convection, and PDW is created by diffusive upwelling of bottom waters. Therefore it is very old.
How does that lead to its characteristic oxygen values? New water has high oxygen because it was recently at the sea surface and respiration has acted for only a few decades (NADW). Old water has low oxygen because it is much, much farther from the sea surface and respiration has acted for up to a 1000 years (PDW).

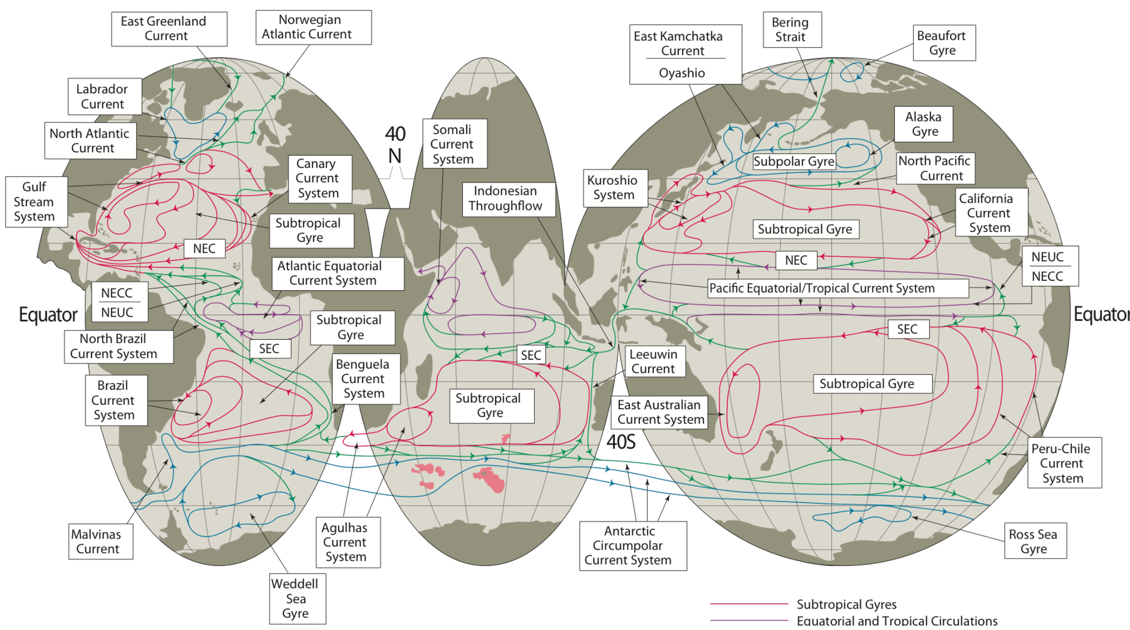




14) (8 points) (2,2,4)
(a) On this schematic map of surface geostrophic circulation, which large-scale circulation features are anticyclonic? The Subtropical Gyres.
Circle one in each of the five ocean basins (N Pacific, S Pacific, N Atlantic, S Atlantic, Indian). Easy to find – they are labeled.

(b) Choose one of your anticyclonic features: relative to that feature, where is the sea surface high and where is it low?
Choosing the N. Pacific: sea surface is high in the middle of the gyre and low on the outside. More specifically, it is highest where the closed contours are shown next to Japan

(c) Explain your answer to (b): what is the force balance in a geostrophic flow?
What does this tell you about where the surface height is high and low?
Force balance in geostrophic flow is between Coriolis and pgf for the x and y momentum equations, and between gravity and vertical pgf for the z momentum equation.
From the x and y momentum equations, flow is around the high pressure center, so clockwise for this N. Pacific ST gyre. From the z momentum equation, high pressure is due to greater surface height.



15) (10 points) (5, 2, 1, 1, 1)
The figure shows potential temperature along a vertical section in the Pacific Ocean (see small map).

(a) Describe and explain the overall structure: Note – this is a pretty open-ended question, will accept a wide range of answers.
Why the observed distribution of cold and warm water?
Warm water at the surface and at lower latitudes because of surface heating, due to larger solar radiation. Cold water at the surface at high latitudes because of cooling dominating lower solar radiation. Cold water in the deep ocean because the cool surface water at high latitudes is also denser, and therefore sinks beneath the warm upper ocean.

