

SIO 210 Final examination  
Wednesday, December 17, 2014  
3-6PM Sumner auditorium

Name: \_\_\_\_\_

Turn off all phones, iPods, etc. and put them away.

This is a **closed book exam**.

You may use **one page** of notes, both sides, written or printed.

You may use a non-communicating calculator.

Please mark initials or name on each page.

Check which you prefer regarding the return of this exam and other graded materials

\_\_\_\_\_ I will pick up the exam in Nierenberg Hall 310 (after Jan. 4)

\_\_\_\_\_ Return the exam etc to me via campus mail (or full address)

Mailcode \_\_\_\_\_

[1-10] 10 Multiple choice/short 1 points each \_\_\_\_\_/10

[11-19] 9 Problems (Talley) \_\_\_\_\_/90

[1-11] 10 Multiple choice/short 1 point each \_\_\_\_\_/15

[12-19] 9 Problems (Talley) \_\_\_\_\_/85

Hendershott \_\_\_\_\_/20

Total \_\_\_\_\_/120

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**Possibly useful expressions and values; you will not need all of these.**

$\rho$ : use  $1025 \text{ kg/m}^3$  for generic calculations

$c_p = 3850 \text{ J/kg}^\circ\text{C}$

$\rho c_p T$

$1 \text{ PW} = 10^{15} \text{ W} = 10^{15} \text{ J/sec}$

Earth's radius: 6371 km

$U_{Ek} = \tau / (\rho f)$

$R_o = U / (fL)$

$f = 2\Omega \sin(\text{latitude})$

$\Omega = 0.73 \times 10^{-4} / \text{sec}$

$\sin(30^\circ) = 0.5$

$\sin(50^\circ) = 0.77$

$1^\circ \text{ latitude} = 111 \text{ km}$

$1 \text{ Sv} = 1 \times 10^6 \text{ m}^3 / \text{sec}$

acceleration + advection + Coriolis force =

pressure gradient force + gravity + friction

**Multiple choice** (1 point each; 10 points total)

For each multiple choice problem, **circle ONE CORRECT answer.**

1. The force balance in an Ekman layer is between

- (a) acceleration and pressure gradient force
- (b) advection and Coriolis force
- (c) Coriolis force and vertical diffusion
- (d) Coriolis force and horizontal diffusion

2. Brine rejection

- (a) creates North Atlantic Deep Water
- (b) causes sea ice to become salty
- (c) occurs in hydrothermal vents
- (d) causes Antarctic shelf water to be denser than Antarctic Surface Water

3. Subducting flow is associated with

- (a) High nitrate at the sea surface
- (b) Formation of slightly warmed water at deep sea tectonic subduction zones
- (c) Central Water
- (d) Nordic Sea Overflow Water

4. During the Asian Southwest monsoon

- (a) the Somali Current flows northward
- (b) the Somali Current flows southward
- (c) India has its dry season
- (d) the tropical Pacific enters a La Nina phase

5. The Subantarctic Front marks

- (a) the northernmost extent of Antarctic shelf water
- (b) the southernmost extent of Antarctic Intermediate Water
- (c) the northernmost extent of sea ice
- (d) the zero of wind stress

6. The northeastward circulation in the northeastern North Atlantic, between the Reykjanes Ridge and Ireland, far to the south of Iceland, is called the

- (a) Labrador Current
- (b) Azores Current
- (c) North Atlantic Current
- (d) Norwegian Atlantic Current

7. Seawater compression

- (a) is important for geostrophic balance

- (b) is important for sound waves
- (c) is important for tides
- (d) is important for the outflow of fjords

8. The Rossby number is
- (a) an indication of existence of a large-scale wave
  - (b) small when flow is geostrophic
  - (c) large in an El Nino
  - (d) an indication of the speed of a tsunami wave

9. The Equatorial Undercurrent
- (a) flows from east to west
  - (b) is driven directly by the frictional wind stress
  - (c) is one of the strongest currents in terms of speed
  - (d) extends to the ocean bottom

10. Wind stress acting on the ocean's surface **NOTE I SHOULD HAVE WRITTEN "CAN CAUSE...."**
- (a) causes surface flow to the right of the wind in the Southern Hemisphere
  - (b) causes counter-rotating vertical cells with convergences aligned with the wind
  - (c) pushes the North Pacific Current to flow downwind beneath the Westerlies
  - (d) heats the ocean

