SIO 210 Problem Set 4 Answer key December 1, 2014 Due Dec. 12, 2014

(20 points)

1. ENSO is a coupled climate phenomenon in the tropical Pacific that has both regional and global impacts.

(2 points)

a) What two parts of the climate systems are coupled in ENSO?__ocean and atmosphere

(6 points)

b) One of the indicators of an impending El Nino event is a weakening of the trade winds.

What is the *normal* ocean circulation in response to the trade winds along the equator? Westward frictional flow driven by easterly trade winds.

[That first line by itself is enough of an answer, but the following can also be included.] Upwelling in the eastern tropical Pacific along the equator.

Pileup of water in the western tropical Pacific along the equator.

Eastward Equatorial Undercurrent driven by the west-east pressure gradient force.

What is the *normal* ocean circulation in response to the trade winds off the equator, but still within about 5° latitude of the equator?

Poleward Ekman transport, with upwelling in equatorial region

Pileup of water north and south of equator that provides westward geostrophic surface flow (part of the South Equatorial Current)

[Additional things: wind stress curl in the ITCZ causes divergent Ekman transport at about 5 degrees N, which drives the NECC.]

(3 points)

c) What happens to the ocean circulation and temperature distribution when the trade winds weaken?

This set of equatorial currents weakens, thermocline deepens in the eastern equatorial Pacific, upwelling no longer sustains cold tongue, so equator warms, reducing the west to east temperature contrast.

(3 points)

d) How does this change in the ocean affect the atmosphere in turn? Reduced SST contrast causes the equatorial trade winds to weaken (i.e. the Walker circulation weakens)

(3 points)

e) During an El Nino event, the surface waters along the Peruvian coast become warmer. Why are the Peruvian surface waters usually cold? Why do they warm during an El Nino event?

Usually cold because of coastal upwelling system, similar to California Current. Warmer during El Nino because thermocline is deeper, so even if the winds are upwelling favorable, they bring up only warm water.

(3 points)

f) What is the time scale of variability of ENSO? What is a possible explanation for why it has this time scale (as opposed to say the shorter time scale for a similar variation in the tropical Atlantic)?

Time scale is 3 to 7 years. Time scale is tied to the propagation time scale of baroclinic Rossby waves westward across the Pacific that help adjust the whole system. Atlantic is much narrower so the time scale for the same climate phenomenon (Atlantic Nino) is much shorter, more like 1 to 2 years.

(15 points)

2. Southern Ocean.

(5 points)

(a) South of the Polar Front, the Southern Ocean is characterized by a shallow temperature minimum layer in summer. Explain how this temperature minimum arises. The temperature minimum arises from sea ice formation in winter. Where ice forms, water is at the freezing point. (It is less dense than the underlying water because it is fresher.) In summer, the very surface warms, which leaves a cold layer between the warmed surface, and the underlying T maximum. The T minimum structure can also be advected away from the sea ice region; in this case T at the Tminimum will gradually increase due to diffusion, and eventually disappear.

(5 points)

(b) If there is a temperature minimum, there must be a temperature maximum below it. What is the source of water in the temperature maximum layer in the Southern Ocean? Use the vertical sections and horizontal maps presented in class to assist with your answer.

The temperature maximum layer arises from advection from non-local waters. In the Southern Ocean, this will be upwelled water along the isopycnals.

From here on, many different approaches are acceptable.

Comparing temperature, oxygen and salinity sections that were shown in class, we see that the T max also has low oxygen and can also have high salinity. Low oxygen water comes from the Indian and Pacific Deep Waters. High salinity comes from the NADW. In any case, a good answer to this question is that the T max comes from upwelled water that arises

(5 points)

(c) If the transport of the Antarctic Circumpolar Current is 100 Sv through Drake Passage, and if the flow is all eastward through Drake Passage, estimate its average

eastward speed. Compare this with the normal maximum ACC speed listed in the class lecture. (You will need to estimate the width of Drake Passage from a map. Assume that the average depth is 4000 m.)

Estimated width of Drake Passage: about 10 degrees latitude, so about 1000 km. I will use 800 km based on a WOCE section in my Pacific atlas, <u>http://www-pord.ucsd.edu/whp_atlas/pacific/a21/sections/printatlas/printatlas.htm</u> Cross-section area A = 800 km x 1000 m/km x 4000 m = 32 x 10⁸ m². Average speed = 100 x 10⁶ m³/sec / (32 x 10⁸ m²) = 3.1 x 10⁻² m/sec = 3.1 cm/sec.

The maximum speed in the fronts of the ACC is approximately 50 cm/sec, which of course is much higher than this average cross-sectional area.

(20 points)

3. Global circulation.

(5 points)

(a) The formation of AABW is approximately 30 Sv. If 12 Sv enters the Indian Ocean across 30°S, estimate the average upwelling velocity within the Indian Ocean assuming that it exits the Indian Ocean at a lower density. You will need to estimate the area of the Indian Ocean; you many simplify this as much as you wish, but please state your approach.

Look at a map of Indian Ocean.

30S section goes from 5E to 120E. Students can figure out this approximate distance. I'll look in my Indian atlas at the 32S section which has a distance axis: 8000 km wide. Width at northern end is about 5000 km, so call the total width about 6000 km.

