SIO 210 Final examination Answer Key for all questions except Daisyworld.
Wednesday, December 10, 2008
3-6 PM

Name:______________________

This is a closed book exam. You may use a calculator.

There are two parts: Talley (weighted 70% of exam) and Hendershott (weighted 30% of exam)

Talley portion: 70 points
[1-5] Multiple choice 3 points each ________________/15
[6-10] Short answer 5 points each ________________/25
[11-12] Long answer 15 points each ________________ /30

Some useful expressions and a global map are found on the last page as reference materials.

Multiple choice (circle the single best answer for each) (3 points each)

(1) Monsoonal winds in the northern hemisphere Indian Ocean
a. blow from the northeast to the southwest over the Arabian Sea in summer.
b. cause upwelling along the southeast coast of the Arabian peninsula in summer.
c. are geostrophic.
d. cause ocean currents to flow from the Indian Ocean to the Pacific Ocean.

(2) In the tropical Pacific
a. The pressure gradient force is eastward along the equator.
b. There is upwelling along the equator in the east during El Nino.
c. Ekman transport is southward north of the equator during normal or La Nina conditions.
d. The North Equatorial Countercurrent is located vertically below the Equatorial Undercurrent.

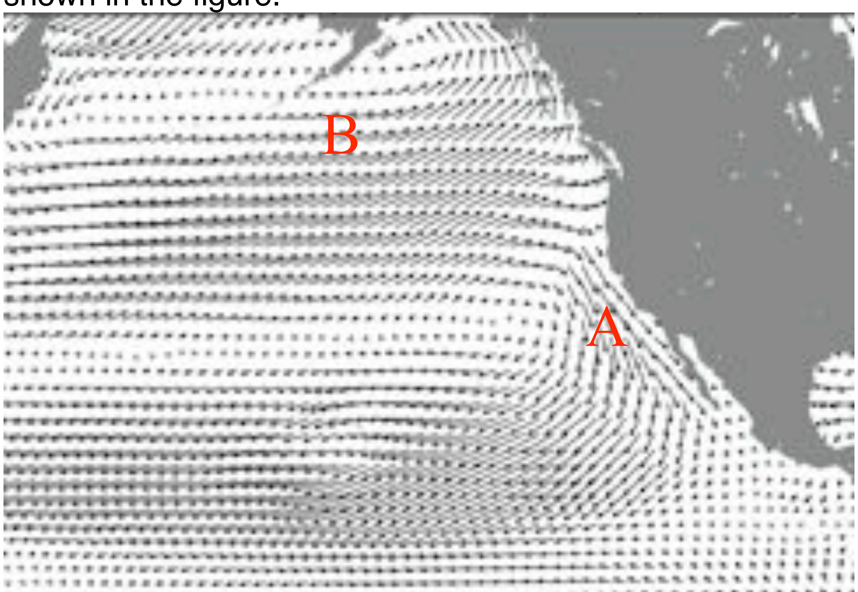
(3) Southern Ocean
a. The Antarctic Circumpolar Current is primarily driven by thermohaline forcing.
b. The Subantarctic Front is the northern boundary of the continental shelf brine rejection region.
c. Brine rejection makes the Antarctic Bottom Water extremely salty in comparison with the North Atlantic Deep Water.
d. The deep waters from the North Atlantic, Indian and Pacific rise to near the sea surface.

(4) Global overturning
a. The formation of deep water in the North Pacific contributes 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.

(5) Sverdrup
a. Upwelling in the subpolar North Atlantic results in northward flow in the large-scale gyre.
b. Wind-driven eastern boundary currents are required to balance the flow of the gyres forced by Ekman pumping or suction.
c. Ekman pumping directly causes anticyclonic eddies of diameter 200 km.
d. The Agulhas retroflection is in Sverdrup balance.

