NAME: ________________________________

SIO 210 Introduction to Physical Oceanography
Mid-term examination
November 2, 2015; 1 hour 20 minutes
ANSWER KEY CORRECTED OCTOBER 29, 2016

Closed book. (100 total points). One sheet of your own notes is allowed. A calculator is allowed. No electronics with communications.

Possibly useful expressions and values
1 Sv = 1 x 10^6 m^3/sec (volume)
f = 1.414 x 10^{-4}/sec * sin (latitude)
1° latitude = 111 km
Ro=f/T
g = 9.8 m/s^2
$\rho c_p T$
ρ = 1025 kg/m^3
c_p = 4000 J/kg°C
1 PW = 10^{15} W
F ~ $\rho V(S_o - S_i)/S_m$
acceleration + advection + Coriolis force = pressure gradient force + gravity + friction

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Multiple choice (10 problems, 2 points each, 20 points total)
For each problem, **circle the CORRECT answer**. (There should be **only one**.)

1. Which of these equations or terms is NOT part of Newton's Laws as discussed in class?
(a) Hydrostatic balance
(b) Continuity equation
(c) Fick's Law
(d) **a** = **F**/ρ

2. Surface waves
(a) have Rossby number much smaller than 1 (Ro << 1)
(b) have wavelengths on the order of several thousand kilometers
(c) can be generated by earthquakes
(d) are always too shallow to feel the ocean bottom

3. If an ocean measurement is clearly offset from the true value, we say that the measurement is
(a) biased
(b) noisy
(c) aliased

(d) uncorrelated

4. In most regions and averaged over the seasons, the smallest term in the local air-sea heat exchange is
(a) latent heat flux
(b) sensible heat flux
(c) solar radiation
(d) longwave radiation

5. Lagrangian observations
(a) can be made at Scripps pier
(b) can be made on a moored current meter
(c) can be made with surface drifters
(d) are often made from steered autonomous gliders

6. The maximum density of seawater occurs *(mistakenly have 2 correct answers)*
(a) at lower temperature for higher salinity
(b) at 0°C
(c) at the same temperature as the maximum density of freshwater
(d) at the freezing point of seawater

7. The ratio of the time scale of diffusion to the time scale of a fluid phenomenon is called the
(a) Reynolds number
(b) Rossby number
(c) Aspect ratio

8. Gravitational force is NOT directly associated with (i.e. in the equation for)
(a) surface waves
(b) the horizontal pressure difference that drives ocean circulation
(c) tides
(d) internal waves

9. The thermocline
(a) is created by or affected by vertical diffusion
(b) is always associated with a strong halocline
(c) is formed by advection along constant depth surfaces
(d) is the name given to tilted isotherms

10. Antarctic Bottom Water is
(a) returned to the sea surface through direct upwelling driven by winds
(b) formed by open ocean deep convection in the Antarctic region
(c) formed in just one location along the coast of Antarctica
(d) is formed by brine rejection along the coast of Antarctica

Short answer or calculations (80 points total)

11. (10 points)

One of the momentum equations is given here.

(a) Which momentum equation is this (which direction)?_x-direction______________

Label each of the terms (viscous, pressure gradient, acceleration, advection)

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

(b) Which term(s) are motivated using Fick's Law?__the last 3 terms (viscous terms)___

(c) What is Fick's Law? Flux of a property is proportional to its gradient.

(d) Why are the horizontal and vertical viscosities expressed as separate symbols? What does this tell you about the assumed source of effective viscosity in this equation? These are eddy viscosities rather than molecular viscosities. The turbulence that is parameterized as eddy viscosity is not spatially homogeneous – that is, it has different spatial scales in the horizontal and vertical. Horizontal scale is that of the mesoscale (or even submesoscale), on the order of kilometers to tens of kilometers. Vertical scale is that of breaking internal waves, so tens of meters.

12. (25 points) (Hendershott) Each part worth 6 points.

(a) Explain what is meant by a "deep water" and a "shallow water" surface wave. What is the difference between them? Deep water waves are in water that is much deeper than the wavelength of the wave, so it does not feel the ocean bottom. Shallow water waves are in waters that are shallow compared with the wavelength, so the velocities in the wave do feel the bottom.

(b) Distant events in the *deep mid-ocean* energize both deep and shallow water (surface) waves. For the following two events, are the generated waves *deep* or *shallow*?
List the typical period and typical phase speed for each of the two. Use the lists provided.