**Very short answer** (5 points)

11. Circle the western boundary currents in the following list. There are several (more than one).

circle WBCs	list the ocean for every current including "South" or "North" if appropriate
Leeuwin Current	___(South) Indian_____
<b>Gulf Stream</b>	___North Atlantic_____
<b>Oyashio Current</b>	___North Pacific_____
Antarctic Circumpolar Current	___Southern Ocean_____

**Problems** 10 to 15 points each

12. (10 points)

(a) In the subtropical *South Atlantic*, the meridional heat transport across 30°S is approximately 0.5 PW northward. Much of this transport is associated with the global overturning circulation. Sketch the circulation in a vertical cross-section, and label the northward and southward portions. If there are specific water masses associated with these portions, please include those names. Indicate which part of the circulation is warmer and which part is cooler.

**A complete sketch would include the (1) the meridional overturning circulation, including northward upper ocean (thermocline) waters, southward North Atlantic Deep Water, and northward Antarctic Bottom Waters; and (2) the Brazil Current**

subtropical gyre circulation with southward Brazil Current in west and northward Benguela plus subtropical circulation in the east and central basin. (1) is responsible for the northward heat transport, since (2) transports heat southwards.

(b) If the circulation transports 10 Sv northward, and returns 10 Sv southward, what is the difference in temperature between the northward and southward parts of the circulation? (*calculate*)

Heat transport is  $Q = \rho c_p V (\Delta T)$

$$\Delta T = Q / (\rho c_p V) = (0.5 \times 10^{15} \text{W}) / [(1025 \text{ kg/m}^3) (3850 \text{ J/kg}^\circ\text{C}) (10 \times 10^6 \text{ m}^3/\text{sec})] = 12.67^\circ\text{C}$$

13. (10 points) The potential vorticity for the general circulation (both wind-driven and abyssal) is

$$PV = (\zeta + f) / H$$

(a) Which terms are the relative vorticity      $\zeta$     , planetary vorticity      $f$     , and related to stretching      $H$     ? (Fill in the blanks.)

(b) For the abyssal circulation, Stommel-Arons model, which terms in the PV are dominant? Which term(s) are ignored?

Dominant terms are  $f$  and  $H$ . Term that is ignored is  $\zeta$ .

(c) For abyssal circulation, explain the external forcing for the flow. (For instance, is it wind, dense water formation, topography, etc.?)

External forcing is addition of water to the layer through a localized source, which causes the layer volume to increase. Therefore the upper interface of the layer rises, which causes  $H$  to increase.

(d) For the abyssal circulation, describe the pattern of horizontal circulation. Assume the ocean has a flat bottom, and that it has vertical sides, including meridional boundaries.

For the Stommel-Arons circulation of parts b and c, the pattern of horizontal circulation is poleward meridional flow due to the stretching ( $1/H$ ) which requires an increase in planetary vorticity ( $f$ ). This poleward flow everywhere is balanced by Deep Western Boundary Currents that carry the water to balance mass of the poleward interior plus the loss of water upward. The zonal (east-west) is whatever is required to connect these meridional flows. This ends up creating cyclonic deep gyres.

14. (10 points) ENSO is a coupled climate phenomenon in the tropical Pacific that has both regional and global impacts.

(a) The Bjerknes feedback between the ocean and atmosphere maintains the distribution of equatorial winds and ocean circulation. Describe how this feedback works during “normal” or La Nina years.

In the Bjerknes feedback, air rises over warm water and sinks over cooler water. This sets up surface winds from cool to warm water. Along the equator, these winds drive the surface water frictionally from cool to warm. This causes even more cooling in the cool regions and warming in the warm regions as water must upwell to fill in the cool region and the warm surface water is pushed towards the warmest region. In a “normal” or La Nina year in the tropical Pacific, there is a warm pool in the west and cold tongue in the east. The Bjerknes feedback maintains and strengthens this contrast. The winds that are driven through this feedback are called the “Walker circulation” and are easterly trades at the sea surface. The ocean surface current that is driven by this is called the South Equatorial Current. The tradewinds cause upwelling along the equator, shoaling of the thermocline towards the east, which means that the upwelled water in the east is cooler than in the west. Because the surface water is warmed, the westward surface flow adds to the warm pool and pushes the thermocline down there.

