SIO 210 Final examination
Wednesday, December 11, 2013
2-5 PM Sumner auditorium
Answer key

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.
Please hand in your notes page, if you have one, with your exam.

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 Dec. 15)
_____Return the exam etc to me via campus mail (or full address)
Mailcode_____

[1-10] 10 Multiple choice/short 2 points each	_____/20
[11] 1 Problem (Hendershott)	_____/10
[12-19] 8 Problems (Talley)	_____/70
Total	_____/100

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

ρ: use 1025 kg/m^3 for generic calculations
c_p = 3850 J/kg°C
$\rho\ c_p\ T$
1 PW = 10^{15} W = 10^{15} J/sec
Earth's radius: 6371 km
$C = 2\pi R$
$A = \pi R^2$
$A = 4\pi R^2$
$U_{Ek} = \tau/(\rho f)$
PV = (relative vorticity + planetary vorticity)/height = $(\zeta + f)/H$
$f = 2\Omega \sin(\text{latitude})$
$\Omega = 0.73 \times 10^{-4}$/sec
sin (30°) = 0.5
sin(50°) = 0.77
1° latitude = 111 km
1 Sv = 1x10^6 m^3/sec
acceleration + advection + Coriolis force =
pressure gradient force + gravity + friction

Multiple choice and very short answer (2 points each; 20 points total)
For each multiple choice problem, **circle ONE CORRECT answer**.

1. Upwelling at the ocean's surface creates
(a) inertial circles following a strong storm
(b) surfacing of abyssal (> 2 km depth) water in the California Current
(c) equatorward Ekman transport
(d) high nitrate at the surface in the Southern Ocean

2. Wind stress acting on the ocean's surface
(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) directly pushes the North Atlantic Current to flow downwind beneath the Westerlies
(d) heats the ocean

3. 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

4. The *undercurrent* in the California Current system
(a) is forced by offshore Ekman transport
(b) carries subpolar water southward
(c) sits at about 200 m depth
(d) is located offshore of the California Current

5. The atmosphere's Hadley circulation
(a) is forced mainly by high surface temperatures in the tropics
(b) creates eastward winds at the sea surface
(c) includes rising air directly along the equator in the annual mean
(d) has sinking air near the north and south poles

6. In the large-scale ocean gyres, the potential vorticity balance in the open ocean (not near the boundaries) is between
(a) Coriolis force and stretching
(b) Coriolis force change with latitude and stretching
(c) Stretching and eddies (relative vorticity)
(d) Coriolis force change with latitude and eddies (relative vorticity)

7. 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

8. In the tropical Pacific, the Walker circulation
(a) weakens during El Nino events
(b) strengthens during El Nino events
(c) causes the surface water along the equator to flow eastward
(d) is associated with excess rainfall near Ecuador and Peru

Very short answer. Problems 9 and 10 are to be answered together.
9. Circle the eastern boundary currents in the following list. There are several (more than one).

(9) circle EBCs	(10) list ocean
East Greenland Current	____North Atlantic_____
Canary Current	____North Atlantic_____
Peru-Chile Current	____South Pacific_____
Agulhas Current	____Indian_____

10. For ALL of the boundary currents in the previous question: list the appropriate ocean basin (South Atlantic, North Atlantic, South Pacific, North Pacific, Indian)

Problems 4 to 15 points each

11. (10 points) (Hendershott)
This is a list of astronomical events associated with tides:

A. times of half moon
B. time of full moon
C. time of new moon
D. time of lunar perigee
E. times when moon is in earth's equatorial plane
F. times when moon is farthest out of earth's equatorial plane
G. times when the sun is in the earth's equatorial plane
H. times when sun is farthest out of earth's equatorial plane

Answer the following questions using letters "A" through "H":

(a) Which one of the above events occurs at the equinoxes, that is, the times of year when day and night are the same length? ____G_____

(b) Which one of the above events occurs at the solstices, when the sun is as far north or south in the sky as it will be during the year? ____H_____

(c) Flooding once per day at La Jolla Shores at e.g. the Marine Room due to strong winter storms is particularly common in early January. Which one event on the list A through H

is this close to in time? ___H____

(d) Spring tides are most pronounced around the time(s) of which astronomical events on the list A through H? (one or more events) ___B, C_____

(e) The daily inequality is most pronounced around the time(s) of which astronomical events on the list A through H? (one or more events) ___F, H_____

12. (6 points)
(a) Sketch the pathway of inertial motion in the Northern Hemisphere. Make sure you have the correct direction.