	Deep or shallow?	Typical period	Typical phase speed
(a) Storm	Deep	15 sec	20 m/s
(b) Submarine earthquake	Shallow	many minutes to a fraction of an hour	200 m/sec

Typical period: 1 sec, 5 sec, 15 sec, many minutes to a fraction of an hour, few hours, 12 hours, 24 hours.

Typical phase speed: few cm/sec, 1 or 2 m/sec, 20 m/sec, 200 m/sec, 1500 m/s

(c) For deep water waves, the group speed c_g is half the phase speed c_p. The sum of two nearly identical plane waves with wavenumber k and k+Δk consists of a **carrier wave** $\cos(k(x-c_p t))$ of wavelength 2π/k that moves at phase speed c_p, and an **envelope** $\cos(\Delta k(x- c_g t))$ of much greater wavelength 2π/Δk that modulates the carrier wave and moves at the group velocity c_g.

Explain, just in words, how this combination of carrier wave and envelope affects the deep water ocean surface waves that we see arriving from a distant storm.

The fact that the sum of two nearly identical plane waves consists of a carrier wave $\cos(k(x-c_p t))$ of wavelength 2π/k that moves at phase speed c and is modulated by an envelope $\cos(\Delta k(x- c_g t))$ of much greater wavelength 2π/Δk that moves at the group velocity explains why deep water waves from a distant storm are observed to occur in "sets"; that is, a group of several successive high amplitude crests and troughs is followed by a succession of several low amplitude crests and troughs, etc. If the storm radiated only two nearly identical plane waves then the sets would correspond to the envelope of the sum of two nearly identical plane waves and would repeat regularly. Because a storm radiates many nearly identical plane waves and not just two, the sets come and go irregularly. The fact that the sum of two nearly identical plane waves is a plane wave modulated by a low frequency envelope does NOT explain why low frequency waves go faster than high frequency waves; that is explained by the dispersion relation $\sigma=\sqrt{(gk)}$.

(d) Sketch the locations of the Earth, moon, and sun during a spring tide and during a neap tide.

13. (25 points)
In the Kuroshio region there is a large amount of heat loss from the ocean to the atmosphere, in the annual mean. The attached map shows the surface heat exchange. Negative means the ocean is losing heat, positive means the ocean is gaining heat. (A color version of the map is shown on the last color figure page.)

(a) 4 Explain how the annual mean temperature of water in a region including the Kuroshio has almost no variation even though there is very large annual mean net heat loss in that region. In an annual mean state, the Kuroshio advects heat into the heat loss region, heat is lost in that region, and cooler water is advected out of the region. That is, the heat loss is balanced by advection and not by change in temperature in a given location.

(b) 4 A long-dashed line is drawn at 20°N in the attached figure. Assume that all of the heat exchange in the North Pacific north of 20°N is in the upper ocean (ignoring deep and intermediate waters). Assume that the temperature of Kuroshio water crossing 20°N is

25°C, and that the temperature of gyre water returning southward across 20°N is 18°C. What is the direction of ocean heat transport at 20°N? Why?

Heat transport is northward.

Because warm water is advected northwards, and it is returned southwards as cooler water.

(c) 6 Assume that the volume transport of this circulation is 30 Sv. What is the magnitude of the heat transport across 20°N? (Calculation.)

Heat transport = $V\rho c_p \Delta T$ = (30 Sv) (1025 kg/m^3) (4000 J/kg°C)(25°C – 18°C) =
(30 x 10^{6}m^3/sec) (1025 kg/m^3) (4000 J/kg°C)(7°C) = 0.86x10^{15}W = 0.86 PW

(d) 2. How much heat does the ocean gain or lose north of 20°N based on your answer to (c)? (Assume that there is no leakage through Bering Strait.)