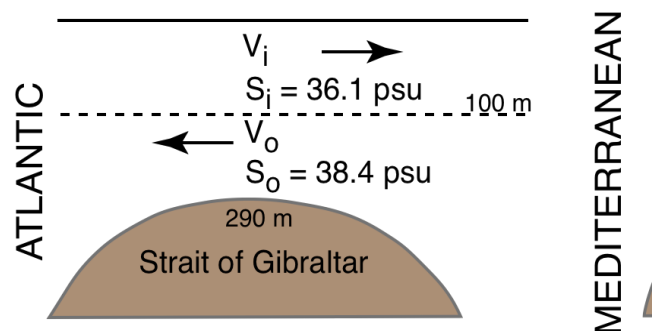
(b) Describe how the ocean-atmosphere system is different during El Nino years. During El Nino years, the cycle is broken. The trades are weaker, the upwelling is weak, the temperature contrast between warm west and east is reduced, and this further reduces the strength of the trades.

c) During an El Nino event, the surface waters along the Peruvian coast become warmer. Why are the Peruvian surface waters usually cold?

The Peruvian surface waters are usually cold because of the equatorward winds along the South American coast which drive coastal upwelling as part of the Peru-Chile Current System.

15. (10 points) The North Atlantic and the Mediterranean Sea are connected through the narrow Strait of Gibraltar, which has a two layer flow. See the figure. In the Strait, all inflow to the Mediterranean is in the surface layer, and all outflow back to the Atlantic is in the bottom layer.

(a) for MEDITERRANEAN



Assume that the inflow transport and outflow transport are approximately equal.

Given:

average inflow salinity is 36.1

average outflow salinity is 38.4

Average exchange volume transport  $V$  is  $0.7 \text{ Sv} = 0.7 \times 10^6 \text{ m}^3/\text{sec}$

(a) (7 points) Freshwater: calculate the net Evaporation – Precipitation – Runoff within the Mediterranean. Use the Average exchange volume transport. Express your answer in Sv (either mass or volume based).

Use the formula  $F \sim \rho V(S_o - S_i)/S_m$

Calculate a mean salinity of 37.25

$F = 1025 \text{ kg/m}^3 * 0.7 \times 10^6 \text{ m}^3/\text{sec} * (2.3)/37.25 = 4.4 \times 10^7 \text{ kg/sec} = 0.04 \text{ Sv}$

(b) (3 points)

Using your answer to (a), if the inflow volume transport is exactly 0.7 Sv, what is the estimated outflow volume transport? (Note that we assumed they are approximately equal in (a), and now we being more accurate and saying that they are not exactly equal.)

Just subtract:  $0.7 \text{ Sv} - 0.04 \text{ Sv} = 6.96 \text{ Sv}$ .

**16.** (10 points) A map of adjusted steric height, corresponding to geostrophic streamlines, in the Pacific at the sea surface and near the ocean bottom.

(a) On the map, mark the Kuroshio and California Current.

(b) Mark the high and low pressure regions associated with the Kuroshio and its associated large-scale circulation (gyre). Highest pressure for Kuroshio is just to the east and south. Low pressure that I was thinking of is to its west and north (inshore), but I was OK with answers that showed low pressure far to the east at California coast, especially given (c).

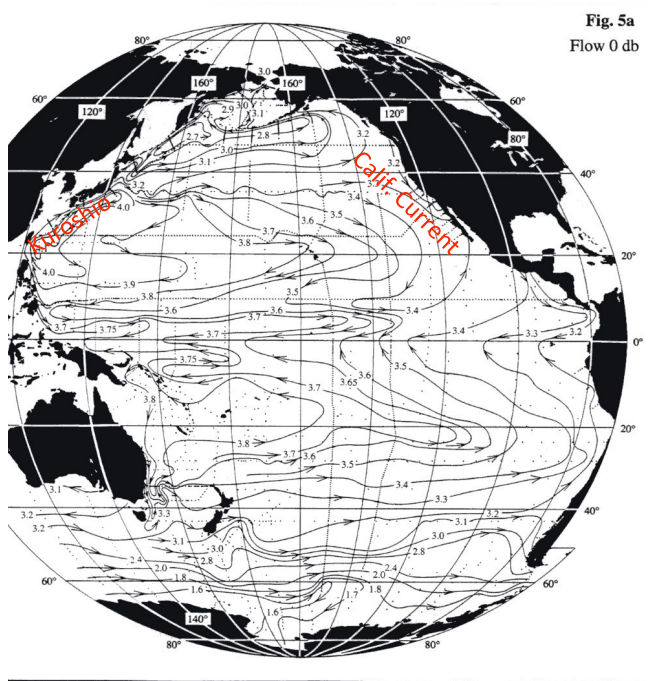
(c) Are these circulations associated with anticyclonic or cyclonic flow? Explain the direction of the flow in this current system relative to the highs and lows.