Answer should be a circle, with arrows showing clockwise motion

(b) What is the force balance in an inertial motion? __acceleration_____ and ____Coriolis force_____

(c) Explain the direction of the inertial motion in terms of this force balance.

Water parcel turns to the right (accelerated to the right) due to Coriolis, NH.

13. (6 points)
The equation of state of seawater relates the seawater density ρ to physical properties of seawater. That is, ρ = ρ(property i, property ii, property iii).
(a) What are the three properties (in any order)?
property i. __T____
property ii. ___S___
property iii. ___P___

(b) Seawater density dependence on these properties can be expressed as

$$\frac{\partial \rho}{\partial property}$$

Which property, when placed in this expression, is related to *sound speed*?___pressure_____ (actually sound speed is the square root of the inverse of this expression)

(c) Explain why sound speed has this dependence: that is, what is an acoustic wave?

Any answer that explains that sound is a compressional wave; for instance as pressure changes in the wave, particles get closer together, which changes the density.

14. (10 points) (a) In the subtropical North Pacific, the meridional heat transport across 24°N is approximately 0.8 PW northward. Almost all of this transport is associated with the subtropical gyre circulation. If the circulation transports 30 Sv northward, and returns 30 Sv southward, what is the difference in temperature between the northward and southward parts of the circulation? (*calculate*)

Use the expression $\rho c_p T$ for heat (from page 1), and other values also from page 1

Heat transport is

$$Q_{trans} = V \rho c_p \Delta T$$

Therefore

$$0.8 \text{ PW} = (30 \text{ Sv})\ (1025 \text{ kg/m}^3)(3850 \text{ J/kg°C})\ \Delta T$$

Therefore $\Delta T = 6.75$°C

(b) Sketch the circulation for part (a), and label the northward and southward portions. If there are specific current names associated with these portions, please include those names. Indicate which part of the circulation is warmer and which part is cooler.

Sketch should show a subtropical gyre circulation (clockwise), should show northward Kuroshio as an intense, narrow western boundary current, and broader southward return flow in rest of the gyre. Sketch should show that the Kuroshio is warmer and southward return flow is cooler.

(c) In the South Atlantic, the total meridional heat transport at 30°S is approximately 0.3 PW northwards. 30°S is across the center of the subtropical gyre. Explain why the South Atlantic's meridional transport is northwards, including insight from parts a and b.

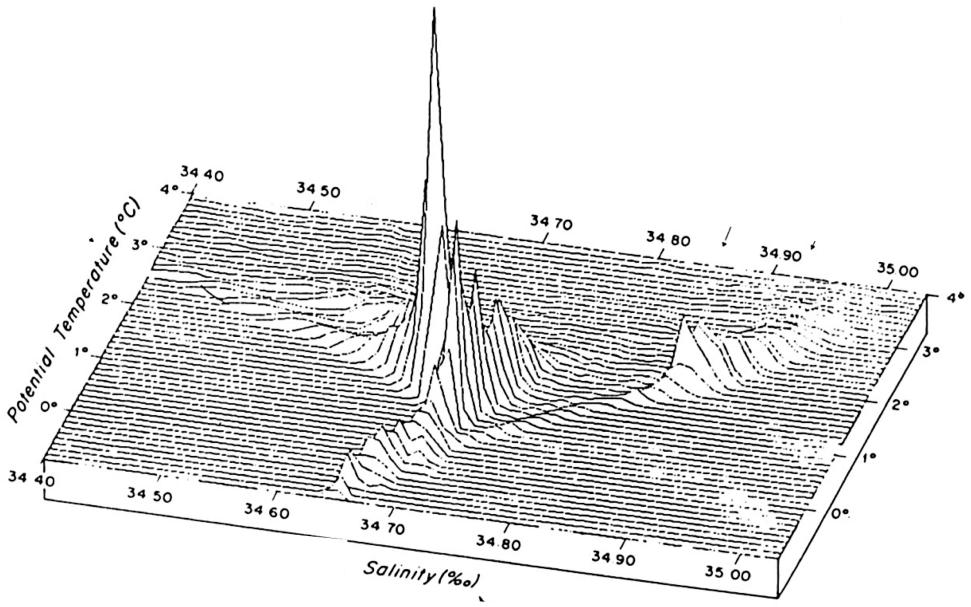
The S. Atlantic subtropical gyre has a warm, southward western boundary current (Brazil Current) and cooler northward return flow. This would yield a southward heat transport. The total heat is northward because of the meridional overturning circulation of the NADW: superimposed on the ST gyre, there is northward flow of warmer thermocline water and southward flow of dense, cold NADW, which in itself transports heat northward. It turns out that this northward heat transport is larger than the ST gyre's southward heat transport.