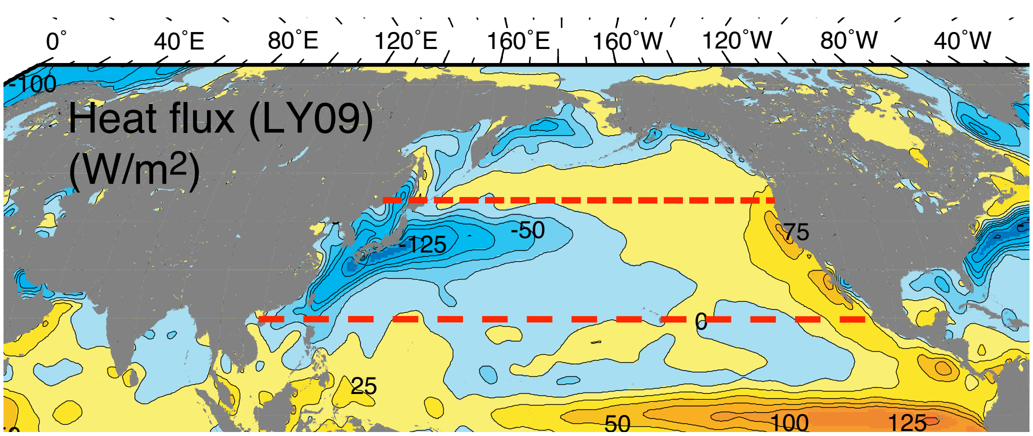
It loses 0.86 PW north of 20°N.

(e) 6 If all of this ocean heat gain/or loss occurs between 20°N and 45°N (see short-dashed line figure), what is the average surface heat loss/gain in that box? To do this, estimate the surface area of the N. Pacific between 20°N and 45°N. (Just assume that it is a rectangle, and give your estimate of distances.)

Estimate area of the region: your answer will vary depending on your estimate. Looking at the map, the zonal dimension is about 120° longitude (100 to 140°). At 20° to 40°N, estimate about 60 km/° longitude, so width of region is about 120*60 km = 7200 km. Meridional dimension is 25° latitude, 111 km /°, so 2775 km (you can round this). Area ~2800 x 7200 km^2 = 2.8 x 7.2 x 10^{6}x10^{6}m^2 = 20 x 10^{12} m^2

So average heat loss in the whole region is 0.86 x 10^{15}W/(2 x 10^{13}m^2) = 43 W/ m^2. (Estimates will vary – should have this order of magnitude for answer.)

(f) 2 How does your average from (e) compare with the air-sea heat flux in the map? (small, comparable, large)? Comparable – it does look like about the mean value, given that there is much larger heat loss in the Kuroshio, but also a large region of mild heat gain.



For Problems 14 and 15, refer to the color figures on the last page.

14. (10 points)
The attached page with color figures shows various properties in the Pacific Ocean. The location of the section is in the small map.

(a) On the potential temperature section, circle and label the "Antarctic Bottom Water".
Coldest water at left and bottom, say $< 1°C$.

(b) On the oxygen section, also circle the Antarctic Bottom Water.
Higher oxygen, say 180 μmol/kg or so. Feature does not align perfectly with potential temperature feature, because oxygen is not conservative. Potential temperature changes due to mixing alone (plus a small amount of geothermal heating), while oxygen changes both through mixing and biological utilization.

(c) Water masses are identified through a common formation history. What is the mechanism for formation of Antarctic Bottom Water? ______________________________
It is formed through brine rejection during formation of sea ice. The most important aspect of this is that it forms at the freezing point so it is very cold. It is also composed of "new" water, so oxygen is high. Its salinity increase due to brine rejection is actually mild compared with the much higher salinity of the warmer salinity maximum in the south that comes from North Atlantic Deep Water, but the small increase in salinity is apparent in the deep potential temperature-salinity diagram from the Atlantic that we used several times in class.

(d) Explain how you identified Antarctic Bottom Water and how this relates to its formation mechanism.
Cold layer, arises from being very cold the source.

15. (10 points)
(a) Define the "thermocline".
The thermocline is the vertical region of high vertical potential temperature gradient (or actual temperature), lying at the base of the upper layer in the mid-latitudes and low latitudes.