Meridional distance: about 5000 km, also based on an atlas section at 95E. Area A = $6000 \text{ km x} 5000 \text{ km} = 30 \text{ x} 10^6 \text{ km}^2 = 30 \text{ x} 10^{12} \text{ m}^2$

Upwelling velocity w = transport/area = $30 \times 10^6 \text{ m}^3/\text{sec} / (30 \times 10^{12} \text{ m}^2) = 1 \times 10^{-6} \text{ m/sec}$ = $1 \times 10^{-4} \text{ cm/sec}$

(5 points)

(b) If the potential temperature of the upwelled AABW in the Indian Ocean changes from 1°C to 5°C, what is the heating rate for this upwelled water?

Use 12 Sv transport from part (a).

Easiest approach is to calculate the total rate of heating for the 12 Sv. $\rho c_n T_5 - \rho c_n T_1 x$ Volume transport

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$$1025 \text{ kg/m}^3 \text{x} 4000 \text{ J/kg}^\circ \text{C x} (5^\circ \text{C}-1^\circ \text{C}) \text{ x} 12 \text{ x}10^6 \text{ m}^3/\text{sec}$$

= $1.97 \text{ x} 10^{14} \text{ J/sec} = .197 \text{ x} 10^{15} \text{ W} = .197 \text{ PW}$

Students might choose to express this in W/m^2 , so divide this net heating rate by the area from part (a):

Heating rate per unit area = $.197 \times 10^{15} \text{ W} / (30 \times 10^{12} \text{ m}^2) = 197/30 \text{ W/m}^2 = 6.6 \text{ W/m}^2$

(5 points)

(c) Find a vertical section of potential temperature at 30S in the Indian Ocean (textbook or online atlases). What is the approximate depth of water at 1°C and at 5°C in the Indian Ocean?

1°C water is at about 3500 m. 5°C water is at about 1000 m.

(5 points)

(d) What is the mechanism for this heating that allows AABW to warm to 5°C, assuming that the 1°C water flows northward into the Indian and 5°C water flows back to the south? (Look at a map of surface temperature for the Indian Ocean to assist with this answer.)

Diapycnal heating resulting from diapycnal diffusion allows this 1°C water to be warmed up to 5°C. The tropical Indian Ocean is very warm, so there is a ready source of heat to be diffused downward.

(21 points)

4. Eastern boundary currents.



Subtropical eastern boundary currents are driven by wind.

(3 points for each answer)

(a) On the wind stress map, circle three regions with the eastern boundary currents described in lecture, and label them with their names. (The Atlantic boundaries are missing of course.)

Circle the California Current, Peru-Chile Current, and Leeuwin Current regions.

- (b) In the North Pacific California Current region, indicate where there is upwelling. Indicate the region along the coast where winds are southward.
- (c) Describe one mechanism for EBC upwelling. Alongshore winds create offshore Ekman transport. Right along the coast, this requires upwelling to supply the offshore Ekman transport.
- (d) Describe the second mechanism for EBC upwelling. Farther away from shore, the alongshore wind is stronger. This means that offshore Ekman transport increases with increasing distance offshore, so there must be open ocean Ekman upwelling.
- (e) On a separate piece of paper, sketch the sea surface height that you would expect from west to east across the California Current. Assume the simplest profile, without eddies – that is, the climatological mean. Make sure to indicate where it is high and low, and indicate the coast (land). Draw surface height that is lowest at the coast, and increases offshore.
- (f) On your sketch for (e), indicate the direction of the California Current, using either arrows or the circle-dot or circle-x symbols for current direction. California Current should be coming up out of page (circle-dot symbol).
- (g) On your sketch for (e, f), sketch the near surface isopycnals, making sure to indicate how they are related to the upwelling.These might be shown as more or less mirroring the sea surface height. Where the isopycnals bend up to the surface, the is an indication of upwelling.

(24 points)

5. 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.

(3 points)

a. What is a feedback? (short answer)

A feedback occurs when two phenomena interact.

[That would be a correct answer. Some might provide longer answers, e.g.] Positive feedback is when an increase in one causes an increase in the other, which then causes an increase in the first. This is "runaway" feedback. Negative feedback is when an increase in one causes an increase in the other, which in turn causes a decrease in the first. This is "damped" or "stable".

(4 points)

b. 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. [note that the answer is partially given in (e)]

The line with arrow means that an increase in the first quantity causes an increase in the second. So an increase in surface temperature causes an increase in daisy coverage in the left half.

The line with a circle means that an increase in the first quantity causes a decrease in the second. So an increase in surface temperature causes a decrease in daisy coverage in the right half.



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(3 points)

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

Albedo is the reflectance of a surface. It ranges from 0 to 1. A surface with an albedo of 1 reflects all radiation. A surface with an albedo of 0 absorbs all radiation.

(2 points)

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

Albedo of black ground is low and albedo of white daisies is high.

(4 points)

e. As daisy coverage increases, what happens to surface temperature (given your answer to d)? Illustrate this coupling with a box diagram like those at the top of the figure. (A line-arrow connecting boxes means that an increase in one quantity causes an increase in the other. A line-circle connecting boxes means that an increase in one quantity causes a decrease in the other.)

As daisy coverage increases, albedo increases, more light is reflected, and temperature should go down.



(4 points)

f. 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? ____negative (damping, stable)_____

(4 points)

g. 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?

Ice-albedo feedback: as ice cover increases, albedo increases and surface temperature decreases. As surface temp. decreases, ice cover increases. This is therefore a net positive feedback (runaway, unstable).

[This is the feedback on the right side of the diagram.]