15. (10 points)
(a) If 20 Sv of NADW is formed in the far northern North Atlantic and adjacent seas, and rises uniformly over the entire ocean, *calculate* the average vertical velocity of the upwelling.
(Assume that the oceans cover 70% of Earth's surface and, for simplicity, assume the ocean is flat bottomed and is all very deep, with no shelves, etc.)
Calculate the surface area of the Earth, using expression from page 1 (I provided both the area of a circle and the area of a sphere. They should be able to figure out which one to use without being told.)
Area = $4\pi R^2 = 5.10 \times 10^{14}$ m^2
R = 6371 km (provided on page 1)
Multiply by 0.7 to get 70 %
Areaocean = $0.7 * 4\pi (6371 \times 10^3 \text{ m})^2 = 0.7 \times 5.10 \times 10^{14}$ m^2 = 3.57×10^{14} m^2
W = 20 Sv / Areaocean = 20×10^6 m^3/sec / $(3.57 \times 10^{14}$ $m^2) = 5.6 \times 10^{-8}$ m/sec

(b) From the simplified Stommel-Arons theory of abyssal circulation, what direction is the deep circulation associated with (a) in the North Atlantic, if you assume that the ocean has a flat bottom? (use words and/or a sketch)
Should indicate that there is poleward flow in the interior ocean, and a southward DWBC.

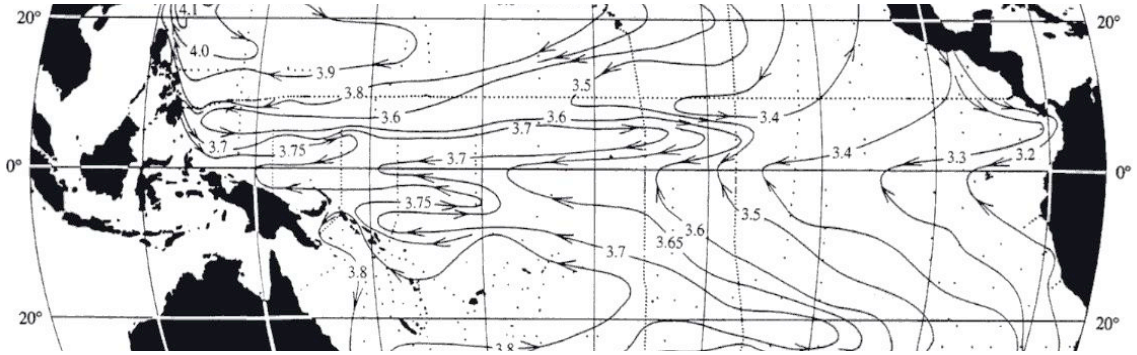
16. (4 points) The figure shows the amount of water in each potential temperature-salinity grid box for the deep World Ocean (potential temperature < 4°C).
(a) Label the portions that are in the Atlantic, Pacific, and Southern Oceans. (Mark on the figure.) Atlantic is ridge to the right (high S), Pacific includes huge peak in center, Southern is coldest tail at bottom.

(b) Explain how you can tell the difference between the Atlantic and Pacific waters in this plot.
Various answers are acceptable: Pacific is fresher than Atlantic, know that Pacific has huge volume of single T-S class (Common or Deep Water), etc.


Potential Temperature (°C)
4°
3°
2°
1°
0°
34 40
34 50
34 70
34 80
34 90
35 00
34 40
34 50
34 60
34 70
34 80
34 90
35 00
Salinity (‰)
4°
3°
2°
1°
0°

17. (4 points)
(a) The Pacific surface steric height and inferred direction of circulation is shown in the figure (from Reid, 1997). Label the:
North Equatorial Current westward flow between 10 and 20°N
North Equatorial Countercurrent eastward flow in narrow range 5 to 10°N
South Equatorial Current westward flow in S. Pacific and also just north of equator

(b) Is the equatorial surface current geostrophic? If not, what is the force balance for this surface current (top 50 meters of the ocean)? Not geostrophic. Force balance is between wind stress and vertical viscous term (or also acceptable to say acceleration).