Why the tilting isotherms and what do they indicate? Tilting isotherms are mostly equivalent to tilting isopycnals. These indicate that the geostrophic flow has vertical shear (thermal wind balance).

Differences between the South and North Pacific?
South Pacific has cold water all the way to the sea surface in the south, and very cold at the surface where sea ice forms. North Pacific is much warmer at the sea surface.
In the abyssal ocean, the cold water from the south spreads northward along the bottom. Bottom water is warmer in the N. Pacific, because downward diffusion of heat has warmed it (this is the diffusive formation of PDW).

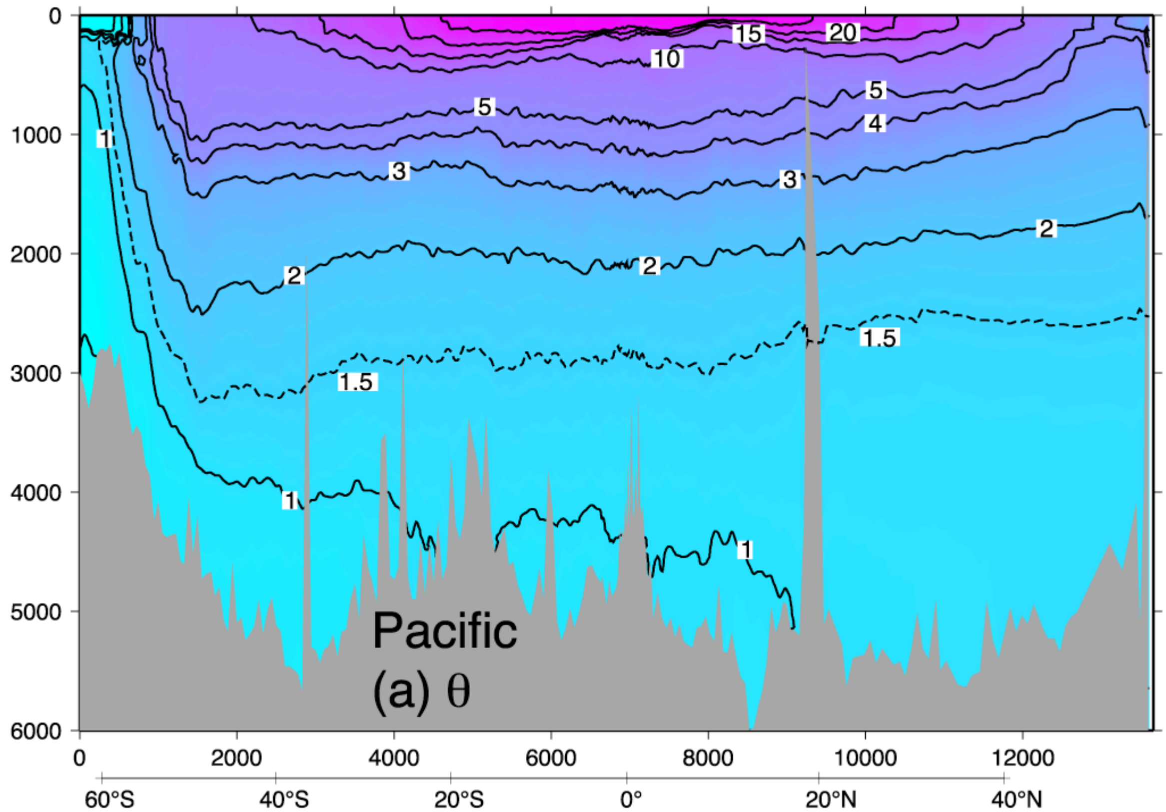
(b) Where is the thermocline in this figure? Indicate it on the figure.
Thermocline is where the isotherms are more concentrated vertically. It reaches down to about 5 to 10°C (note that the contour interval changes below 10°C).

