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pSIO 210 Introduction to Physical Oceanography
Mid-term examination
November 3, 2014; 1 hour 20 minutes
Answer key

Closed book; one sheet of your own notes is allowed. A calculator is allowed.
(100 total points.)

Possibly useful expressions and values
1 Sv = 1 x 10^6 m^3/sec (volume) or 1 Sv = 1 x 10^9 kg/sec (mass)
f = 1.414 x 10^{-4}/sec * sin (latitude)
$\delta = H/L$
g = 9.8 m/s^2
ρ = 1025 kg/m^3
c_p = 4000 J/kg°C
$F \sim \rho V(S_o - S_i)/S_m$
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. The Northern Hemisphere ocean's **inertial response** to a strong pulse of wind
(a) makes the water circle to the right (clockwise)
(b) creates a strong pressure gradient downwind
(c) results in a frictional spiral of the water to the right of the wind
(d) makes the water circle cyclonically

2. If surface waves are sampled once a week by a satellite altimeter, then
(a) their frequency is lower than the **Nyquist frequency**
(b) their frequency is higher than the **Nyquist frequency**
(c) the **fundamental period** is 1 week
(d) the **fundamental period** is 1 minute

3. **Antarctic Intermediate Water** is characterized by
(a) very cold water, close to freezing
(b) a mid-depth salinity maximum extending southward
(c) a mid-depth salinity minimum extending northward
(d) low oxygen

4. An **Eulerian measurement**
(a) follows the water
(b) is the same as a Lagrangian measurement
(c) is made from a mooring
(d) is made using a float

5. Assuming we are in seawater with a salinity of 33 (psu): At its **freezing point**, seawater is
(a) more compressible than seawater at 4°C
(b) at a lower density than seawater at 4°C
(c) 0°C

6. The **Hadley circulation** has
(a) a very strong response to seasonally-changing temperatures over Asia
(b) low surface pressure at 30°N
(c) sinking air near the equator
(d) westerly winds at the top of the troposphere

7. **Potential temperature** in the ocean
(a) always decreases downward
(b) is uniform in very deep trenches with single sources of seawater
(c) at 1000 m depth is higher than the locally measured temperature
(d) results from the mechanical compression of molecules

8. **Geostrophic balance** describes the force balance between:
(a) acceleration and pressure gradient force
(b) advection and diffusion
(c) gravitational force and pressure gradient force
(d) Coriolis and pressure gradient force

9. Of these terms that contribute to air-sea heat flux, which is most directly related to planetary boundary layer turbulence? (that is, turbulence in the atmosphere layer just above the ocean)
(a) latent heat flux
(b) solar radiation
(c) longwave radiation

10. Centrifugal force
(a) caused the Earth to bulge outward at the poles by 21 km compared with the equator
(b) causes the Indian Ocean region to be 200 m deeper than the nearby continents
(c) is pointed away from the Earth's rotation axis
(d) is important in geostrophic flow

Short answer or calculations (80 points total)

11. (10 points) (2 points, 2 points, 6 points)

2 (a) What is the name for the following force/momentum balance? (short answer)

0 = pressure gradient force + gravity force

Hydrostatic balance

2 (b) Is this balance in (a) from the x, y, or z momentum equation? ___z-momentum__________

6 (c) If we write (a) out in differential form, it becomes

$$0 = -\Delta p/\Delta z - \rho g$$

If the water column density is 1025 kg/m^3, calculate the pressure at 100 m depth. You should express it in mks units. ("mks" means "meters-kilograms-seconds")

Rewrite as $\Delta p = -\rho g\, \Delta z = (1025\ \text{kg/m}^3)(9.8\ \text{m/sec}^2)(100\ \text{m}) = 100.45 \times 10^4\ \text{kg/(m sec}^2)$

You can leave it in these units, or recognize that this is 100.45×10^4 Newton/m^2

You might further convert this to bars or decibars: 100.45 dbar

12. (10 points) (3 points, 3 points, 4 points)