Circulation is anticyclonic. Flow is clockwise around the high pressure offshore of the Kuroshio.

(d) What is the approximate steric height difference across the Kuroshio? From the inshore side of the Kuroshio to highest height offshore, difference is 3.2 to 4.1 dyn m or 90 cm. I also accepted answers that looked at highest height offshore of Kuroshio and California coastline value, which is the same height difference since the height at both coasts should be the same (very small net

meridional transport).

- (e) What is the approximate steric height difference across the California Current? **From about 3.2 dyn m at coast to 3.3 or 3.4 offshore, so total of 10 to 20 cm.**
- (f) Estimate the *relative strength* of the surface current in the Kuroshio and in the California Current. Do not calculate the absolute velocities, just the relative sizes. **If both currents are taken to be about 100 km across, then the relative height difference is also the relative current speed difference, so 90/10 or 9 to 1 (Kuroshio to CA Current).**



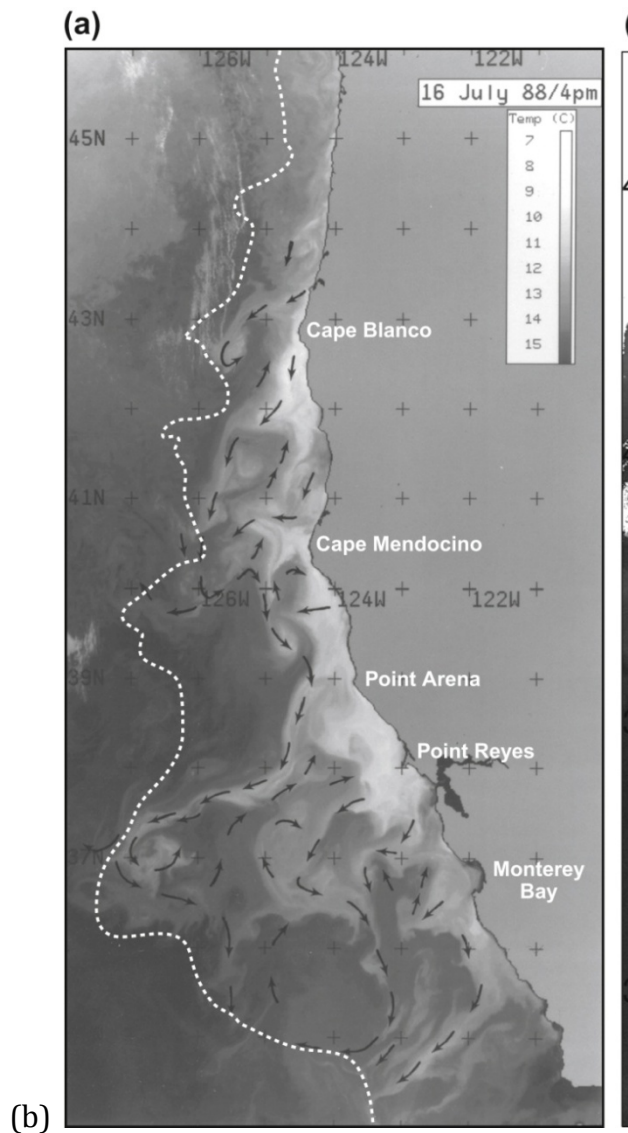
17. (10 points) The satellite image shows surface temperature on a particular day, in shades of gray, along the coast of California and Oregon. Surface currents are also shown (small arrows).

- (a) Explain in the simplest terms why there is cold water along the coast. Draw the direction of the wind as part of your explanation. **Cold water along coast is due to upwelling of subsurface water. Upwelling is driven by alongshore winds (equatorward or north to south). For answer key I am not drawing in.**

(b) What is the name of this circulation system? What direction is the overall surface current, at the largest scale? **California Current System. Surface current is southwards.**

(c) The synoptic temperature and current distribution is more complicated than this simplest description. Explain in simple terms why this is so.

**Many reasons: principal reason is that the flow is highly unstable with spatial scales associated with the coastline shape (capes); the offshore Ekman transport occupies about the same depths as the CA current itself which also creates complexities; forcing is highly time dependent.**



18. (15 points) The attached color figures are zonal sections of various properties



(potential temperature, salinity, oxygen, CFC-11) across the North Atlantic, at 24°N. The map of the section is inserted on the CFC-11 figure.

