SIO 210 Final examination
Wednesday, December 12, 2018
11:30-2:30 Eckart 227 Name:________________

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.

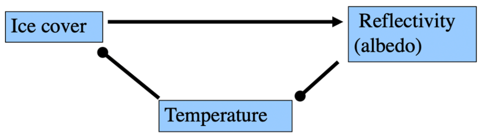
Check which you prefer regarding the return of this exam and other graded materials
______I will pick up the exam (after Jan. 2)
______Return the exam etc to me via campus mail (or full address)
Mailcode______________________

Possibly useful expressions and values; you will not need all 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
sin (30°) = 0.5
sin(50°) = 0.77
1° latitude = 111 km
1 Sv = 1x10^6 m^3/sec
g = 9.8 m/sec^2

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

1) 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

2) The climate interaction between sea surface temperature, sea ice extent, and solar radiation (reflectivity) shown in the figure is an example of
a) stable equilibrium
b) negative feedback
c) neutral stability
d) positive feedback



3) North Atlantic Deep Water is formed mostly by
a) Downward diffusion of heat accompanied by deep upwelling
b) Brine rejection due to sea ice formation in the Greenland Sea
c) Open ocean convection in limited locations
d) Inflow of Arctic waters through the Canadian archipelago between Canada and Greenland

4) Geostrophic balance
(a) Results from tilting (sloping) of isopycnals
(b) In the Brazil Current is associated with high surface height in the center of the gyre (mid-Atlantic ridge region) and low surface height along the Brazilian coastline
(c) Results from Ekman convergence in the mixed layer
(d) In the Gulf Stream is associated with low surface height in the center of the gyre (near Bermuda) and high surface height along the U.S. coastline

5) Which of the following water mass/strait circulations is NOT associated with dense water formation in a semi-enclosed sea?
a) Indonesian Throughflow Water
b) Mediterranean Overflow Water
c) Nordic Seas Overflow Water
d) Red Sea Water

6) The Nyquist frequency
a) Is calculated from the total length of time of a time series
b) Is the typical frequency of surface waves
c) Is calculated from the time separation between samples in a time series
d) Is the typical frequency of internal waves

7) Upwelling in the California Current system
a) Occurs only within a very narrow zone along the coast
b) Is due to northward alongshore winds

c) Is often associated with large eddies/filaments of upwelled water that spread westward offshore
d) Brings water from the abyssal ocean (>1000 m) to the sea surface

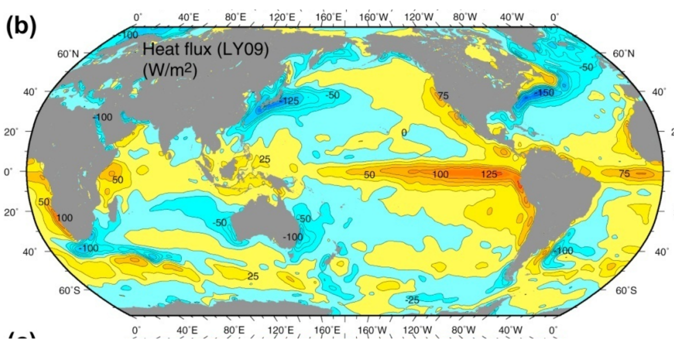
8) Subtropical gyres such as the Gulf Stream gyre
(a) Extend down to the bottom of the ocean without change of horizontal extent
(b) Are driven by Ekman convergence and downwelling (pumping)
(c) Usually have very fresh water in the center at the sea surface
(d) Are driven by cooling of the separated western boundary current (Gulf Stream)

9) Potential temperature
a) Does not change as a parcel of water is moved adiabatically from the sea surface to the deep ocean
b) Changes as a parcel of water is moved adiabatically from the surface to the deep ocean
c) Cannot have a vertical inversion (cold above warm)
d) Is measured directly with a thermistor or thermometer

10) The Leeuwin Current is
a) The western boundary current of the Indian Ocean
b) The eastern boundary current of the South Atlantic Ocean
c) An equatorward flowing eastern boundary current
d) A poleward flowing eastern boundary current

Problems

11) 14 (2, 3, 2, 3, 2, 2)
At the surface of the ocean, the tropical ocean is heated and the high latitude ocean is cooled, in the annual mean (average over many years). The **map** shows the annual mean surface heat flux. Positive: ocean is heated. Negative: ocean is cooled.