18. (15 points)
The attached color figures show (i) oxygen on the neutral density surface $\gamma^N = 28.10$ kg/m^3, (ii) the depth of the neutral density surface surface $\gamma^N = 28.10$ kg/m^3, and (iii) oxygen at 3500 m depth, and in the Pacific and Atlantic. NOTE: the color scales are DIFFERENT in the two panels. (Yellow-purple break is 160 μmol/kg in both Pacific maps but 244 μmol/kg and 225 μmol/kg in Atlantic neutral density and 3500 m maps.)

(a) Explain the oxygen pattern on the isoneutral surface in the Atlantic in terms of water mass formation and circulation that affect this isoneutral surface:
(i) What water masses dominate the Atlantic map?
North Atlantic Deep Water (high oxygen in north and along western boundary –purple)
Various answers for Antarctic Bottom Water or Circumpolar Deep Water (high oxygen in Weddell) – AABW is not technically correct, but I don't expect them to know this.
Pacific Deep Water or Circumpolar Deep Water (low oxygen, yellow in ACC region)

(ii) Choose one of these water masses and explain where and how it is formed.
NADW is formed in the northern North Atlantic. Students should answer this one at great length – too much for this answer key.
AABW/Weddell Deep Water formed in the Weddell Sea

Pacific/Indian Deep Water formed by upwelling and diffusion in those oceans.

(iii) What circulation of those water masses is implied by the oxygen pattern?
Southward flow in the western N. Atlantic, especially in the DWBC. Northwrad flow in the eastern South Atlantic. Eastward flow in the ACC region.

(b) Explain the oxygen pattern on the isoneutral surface in the Pacific in terms of water mass formation and circulation that affect this isoneutral surface:

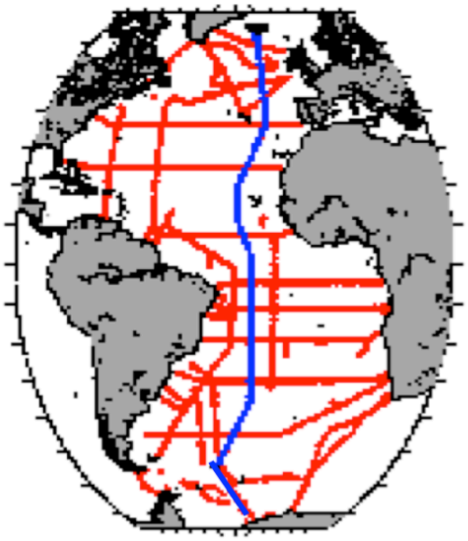
(i) What water masses dominate the Pacific map?
Pacific Deep Water - low oxygen
Ross Sea bottom water – highest oxygen near Antarctica
Circumpolar Deep Water, could mention some NADW component – high oxygens in ACC

(ii) What circulation of those water masses is implied by the oxygen pattern?
Eastward flow in ACC
Northward DWBC (very very broad) into Pacific, weak sign of southward flow back

(c) Where is this isoneutral surface the shallowest on these maps? Why is it shallowest there? (Explain in terms of the large-scale external forcing in the region where it is shallowest.)
Shallowest in the Southern Ocean, where it surfaces.
Isoneutral surface slopes up to sea surface because of wind-driven Ekman suction, northward Ekman transport.
Could also accept answer about formation of very dense water in the south that displaces this isoneutral surface upwards.

19. (15 points) The last color figure (last page of exam) is a section of neutral density through the center of the North Atlantic, at about 20°W.

For your information, here is a section location map (dark central section from Iceland to Antarctica). Please answer this question by labeling the NEUTRAL DENSITY SECTION and not this small map.



Assume that neutral density and potential density provide similar information about geostrophic shear. (We did not discuss this equivalence in class.)

While you are answering parts (a) through (d), leave enough space about the section for the answer to part (e).