Short answers. (5 points each)

(6) The mean wind stress (in N/m^2) in the eastern and central North Pacific is shown in the figure.



a. Indicate on the figure where coastal upwelling could be found. What is the name of the current system where this occurs?_California Current System

b. Indicate on the figure where open ocean upwelling is likely to be found. What is the name of this part of the general circulation?_Subpolar gyre

c. In the Ekman layer in the northern hemisphere, what direction is the vertically-integrated transport? Perpendicular and to the right of the wind stress

d. What are the two dominant forces that balance in an Ekman layer?__Coriolis_ and __friction

(7) Sea ice forms every winter and melts away every summer in many large regions.

a. What happens to the water *beneath* the sea ice as the sea ice forms in the fall/winter? (Consider temperature, salinity and density.) Temperature drops to the freezing point, salinity increases due to brine rejection, and density increases. (This can be vertically stable because the layer is significantly fresher than an underlying layer, separated by a halocline.)

b. What is the process called that you described in (a)?____brine rejection_

c. Just after the sea ice melts in spring/summer, what characterizes the salinity of the ocean surface layer? Why? The surface layer is relatively fresh, in part because of the melted (low salinity) sea ice.

d. Name one region where this process (b) occurs and the water mass that this process contributes to. (There are several correct answers.)
Okhotsk Sea – North Pacific Intermediate Water
Antarctic continental margins - Antarctic Bottom Water
Arctic continental margins – all of the renewed waters of the Arctic

(8) Suppose that the most of the water transported from the Indian Ocean to the South Atlantic is in Agulhas rings.

a. Where and how do Agulhas rings form? The Agulhas retroflects just south of Africa. The retroflection is unstable, and forms large rings that pinch off and propagate westward into the S. Atlantic.

b. Calculate the volume of the upper layer (0-500 m) of an Agulhas ring if its diameter is 300 km. Assume the rings are cylindrical for simplicity.
Volume is $V = 500\text{m} \times \text{pi} \times (150 \times 1000\text{m})^2 = 3.5 \times 10^{13}\ \text{m}^3$

c. If nine (9) Agulhas rings are produced each year that enter the Atlantic, calculate the total warm water volume transport associated with these rings.
$9 \times V/(1\ \text{yr}) = 31.5 \times 10^{13}\ \text{m}^3/\text{yr} \times (1\ \text{yr}/3.15 \times 10^7\ \text{s}) = 10 \times 10^6\ \text{m/s} = 10\ \text{Sv}$

(9) Suppose that modern science culture arose in the southern hemisphere and so the convention for mapping has the South Pole at the top of the map. However, the Earth would still be the same Earth.

a. Indicate the direction of rotation of the Earth on this map.
Hard to draw on answer key – rotation vector points towards bottom of page and Earth rotates towards left of page.

b. Mark the major zonal wind patterns for this part of the Atlantic and Southern Ocean. Include the trade winds blowing from Africa to S. America in the band from the equator to about 20S and westerly winds blowing the other direction in latitudes from southern Africa to Antarctica.

c. Mark the direction of Ekman transport relative to these wind patterns on this map. Ekman transport is towards equator under the westerlies and towards Antarctica under the trades.

d. Indicate the main large region of Ekman convergence on the map, and the regions of Ekman divergence on the map. Convergence is throughout the subtropical S. Atlantic and divergence is in the Drake Passage region and towards Antarctica.

e. What are major meridional boundary currents? Name them, and indicate the direction they flow on the map. Within the S. Atlantic: Brazil Current along coast of S. America towards Antarctica (subtropical gyre), Malvinas Current northward along the southern coast of S. America, Benguela Current towards equator along the southern/central coast of Africa. Can also include the Agulhas in the Indian ocean and Peru-Chile Current System in the S. Pacific.