(b)


a) Circle the two regions of maximum ocean heat loss in the *mid-latitude* Northern Hemisphere. Name the major surface currents associated with these heat loss areas.

_Kuroshio_______________ (North Pacific)

_Gulf Stream_______________ (North Atlantic).

Circle the one area of major heat loss in the *high-latitude* Northern Hemisphere. Circle region off Norway (a little hard to find in this map projection – you can see it best in the upper left corner)

b) Circle the three regions of maximum ocean heat loss in the mid-latitude Southern Hemisphere. Name the major surface currents associated with these heat loss areas.

_East Australian Current________________(South Pacific)

_Brazil Current________________(South Atlantic)

_Agulhas________________(Indian)

c) Explain in general terms how these currents in (a) and (b) contribute to large heat loss in these regions.

All of these currents are poleward. The background ocean temperature gradient (upper ocean) is high in the tropics to low in the subpolar/polar regions. Poleward currents carry warm water. The atmosphere circulation is much more zonal, and so the warm currents encounter cooler air in regions where insolation is lower than in the tropics. This causes ocean cooling.

e) In the equatorial Pacific Ocean, there is heat gain. Where is the heat gain largest? (circle it) Circle the high heat flux region along the eastern equator.

Explain why the equatorial heat gain is larger in this region than at other locations along the equator. Describe the ocean circulation that results in this large heat gain.

Surface water is cooler here, so the water heats more than in other parts of the tropics, given the approximately same insolation and air temperature. Surface water is cooler here due to upwelling of cooler water from below. Upwelling here is due to the easterly trade winds (Walker circulation), which moves surface water from eastern equator to pool in the west. The deeper warm pool in the west means that local upwelling there due to Ekman divergence only upwells warm water, so does not create cool surface temepratures. Because the thermocline is much shallower in the eastern Pacific due to the westward flow of surface water, local upwelling accesses cooler water and creates the equatorial cold tongue.

f) In the mid-latitude North Pacific (around 30°N), the ocean's meridional heat transport is poleward (and large). Describe the circulation and heat loss/gain that creates this poleward heat transport. (Assume that the deep North Pacific does not contribute much to ocean heat transport.)

Poleward (northward) Kuroshio moves warm water north across 30N. There is large heat loss to the north. Water returning southward in the subtropical gyre is cooler. The net balance of northward warm and southward cool flow in the gyre transports heat poleward (into the heat loss region).

12) (6 points)
The horizontal momentum equations in a fluid in a rotating reference frame include acceleration, advection, Coriolis, pressure gradient, and viscous terms.

x: $\partial u/\partial t + u\,\partial u/\partial x + v\,\partial u/\partial y + w\,\partial u/\partial z - fv = -(1/\rho)\partial p/\partial x + \partial/\partial x(A_H \partial u/\partial x) + \partial/\partial y(A_H \partial u/\partial y) + \partial/\partial z(A_V \partial u/\partial z)$

y: $\partial v/\partial t + u\,\partial v/\partial x + v\,\partial v/\partial y + w\,\partial v/\partial z + fu = -(1/\rho)\partial p/\partial y + \partial/\partial x(A_H \partial v/\partial x) + \partial/\partial y(A_H \partial v/\partial y) + \partial/\partial z(A_V \partial v/\partial z$

(a) Which pairs of terms yield geostrophic balance? (circle and name the terms)
Coriolis and pressure gradient terms in both equations.

(b) Which pairs of terms yield Ekman balance? (circle and name the terms)
Coriolis and vertical viscous terms

(c) Which pairs of terms yield inertial balance? (circle and name the terms)
Coriolis and acceleration terms

13) 22 (2, 2, 4, 4, 4, 2, 4)
The map shows the annual mean wind vectors for the Pacific Ocean.

(a) Mark the location of the westerly winds in the North Pacific and South Pacific. General region surrounding 40°N and 50°S.

(b) Mark the trade winds in the North and South Pacific. General region around 20N to 10N and likewise in southern hemisphere.

(c) In the eastern North and South Pacific, circle the regions where there is upwelling along the boundary. What is the name of the current system in each of these upwelling regions?