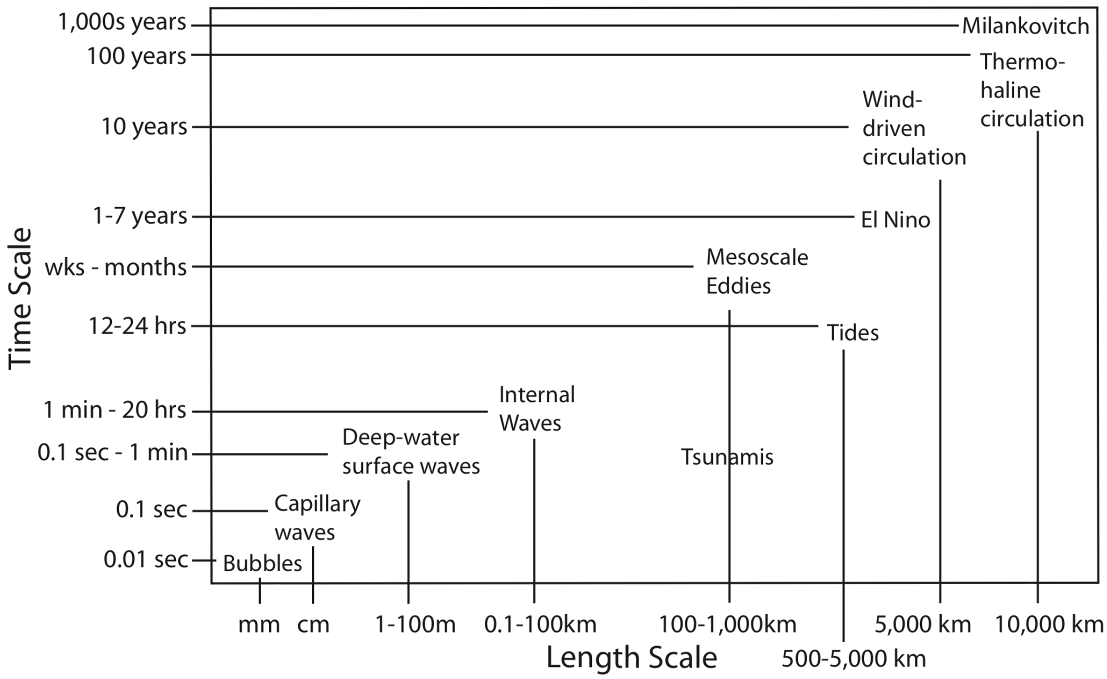
A tsunami is a surface wave forced by an under-sea earthquake. A tsunami propagates like a normal surface wave, but it feels the deep ocean bottom. We have not studied them yet, but they are listed on the graph of length/time scales attached. In the following, compare the space and time scales of a tsunami with mesoscale eddies.

(a) What is the approximate ratio of the rotation time of the Earth to the time scale of a tsunami? Is it much smaller or larger than 1? Earth rotation time scale T_{Ea} = 1 day. Tsunami time scale T_{Ts}= 1 minute or 1 hour. Ratio T_{Ea}/T_{Ts} = order(1 day/1 minute) = order(86400 min/1 min) = order (10^5) >> 1

(b) What is the approximate ratio of the rotation time of the Earth to the time scale of a mesoscale eddy? Is it much smaller or larger than 1? Mesoscale eddy time scale T_{ME} = O(10 days), so ratio T_{Ea}/T_{ME} = order(1 day/10 days) = O(0.1) << 1

(c) Which of the two (tsunami or mesoscale eddy) is most likely to be affected by Coriolis force? Why? (use your answers to (a) and (b).)

The mesoscale eddy will be strongly affected by the Coriolis force, while the tsunami will not, because the time scale of the eddy is much longer than the rotation time scale of the Earth, and vice versa.



13. (10 points) (5 points, 5 points)
Consider the concentration in a volume of the ocean of a conservative tracer (call it chlorofluorocarbon or CFC). The units of concentration are (moles tracer)/(kg seawater), that is, moles/kg.