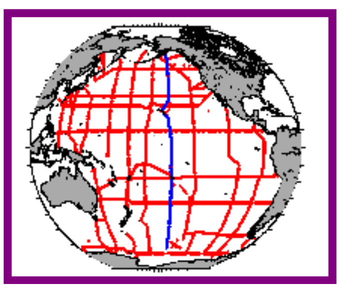
(c) Assuming that density looks mostly like this temperature distribution, use the sloping isotherms to

Identify the location of the current with the strongest vertical shear (geostrophic velocity). MARK it on the section. It is between about 50°S and 60°S.

What is this current called?__Antarctic Circumpolar Current___

Which direction does this current flow? __eastward___________________
MARK it on the section using our symbols for current direction. Use circles with points in center, locate these circles over the maximum slope of the isotherms and down to the bottom. You can show that the circles are largest at the surface (strongest current) and become smaller with depth (weak current).





16) (6 points) (2, 1, 2, 1)

A wave is characterized by its wavelength and its frequency.

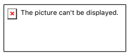
(a) For surface gravity waves that we observe from the beach here in La Jolla, what is a typical wavelength? __a few meters up to about 20 m__What is a typical frequency?__Could report a period here: about T = 10 to 20 sec. frequency is 2pi/T_________

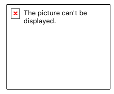
(b) If the water depth is 4000 m, and you have a surface gravity wave with the wavelength you just specified in (a), is that wave a

DEEP WATER wave or a SHALLOW WATER wave? (Circle correct answer)

(c) Which of these two expressions is the phase speed of a SHALLOW WATER wave? c is phase speed, g is gravity, H is depth, and k is wavenumber.

Sqrt(gH)



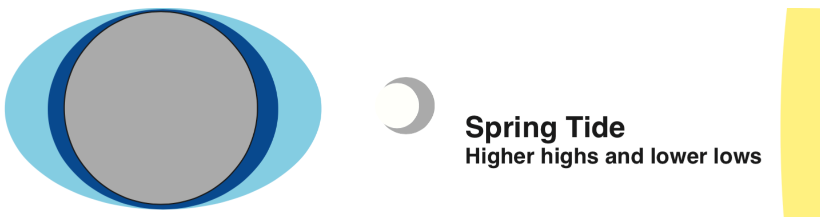
or


(Circle correct answer)

(d) In either of these surface gravity waves (deep or shallow), what is the restoring force for the wave? That is, when the water is disturbed, what force causes the disturbance to change? Restoring force is gravity.

17) (8 points) (2,1,1,1,3)
During particular times that occur regularly, the earth, moon and sun are aligned to produce **anomalously (high) high tides**.

(a) Sketch the alignment of the moon and sun relative to the earth at such a time.
I'm taking it from the powerpoint.



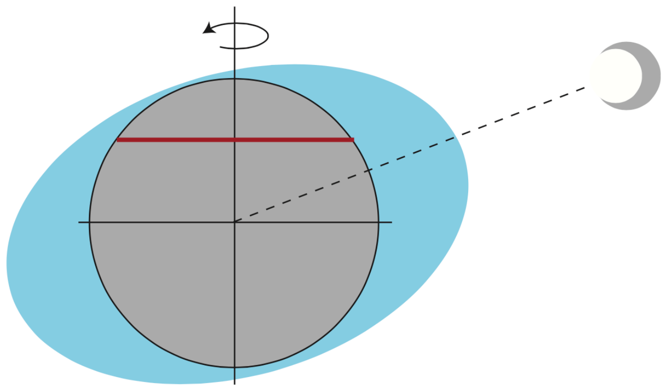
(b) What are these 'particular times' relative to the monthly lunar cycle (added words during exam)? every full and new moon

(c) What is the name given to this anomalously high tide?__spring tide___________

(d) What is the typical period for the anomalous high tide? (That is, what is the time interval between anomalously high tides?) They occur twice a lunar month, so about every 2 weeks.

(e) The semi-diurnal tide has high tide twice a day. Why are these two high tides usually not the same height? Because the moon's orbit is not in the equatorial plane of the earth, that is taking into account its declination. Therefore the size of the tidal bulge when we face the moon is different from when we are on the opposite side of the Earth.