__California Current System____________________(North Pacific)

__Peru-Chile Current System(I also accept 'Humboldt Current")___ __(South Pacific)

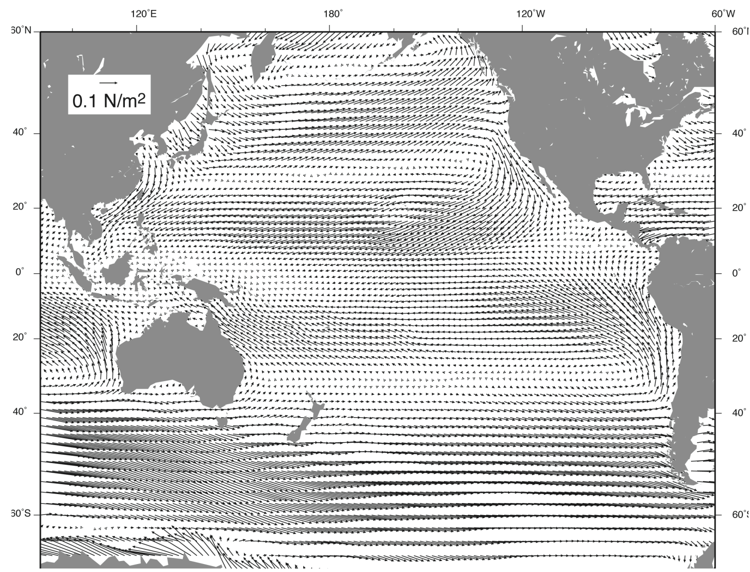
(d) Explain the upwelling in these two regions in terms of Ekman transport. You may draw relevant arrows on the map, and describe here in words.
Equatorward winds that are part of the subtropical high pressure systems (westerly winds striking the coastlines/mountains) drive offshore Ekman transport. This requires coastal upwelling for continuity.

(e) Describe the horizontal velocities within an Ekman layer, starting at the sea surface. Use your answer to Problem 12b as part of your explanation.
Wind creates frictional stress at the sea surface. Because of Coriolis force, the surface currents are at an angle to the wind (to the right in the northern hemisphere and left insouthern hemisphere). The a

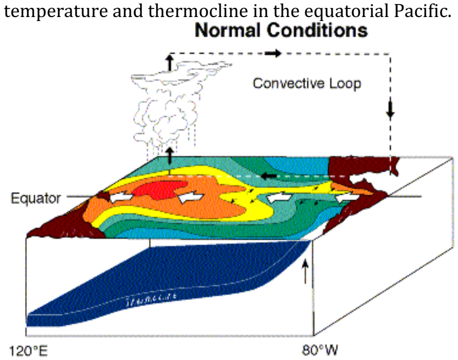
(f) How deep is a typical Ekman layer in meters?____50 meters________

(g) In the central North Pacific (180° to 160°W, and 10°N to 40°N), indicate the general direction of Ekman transport relative to the westerly and trade winds. Use arrows on the map. Is this a region of Ekman convergence (pumping) or divergence (suction)?
Under the westerlies, Ekman transport is equatorward (use arrows).
Under the trades, Ekman transport is poleward (use arrows).

Between the equatorward and poleward Ekman transports there is convergence (pumping), i.e. downward vertical velocity



14) 12 (2, 2, 2, 2, 4)
The figure shows the cartoon of the normal winds, precipitation, currents, surface temperature and thermocline in the equatorial Pacific.

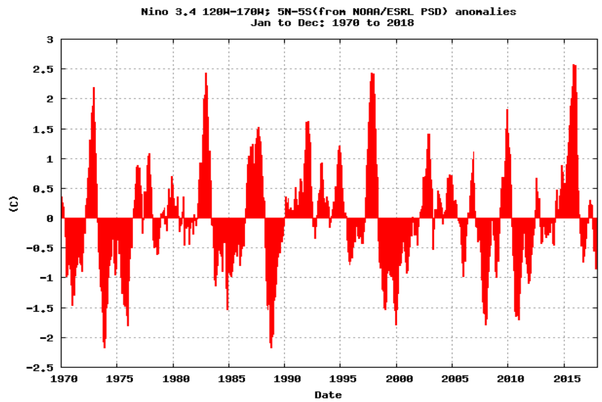


(a) On the figure, circle the part that is the trade winds and the Walker circulation. Explain how this circulation is driven by the ocean.
Circle the little black arrow in the middle, pointing westward – this is the trade winds. The whole dashed 'convective loop' is the Walker circulation. This is driven by the SST distribution illustrated in color, with warm SST to the west and cool to the east, resulting in rising air over the warm and sinking over the cool.