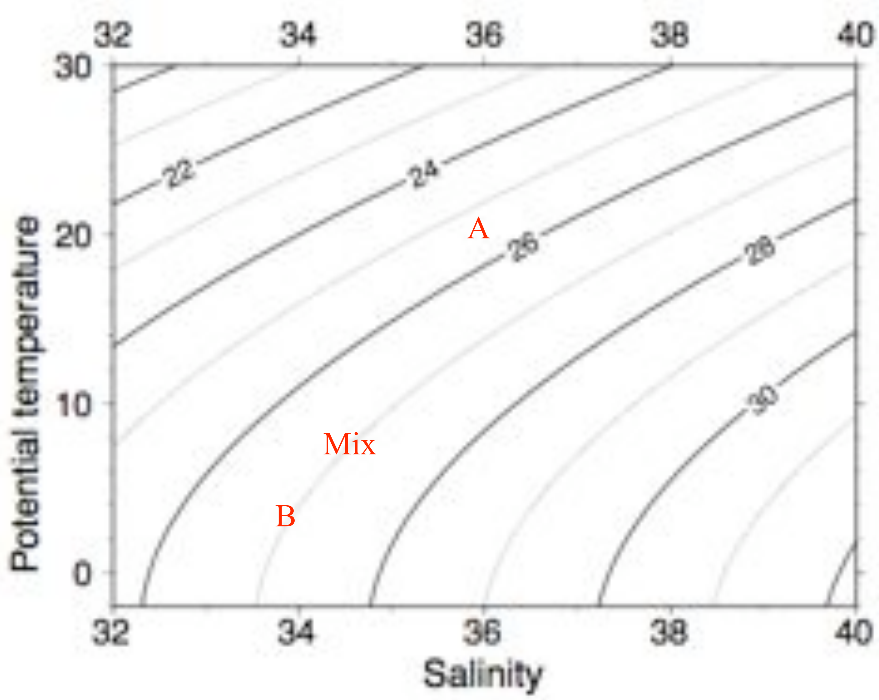
(10) Two volumes of water with different properties are mixed together. The potential temperature and salinity of volume A are 20°C and 36 psu. The potential temperature and salinity of volume B are 4°C and 34 psu.

a. If Volumes A and B are the same, what are the potential temperature and salinity of the mixture? Linear mixing: 12 °C and 35 psu.

b. If both volumes cover the same horizontal surface area, but Volume A is 500 m thick and Volume B is 2000 m thick, what are the potential temperature and salinity of mixture? (500*TA + 2000*TB)/2500 = 7.2°C; same for salt = 34.4

c. The figure shows potential density contoured as a function of potential temprature and salinity. Indicate the location on the plot of the answers to (a) and (b). What is the potential density for mixture (a) based on the graph? Can't draw on key – connect A and B with straight line, place mixture at 7.2 and 34.4. Potential density of mixture is about 26.9

d. Compare this with the potential density mixture (a) would have if the equation of state were linear. Density of A and B from graph are: 25.5 and 27. Linear mixture would have density of 26.7. Actual mixture is denser ("cabbelling")



Long answers or calculations (15 points each)

(11) Climate feedbacks

a. What is a feedback? (short answer) When two or more processes interact such that changes due to one process affect the second, which at the same time affects the first process.

b. What is the difference between asymptotically stable, neutrally stable and unstable states? (provide definitions) Stability is in reference to a disturbance away from the original state. Asymptotic stability is when the system returns to the original state; neutral stability is when it stays where it is (no return, no further divergence from original state), unstable when it continues to diverge from original state.

(11 continued)

Climate feedbacks can be simply illustrated with examples from "Daisyworld", which is a very simple model developed by J. Lovelock to help teach about feedbacks.