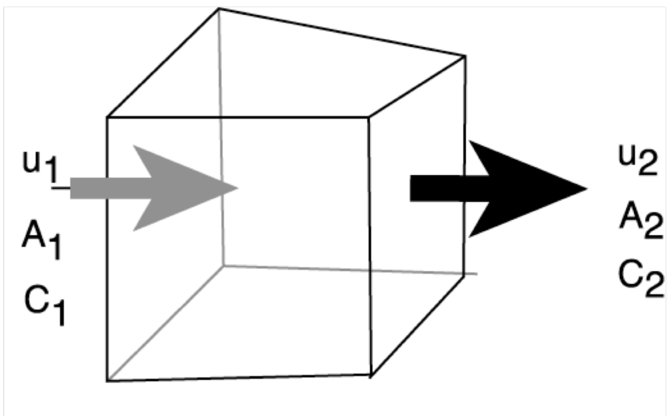
(a) What is the difference between a conservative and a non-conservative *tracer* ?
A conservative tracer does not interact with the environment within the water column other than through mixing. A non-conservative tracer does change within the water column as a result of chemical or biological processes.

(b) Is it possible for the concentration of a tracer within a volume of water to change while the mass in the volume does not change? YES or NO (circle one)

Explain. A simple explanation is fine. If a tracer is non-conservative, then clearly it can change while within a volume of water. Biological processes in the water (which we do not account for specifically, e.g. how does oxygen become incorporataed in organic matter), or chemical reactions can change its properties, even while the mass of water within the volume does not change.

14. (25 points) (4 points for each part, 1 point extra)

Consider the volume in the figure. There is flow into the left side of the volume and flow out of the right side of the volume. The inflow has velocity u_1. The outflow has velocity u_2. The area of the inflow is A_1 and the area of the outflow is A_2. Assume *there is no flow through any other side of the box*. Assume that the top surface of the box is the sea surface and that heat can be exchanged with the atmosphere across this surface.



$u_1 = 0.1$ m/sec	$u_2 =$???
$A_1 =$ width x height = 10 km x 10 meters	$A_2 =$ width x height = 10 km x 100 m
$T_1 = 15°C$	$T_2 = 10°C$
$\rho \sim 1025$ kg/m^3	$\rho \sim 1025$ kg/m^3

(a) What is the mass transport through the left side? (side "1")

Mass transport = $\rho A_1 u_1 = (1025\ \text{kg/m}^3)*[10\text{km} * (1000\ \text{m/km})]* 10\ \text{m} * 0.1\ \text{m/sec} = 1025 \times 10^4$ kg/sec (To express this in Sv, need to recall that in mass transport, 1 Sv = 10^9 kg/sec. So this is .01025 x 10^9 kg/sec = 0.01025 Sv.

(b) Calculate u_2 using the given values. (To keep this simple, assume the density is the same through both faces; the small difference does not matter for this problem.)

Recognize that the transports through the two faces must be equal. Therefore

$\rho A_1 u_1 = \rho A_2 u_2$ so $u_2 = (A_1 u_1)/ A_2 = (A_1 / A_2) u_1 = (10\ \text{m} /100\ \text{m}) * 0.1\ \text{m/sec} = 0.01$ m/sec

(c) Calculate the difference in heat transport between the left side and right side. Again assume a density of 1025 kg/m^3 and specific heat as given in the "useful values".

$H_1 = \rho\, c_p T_1 A_1 u_1 = (\rho A_1 u_1)\, c_p T_1 = (1025 \times 10^4\ \text{kg/sec})* (4000\ \text{J/kg°C})* 15°C = 6.15 \times 10^{11}\ \text{J/sec} = 6.15 \times 10^{11}\text{W}.$

(It's fine if you express this as J/sec rather than W.)