Neutral density sections at 24°N (left) and 36°N (right) are also attached. Some density features are clearer at 36°N because there is no island near the western boundary.

(a) Locate and mark the Gulf Stream on the 36°N neutral density section. (see attached)

(b) Locate and mark the Canary Current on the 24°N neutral density section. (see attached)

(c) Locate and mark the southward flow of the North Atlantic's subtropical gyre on both neutral density sections. (see attached)

(d) The above circulations are all surface-intensified circulations. Along the top of the 36°N neutral density section, sketch a smoothed version of the sea surface height that is associated with these circulations. Make sure that your sketch corresponds with a smoothed version of the neutral density section. Make sure that your sketch shows the regions that have high and low surface height. (I can't freehand this in powerpoint. Height should go up fast over the Gulf Stream, very narrow, then return downward towards east; you can mirror the large eddies to be a little more accurate.)

(e) At the left side of the 36°N section, explain the direction of the circulation in terms of the sea surface height that you have just sketched. That is, given the sea surface height, what direction does the circulation go? Why? Sea surface height difference across the Gulf Stream – low at the coast, high offshore. Therefore the p<sub>gf</sub> is westward. Due to Coriolis force, the geostrophic surface flow is therefore northward.

(f) On the same 36°N section, please indicate on the section the direction and magnitude of the current at the surface and then down through the water column to the bottom. can't get the symbols working in powerpoint. Large X northward at Gulf Stream, smaller and smaller X northwards with depth under that, in the Gulf Stream. Can show DOT southward under Gulf Stream along western boundary. Then show small DOTS southward all the way across the surface of the section to the eastern side, and then represent decrease of circulation with depth.

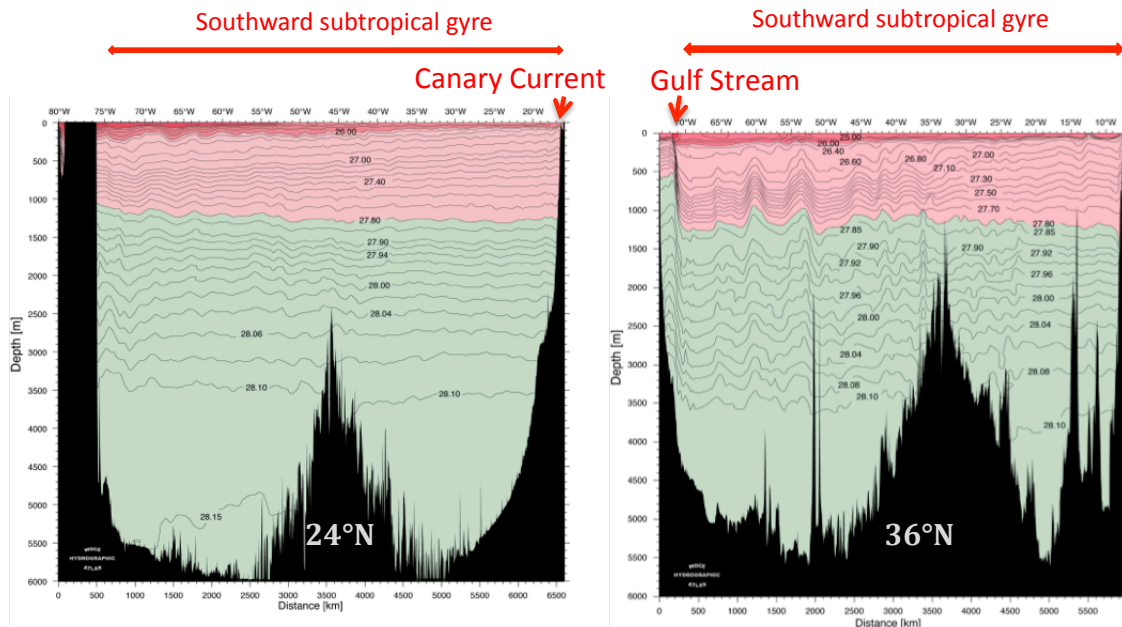
Use symbols like these to show direction, and vary the size of the symbols to show magnitude.