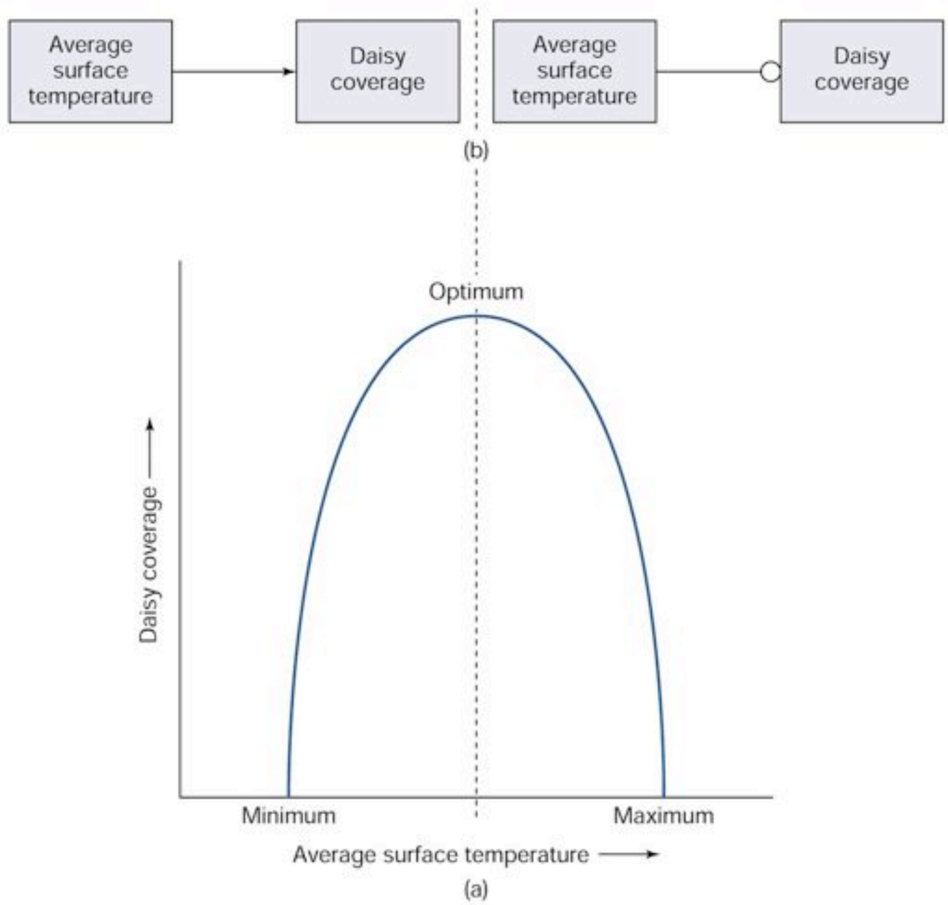
In a very simple Daisyworld (simpler than Lovelock's), there are just BLACK ground and WHITE daisies.

The sun will shine on Daisyworld and there will always be enough water for the daisies.

Daisies have an optimum temperature range for growth. When it is too cold, they die; when it is too hot, they die.

The temperature of the planet depends entirely on how much sunlight is absorbed and how much is reflected.

c. The figure shows the dependence of white daisy growth on temperature. At the top of the figure there are two diagrams with boxes connecting temperature and daisies. The left diagram is appropriate for the left side of the graph and the right diagram for the right side of the graph. Explain what the two box diagrams mean, including the symbolism of the line-arrowhead and line-circle.



d. What is *albedo*? (give a short, general definition)

e. What is the difference between the albedo of the black ground and of the white daisies?

f. As daisy coverage increases, what happens to surface temperature (given your answer to c)? Illustrate this coupling with a box diagram like those at the top of the figure.

g. Suppose Daisyworld starts out with an average surface temperature that falls on the **left** side ("Minimum") side of the graph above. Use the coupling diagrams to look at the feedback between daisy coverage and temperature.