(a) Locate the Antarctic Circumpolar Current on the neutral density section and mark it.
Mark the region with sloping isopycnals between about 45 and 62 S.
NOTE for Myrl and Chris: they might ask about all the eddy variability (bumps and wiggles) – they should just smooth by eye, ignore that variability.

(b) Locate the Weddell Gyre on the neutral density section and mark it.
Mark region from about 55S or 60S to left side of plot

(c) Locate the South Atlantic's subtropical gyre on the neutral density section and mark it.
Region from about 5S to the northern end of the ACC at about 45

(d) Locate the North Atlantic Current on the neutral density section and mark it.
More gently sloping isoneutrals, from about 40N to northern (right) end of section.

(e) The above circulations are all surface-intensified circulations. Along the top of the 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'm expecting a smoothed curve that more or less is the mirror image of the isoneutral contours near the sea surface. High at Antarctica, low in the Weddell gyre, rising northward to center of S. Atlantic ST gyre, falling towards equator, rising again across N. Atlantic ST gyre, falling gently to north through the N. Atlantic Current.

(f) At the southern end of the section (left side of plot), 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?

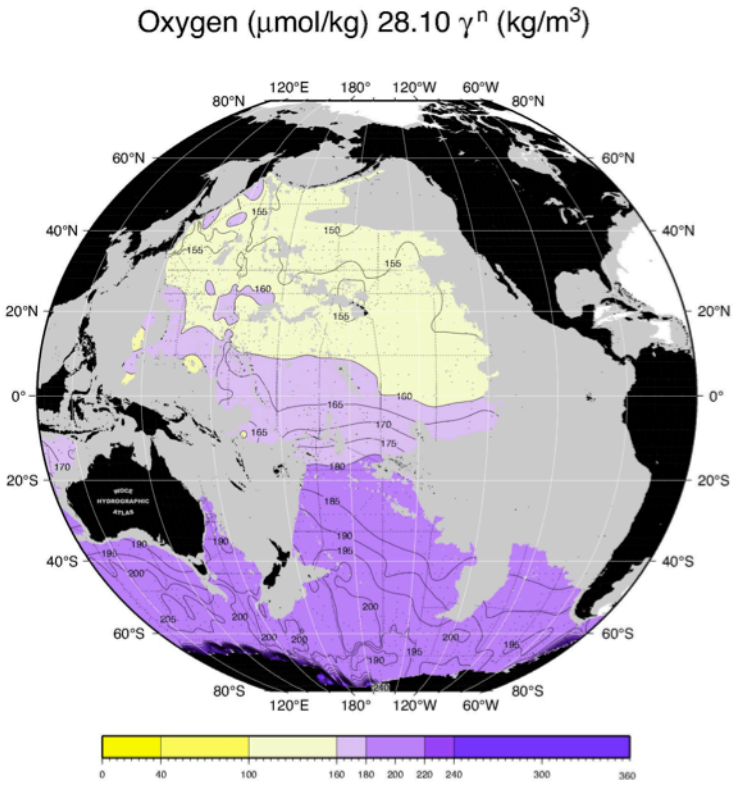
Should explain a clockwise circulation (westward along coast of Antarctica and eastward in the ACC) – geostrophic, flow turned to the left of the pgf implied by the SSH.

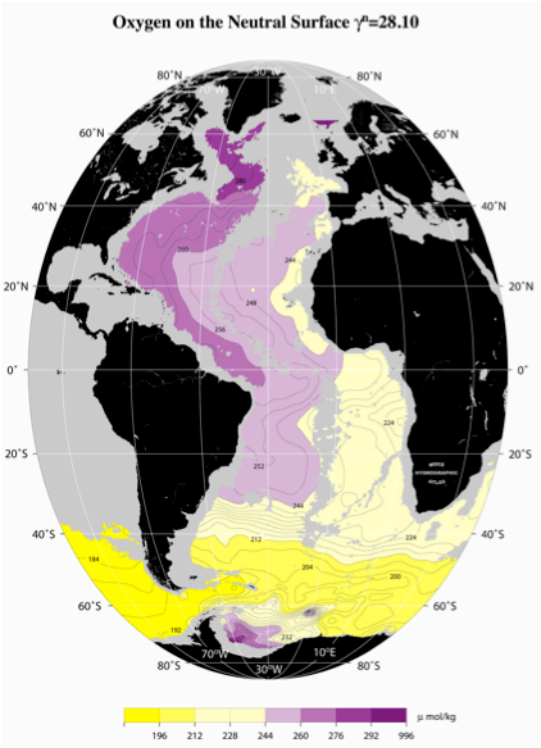
(g) For the Antarctic Circumpolar Current (part a), please indicate on the section the direction and magnitude of the current at the surface and then down through the water column to the bottom.