(b) Suppose the trade winds in the equatorial Pacific *weaken*. Explain how the surface ocean circulation changes in response to the wind change. Is this an El Nino or a La Nina state?
The SST distribution is a result of the winds. If the winds weaken, there is less westward frictional flow (in the South Equatorial Current) at the surface, and there is less upwelling of cool water in the east, and less pileup of warm water in the west. This is the El Nino state.

(c) Explain how these ocean circulation and wind changes affect the ocean surface temperature distribution.
Already implicit in (b) answer: change in circulation creates warm anomaly in eastern Pacific since there is no longer upwelled cool water. (It doesn't actually change the SST much in the west, because the warm pool is so deep, but this is a detail that was not expected in this answer.)

(d) The figure is the time series of temperature anomaly for the tropical Pacific (also called the Nino 3.4 index). Positive means warm temperature anomaly.
Mark at least one major El Nino episode on the figure. Any of the large positive events.
Mark at least one major La Nina episode on the figure. Any of the large negative events.



(e) The equatorial thermocline in the eastern Pacific, as marked by the 20°C isotherm, is centered at 70 meters depth. The vertical temperature gradient through the thermocline is 0.1°C/meter. How ***far up*** or ***down*** must the 20°C isotherm move in order to produce a positive (warm) 5°C temperature anomaly at 70 meters depth?
Straightforward calculation:
$dT/dz = 0.1°C/meter$
To have a warm anomaly at 70 m depth, isotherm must move down.
A 5°C anomaly in a gradient of 0.1°C/meter requires downward motion of 50 m.

15) 10 (3,2, 3, 2)
SEE COLOR FIGURE ON LAST PAGE (SEPARATE PAGE)

NADW (green pathways) forms in the North Atlantic and its marginal seas.

(a) On the map, mark the location of the three deep convection sites that create the new (northern) components of NADW.
Looking for: Greenland Sea, Labrador Sea and western Mediterranean Sea. I accepted a broader range, including Irminger Sea.

(b) What is the approximate net formation rate of NADW (overturning rate in units of Sverdrups) as a whole? (You can give a range of values or an order of magnitude.)
Rate is 15 to 20 Sv. I accepted 10 Sv also as an order of magnitude.

(c) 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 (a), and expressions given at the top of the exam, and calculate the net meridional heat transport associated with the overturn.
This is a simple calculation: heat is given in the equations at top of exam.

Multiply the transport, which goes northward at 17C and southward at 2C, by the temperature, density and specific heat. The transport balances by definition.

Heat transport $= (V_{north}T_{north})\ \rho\ c_p + (V_{south}T_{south})\ \rho\ c_p$
$V_{south} = -V_{north}$
Assume $\rho\ c_p$ is the same for both, for simplicity
Heat transport $= V_{north}(T_{north} - T_{south})\ \rho\ c_p$
Evaluate this with your answer for transport in (b).
I will use 15 Sv, where 1 Sv = 1×10^6 m³/sec.

Heat transport $= (15 \times 10^6\ m^3/sec)(15°C)(1025\ kg/m^3)(4000\ J/kg°C) = 0.92 \times 10^{15} J/sec$

(d) In order for there to be upwelling from the deep ocean to the upper ocean, there must be a process that converts deep water to upper ocean water. List at least one process and circle it on the schematic circulation map__Two processes could be listed: diapycnal diffusivity, and Southern Ocean upwelling from deep to surface___________________

16) 16 (10,2, 2, 2)
The color figure with 4 panels shows Pacific Ocean properties along a meridional section at 150°W.