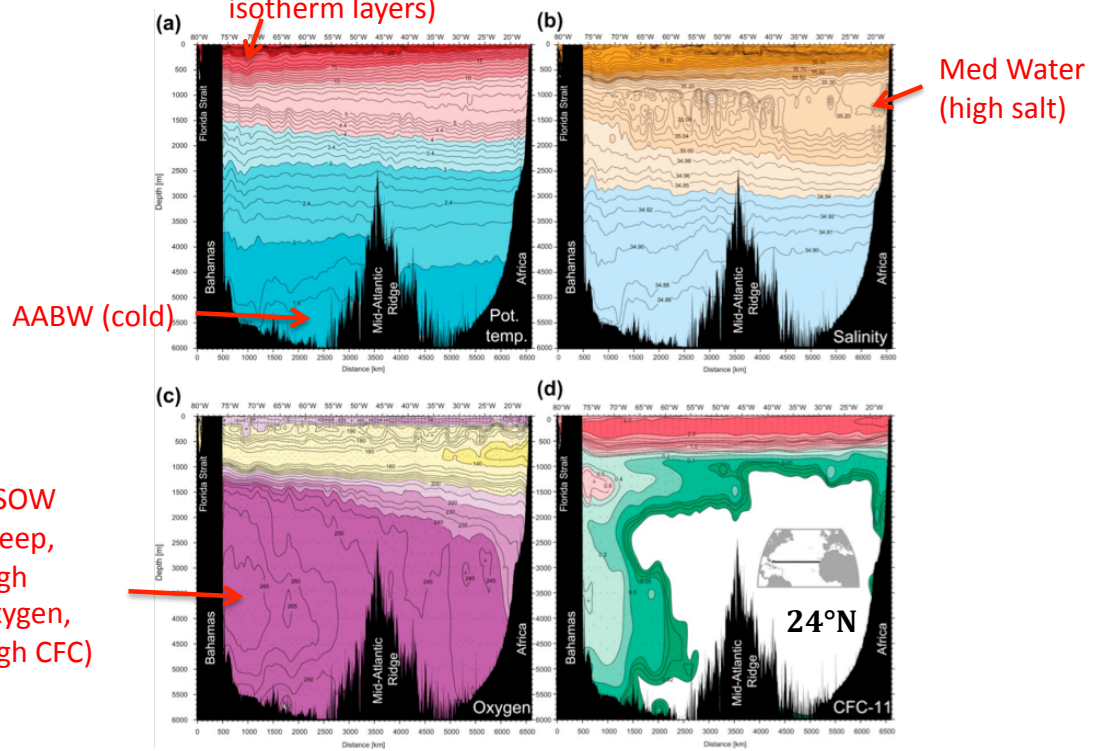
(g) On the colored 24°N property plots, use the properties to identify and mark the following water masses: (see attached)

- (i) Mediterranean Water
- (ii) Antarctic Bottom Water
- (iii) Nordic Seas Overflow Water
- (iv) Subtropical Mode Water

(h) For the Nordic Seas Overflow Water: what properties did you use to identify the water mass? Why do they have the particular signals you use for identification? That is, what is the source of NSOW and how does it reach this latitude? **Properties of NSOW are that it is a recently formed water mass, so it has high oxygen and measurable CFCs. It is also relatively cold, about 1 to 2 deg C. It is carried southward in a Deep Western Boundary Current, evidence for which is the high oxygen, CFC structure at the western side of the section.**



STMW (upper ocean, 18 deg, thicker isotherm layers)



Med Water (high salt)

AABW (cold)

NSOW (deep, high oxygen, high CFC)

24°N

CFC-11

19. (10 points) Consider the attached map of the global overturning circulation.

(a) What water masses (names) are formed in the highest latitude regions in both hemispheres? Label the water masses on the map, in the North Atlantic, North Pacific, Ross Sea and Weddell Sea.

N. Atlantic: North Atlantic Deep Water (arrows into Greenland and Labrador Seas)

N. Pacific: North Pacific Intermediate Water

Ross Sea (farthest southern reaches of Pacific): Antarctic Bottom Water

Weddell sea (farther southern reaches of Atlantic): Antarctic Bottom Water

(b) The blue curves in the Atlantic, Indian and Pacific connect to green, orange and orange, respectively.

What water mass is depicted by the blue curve (name)? AABW

What water mass is depicted by the green curve (name)? NADW

What water mass is depicted by the orange curve in the south Pacific Ocean? Pacific Deep Water (PDW)

(c) Describe the process that occurs when the blue curves connect to the green and orange curves. What happens to the density of the sea water during the connection? How does this occur? **Blue (AABW) becomes warmer through downward diffusion of heat, hence becomes less dense and joins the bottom of the NADW, and feeds into PDW and IDW.**