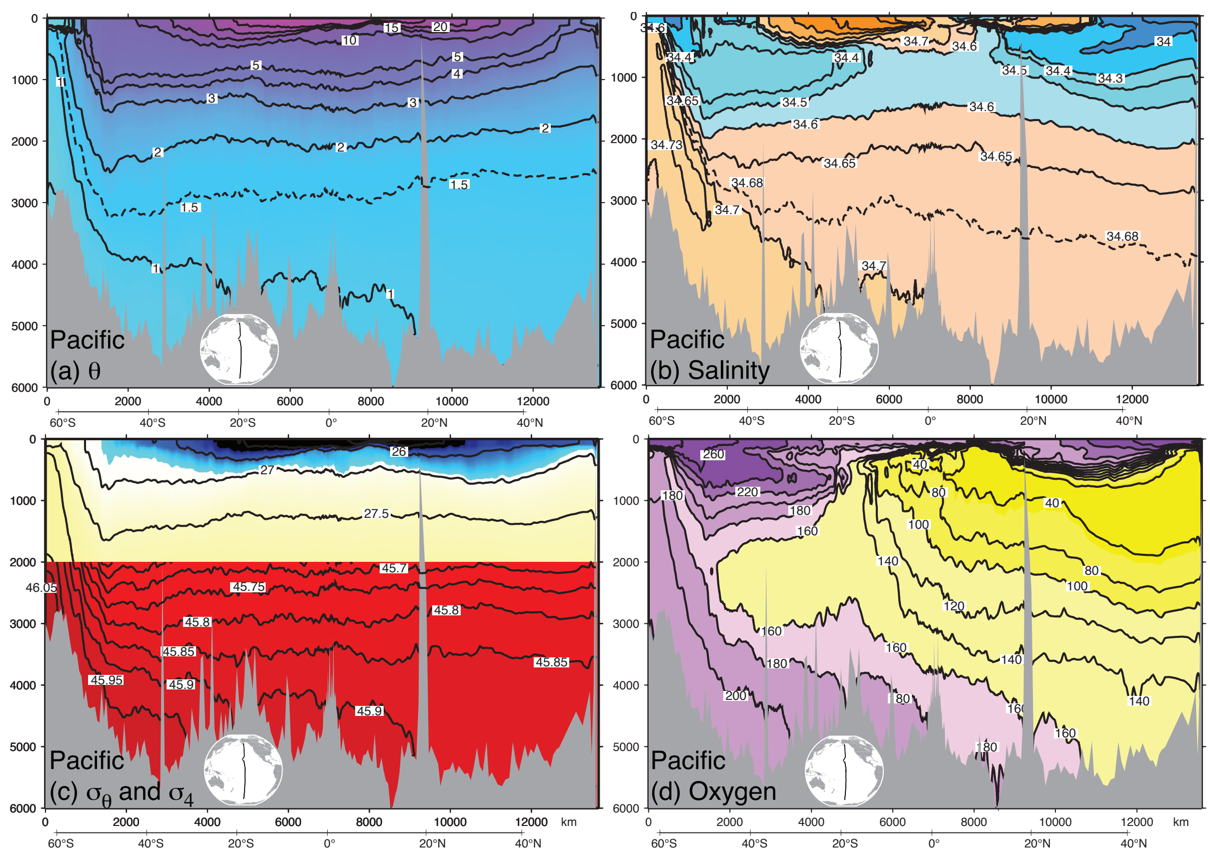
(b) On the color figure (last page), there is a Pacific Ocean potential temperature section. **Circle the main thermocline** of the subtropical Pacific Ocean.
Region from about 4°C up to about 15°C, at latitudes ~50°S to 50°N.

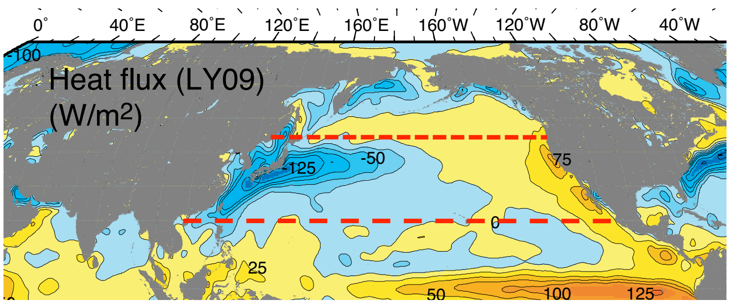
(c) We described two separate mechanisms for producing the main thermocline. Describe one of these mechanisms.
Adiabatic mechanism: Horizontal advection of winter surface properties down along isopycnals to each given location where we make a vertical profile and observe the thermocline.

(d) Extra credit (2 points): describe the other of the two mechanisms.
Diapycnal mixing of heat, between warm water at the surface, which arises from local, low latitude heating and cold water in the abyss, which arises from high latitude cold, deep water sources.

--------End of exam-----

Figure for Problems 14 and 15.





Color version for
Problem 13