(a) Label the following water masses, and describe briefly how you identify them (salinity minimum, etc):

Subantarctic Mode Water (SAMW)__Thick layer (relatively unstratified), north of the ACC______

Antarctic Intermediate Water (AAIW)__Salinity minimum north of the ACC________________

Pacific Deep Water (PDW) ___Deep oxygen minimum throughout Pacific_______________

Lower Circumpolar Deep Water (North Atlantic Deep Water) (LCDW) __Deep salinity maximum, especially in the ACC but also north of the ACC where maximum is at bottom________________

Antarctic Bottom Water (AABW) __Very cold, dense water at bottom, also same as LCDW north of the ACC_________________

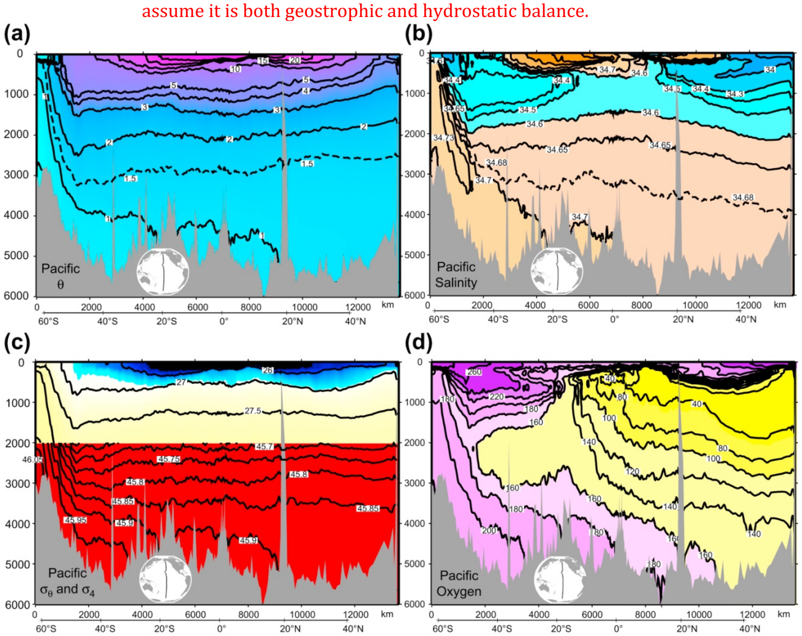
(b) On the potential temperature section (top left), indicate the location of the Antarctic Circumpolar Current (ACC). Use our notation for currents (circle within a circle or x-within-a-circle, or arrow), to show the direction of the ACC.
Draw biggest circle with arrowhead (pointing out towards reader) at surface, AT location of the steep isotherm slope (not at the bottom of the curve where the isotherms flatten!) This is around 50 to 55°S. Then draw directly underneath that, circles with decreasing diameter with depth

(c) Across the top of the potential temperature section, sketch (draw) the sea surface height (SSH) that you infer from your answer to (b), and then continue the sea surface height for the whole section. Make sure that your low SSH and high SSH are in approximately the right locations.

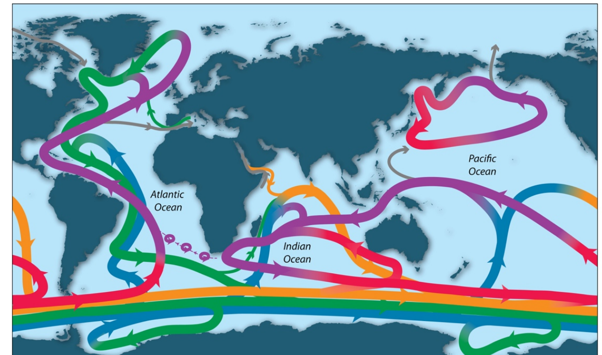
Easiest way to do this is draw the mirror image of the density contours, which are similar to the temperature contours, in the upper 500 m or so. In the ACC you will mirror the flat isopycnals at southern end, steep slope within the ACC. In the subtropical gyres, you will mirror the curving isotherms/isopycnals that represent the subtropical gyres. At the far northern end (Alaska) you will mirror the dive of the isotherms into the coastline.

(d) What dynamical balance (from problem 12) did you use in answering (c)?

Geostrophic balance. If you answered 'hydrostatic' I gave you partial credit, since we assume it is both geostrophic and hydrostatic balance.



----FOR PROBLEM 15---



Simplified global overturning circulation