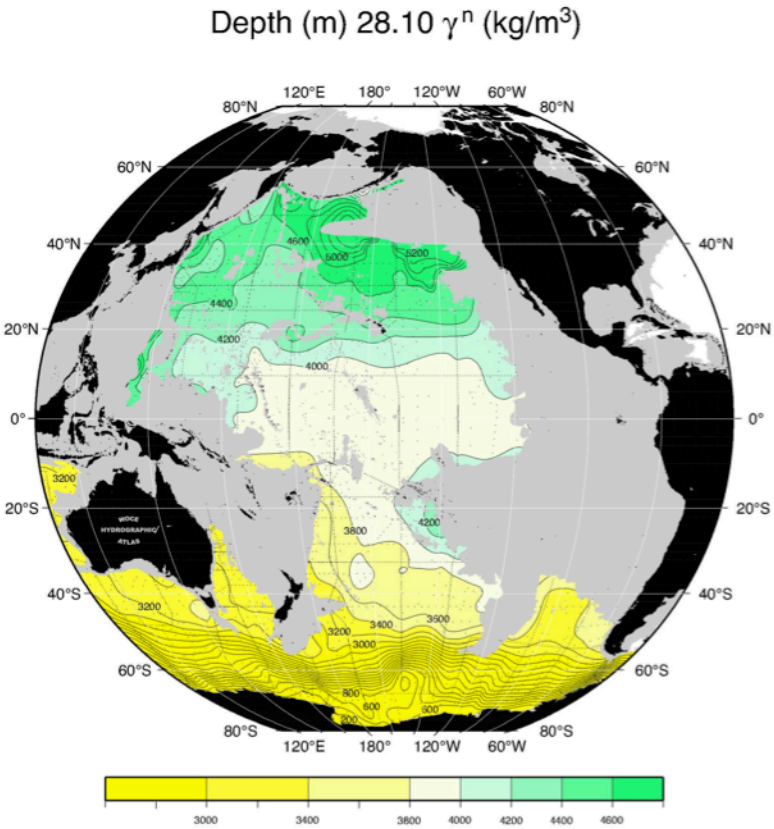
Use symbols like these to show direction, and vary the size of the symbols to show magnitude.

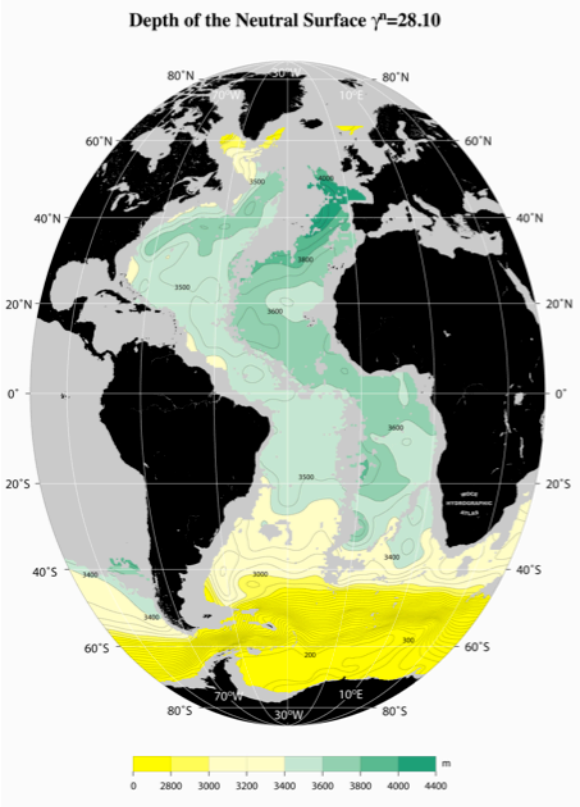
I'm expecting you to show the ACC coming out of the page (leftmost symbol), largest at surface, decreasing size of circle with depth.

For Question 18.









 For Question 19.