That is, explain why there is a diurnal inequality in the tide. You may use your sketch in (a) to assist, or make a new drawing. Again taking the sketch from the powerpoint. Consider a point on the Earth's surface along the red line. We experience the two tidal bulges differently depending on the declination.



18) (10 points) (2, 2, 2, 4)
This figure is our schematic of the global overturning circulation.

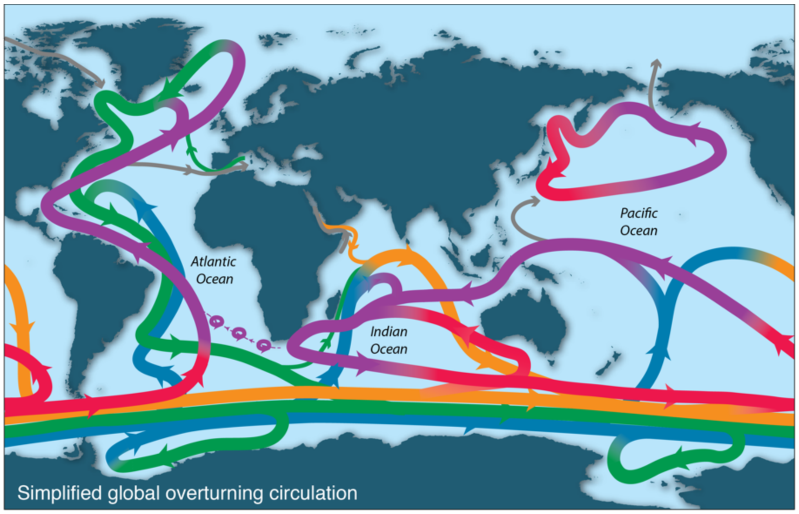
Look at the overturn in the North Atlantic, called the AMOC (Atlantic Meridional Overturning Circulation).

(a) What are the input sources of water from the South Atlantic for this overturn? Circle these sources on the diagram. The purple curve at the surface, and the blue curve at the bottom. The purple also includes the Agulhas rings (purple rings) coming from the Indian Ocean.

Identify them by their water mass names. Purple curves are thermocline water and Antarctic Intermediate Water. Blue curve is the Antarctic Bottom Water.

(b) Where do these source waters transform to components of North Atlantic Deep Water (NADW)? _Upper ocean: Mediterranean Sea, Nordic Seas, and northern subpolar gyre (Labrador Sea, but not depicted well in this schematic). Deep ocean: upward diffusion in the western N. Atlantic is depicted here, but really occurs all along the path from the south_________________________________
Circle these locations. Where the curves change from one color to another.

(c) What are the water mass names of these components of NADW in (b), if different from NADW? Upper ocean: Mediterranean Water (or equivalently Mediterranean Overflow Water), Labrador Sea Water, and Nordic Seas Overflow Water. Deep ocean: just moves up into the bottom of the NADW, could also be called the Lower NADW.



Suppose that the net mass transport involved in the AMOC at 24°N is 20 x 10^9 kg/sec (or a volume transport of 20 Sv).

(d) Assume that the inflow is all at one temperature T_{in} and that the outflow is all at one temperature T_{out}. If the net heat transport associated with the overturning is 1 PW = 1x 10^{15} W (W = Watt), what is the temperature difference (T_{in} - T_{out}) ?
(A sketch may help your thinking about this).

Use our expression for heat transport:

Assume inflow and outflow have the same volume transport, otherwise the calculation makes no sense.

Heat transport = Volume transport x (difference in heat content)
Volume transport V = 20 x 10^6 m/sec
Difference in heat content deltaQ = ρ c_p (Tin – Tout)

Heat transport = V * ρ c_p (Tin – Tout) = 1x 10^{15} W

(Tin – Tout) = (1x 10^{15} W)/(V ρ c_p)

From values at top of exam:

Use ρ = 1025 kg/m^3

c_p = 4000 J/kg°C

(Tin – Tout) = (1x 10^{15} W)/[(20 x 10^6 m/sec)(1025 kg/m^3)(4000 J/kg°C)] = 12°C