Is the feedback positive or negative?____________________

Will Daisyworld be asympotically stable, neutrally stable or unstable for this scenario?

h. Suppose Daisyworld starts out with an average surface temperature on the **right** side ("Maximum") side of the graph. Reanalyze the feedback between temperature and daisy coverage, as you did in part (e). Is Daisyworld now stable or unstable?

i. There is a feedback between large-scale ice coverage and air temperature that is somewhat similar to Daisyworld. Explain the feedback. Is it positive or negative?

j. Does this feedback resemble some part of Daisyworld?

(12) North Atlantic Deep Water is formed from various water masses in the North Atlantic.

a. Choose **one** of the newly-ventilated (locally-formed) water masses that contribute to NADW.__Any of these: Mediterranean Water, Labrador Sea Water or the components of Nordic Seas Overflow Water (including Greenland Sea Deep Water, etc
What local process creates this water mass? Deep convection in the Mediterranean, deep convection in the Labrador Sea, deep convection in the Greenland Sea, respectively.

b. Indicate on the map (surface circulation) the location of formation of this water mass.

c. What is the surface source of this water mass? Surface waters that flow into the Mediterranean through Strait of Gibraltar; Subpolar Mode Water (surface water) circulating around the subpolar gyre and into the Labrador Sea; Subpolar Mode Water circulating into the Nordic Seas via the Norwegian Atlantic Current, mixed with surface waters coming south along Greenland from the Arctic, respectively.

d. Indicate on the map the location and direction of the Deep Western Boundary Current that carries NADW. Along the western boundary, from all along Labrador down the coast of North America and coast of South America.

e. What is the approximate net formation rate (overturning rate) of NADW as a whole? (You can give a range of values or an order of magnitude.) 15-20 Sv.

f. If the temperature of the surface water feeding the Atlantic overturn averages 17 °C and the deep water formed in the overturn averages 2°C, use the overturning volume transport from your answer (g) and calculate the net heat transport associated with the overturn.

Heat transport is (volume transport) x density x specific heat x temperature difference = (15 x 106 m3/sec) x 1025kg/m3 x 4000 J/kg °C x 15°C = 0.92 x 10 14 J/sec = 0.92 PW.

g. Which direction (north, south, east, west) is the net heat transport? Indicate this on the map. Northward because warm water flows north and colder water flows south in the overturn.

h. The return of this new deep water to the upper ocean requires upwelling. If the upwelling occurs in all regions of the deep ocean, estimate the vertical velocity of the upwelling. You can refine your estimate by assuming that the deep ocean occupies about 60% of the earth's surface. Surface area of earth is A=4*pi*R^2 where the Earth's radius is 6371 km (see list given below).
$0.6*A = 0.6*(5.1 \times 10^{14}\ m^2) = 3.1 \times 10^{14}\ m^2$

Vertical velocity w = Volume transport/surface area =
$15 \times 10^6\ m^3/sec/3.1 \times 10^{14}\ m^2 = 5 \times 10^{-8}\ m/sec = 5 \times 10^{-6}\ cm/sec$

i. In order for there to be upwelling from the deep ocean to the upper ocean, there must be a widely distributed process that converts deep water to upper ocean water. What is this process?___downward diffusion of buoyancy (mostly heat)

Discuss what might control this specific physical process. Rate is controlled by the diapycnal diffusivity. Diapycnal diffusivity is related to the level of turbulence in the ocean. Turbulence is mainly created by breaking internal waves, which can be tidally driven or wind driven.

Potentially useful items

Some useful (rounded) relations and constants (you will not need all of these):

1 day = 86,400 seconds
1 Sv = $10^6\ m^3/sec$
1 Watt = 1 Joule/sec
1 Petawatt (PW) = 10^{15} W
seawater density: 1025 kg/m^3
freshwater density: 1000 kg/m^3
seawater specific heat: c_p = 4000 Joule/(kg °C)
$2\Omega = 1.458 \times 10^{-4}\ sec^{-1}$
$f = 2\Omega \sin(latitude)$

6371 km

$4/3\pi R^3$

πR^2

$4\pi R^2$

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

And a map if it helps to have one.