$H_2 = \rho\, c_p T_2 A_2 u_2 = (\rho A_2 u_2)\, c_p T_2 = (1025 \times 10^4\ \text{kg/sec})* (4000\ \text{J/kg°C})* 10°C = 4.1 \times 10^{11}\text{W}.$

(d) Is heat gained or lost through the top surface of the box?

Heat must be lost through the top surface since the inflow is warmer than the outflow.

(e) Calculate the total rate of air-sea heat flux for the box (over the whole box).

The total amount of heat lost out of the top of the box is 2.0×10^{11}W

(f) If the distance between sides 1 and 2 is 1000 km, calculate the average net heating in W/m^2 for the box.

Total area of top of box is (1000 km) x(100 km) = 10^5 km^2 = 10^{11}m^2. So the total heat lost (cooling) is -2.0 W/m^2.

15. (10 points) (3 points, 3 points, 4 points)

The attached page with two color figures shows the Atlantic potential temperature (meridional section) and the potential temperature versus salinity relation for the same data set. The location of the section is in the small map.

(a) On the potential temperature – salinity diagram, circle and label the "Central Water", also known as the "thermocline water".

This is hard to do in the digital copy. It's the long range in T-S space from about 5° up to the top right corner (25°C). For the blue dots (N. Atlantic), a careful student/observer would note that the C.W. is only above the Med Water.

(b) On the potential temperature section, also circle the Central Water. The Northern Hemisphere and Southern Hemisphere Central Waters can be considered to be separate.

Here circle the thermocline, down to about 5°C, but in the N. Atlantic, down to about 10°C. This is an interesting asymmetry between the S. and N. Atlantic, which I hadn't really noted before or mentioned, but very astute students would note that the 5° and 10°C isotherms are quite a lot deeper in the N. Atlantic than in the S. Atlantic and that this is due to the very saline Med. Water. We would generally say that Med. Water lies below the Central Water since it is not formed through a thermocline subduction process.

(c) Water masses are identified through a common formation history. What is a mechanism for formation of Central Water? (There may be more than one theory; as long as you explain one, you will get credit.) ________________________________

Formation mechanism for Central Water is principally subduction from the sea surface. I did also mention in class the vertical (1-D) thermocline theory, of diffusive (diapycnal) mixing between light, warm water at the top and denser water below.

16. (15 points) (5 points, 5 points, 5 points) + 3 points extra credit.

Consider again the potential temperature section (attached color figures). There are several regions where there is a vertical potential temperature inversion.

(a) Circle one of the potential temperature inversions on the vertical section.

One is located near the sea surface in the far south. This is really hard to spot with the size of the figure.

A second is located between 30°S and 10°S at about 1000 m depth. This is the easy one to spot.

(b) Locate the temperature inversion on the θ-S (potential temperature-salinity) diagram, being sure to have the same corresponding potential temperature and general latitude range.

It's most evident in the green dots, around 3-4°C, where the temperature is almost constant and salinity changes rapidly. The slight upturn in temperature to the right of the curve is the temperature minimum.

(c) Explain how there can be a potential temperature inversion that is stable over many years, even though density usually depends strongly on temperature.

A stable temperature inversion requires a strong salinity gradient (variation in salinity in the vertical) through the minimum. This means there must be fresh water overlying salty water. The temperature minimum itself would be in the fresher water, while the higher temperature just below the T min must be in salty water.

(d) EXTRA 3 points. For your potential temperature inversion: explain how it arose – what is the mechanism that results in there being an inversion?

The salinity minimum in the far south arises from presence of sea ice in winter, and its meltback in summer. There is then a very fresh surface layer. Temprature through this surface layer in summer is high, temperature just below is at the freezing point, and then below this, where salinity rises, temperature reaches a subsurface maximum.

The salinity minimum at about 30°S arises from juxtaposition of the fresh Antarctic Intermediate Water lying over the salty North Atlantic Deep Water. This is most easily seen from the potential temperature-salinity diagram, where salt increases rapidly to temperature maximum.

Color figures used for both Problems 15 and 16 NAME________________________