SIO 210 Introduction to Physical Oceanography
Mid-term examination
Monday, November 1, 2010; 2:00-2:50 PM

Closed book. A calculator is allowed.
(100 total points.)

Possibly useful expressions and values

1 Sv = 1 x 10^6 m^3/sec
g = 9.8 m/s^2
ρ = 1025 kg/m^3
$F \sim \rho V(S_o - S_i)/S_m$
c_D = .001
PV = (relative vorticity + planetary vorticity)/height = $(\zeta + f)/H$
f = 2Ω sin(latitude)
Ω = 0.71 x 10^{-4}/sec
acceleration + advection + Coriolis force = pressure gradient force + gravity + friction

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Multiple choice (4 points each, 20 points total)
For each problem, **circle the CORRECT answer**. (There is only one.)

1. The water mass with the largest volume in potential temperature-salinity space is:

(a) Pacific Deep Water

(b) Antarctic Intermediate Water

(c) Mode Water

(d) North Atlantic Deep Water

2. Sensible heat flux is

(a) the exchange of heat through a strait

(b) the exchange of heat associated with the air-sea temperature difference

(c) heat flux due to black body radiation

(d) the exchange of heat due to evaporation at the sea surface

3. The westerly winds at the sea surface are located beneath the

(a) Polar Cell

(b) Walker Circulation

(c) Ferrel Cell

(d) Hadley Cell

4. Potential vorticity is most closely related to

(a) angular momentum

(b) centrifugal force

(c) Neutral density

(d) Coriolis force

5. The Nyquist frequency is

(a) the frequency of internal waves

(b) the highest frequency that can be resolved with given observations

(c) the lowest frequency that can be resolved with given observations

(d) the frequency of eddies spawned by the Gulf Stream

Short answer (10 points each, 50 points total)

6. The flow at the sea surface is composed of several different parts, arising from different force balances. Assume they are all independent (not interacting).

(a) Name two of the several kinds of flow at the sea surface.

(b) A satellite altimeter can be used to calculate one part of the flow at the sea surface. Explain why it does NOT detect *inertial circulation*. You can use the force balance at the top of the page ("useful expressions") to help answer the question.

7. This force balance plays an important (quiet) role in many ocean phenomena:

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

(a) What is the name of this balance? ___________________________

(b) Calculate the pressure at a depth of 100 m, assuming the density is constant (ρ = 1025 kg/m^3). A value for g is given in the "useful expressions".

(c) If this 100-m water column is warmed due to heating at the sea surface, would it expand or contract (get taller or shorter)? ______________________

(d) If the water column height changes by 1 cm due to heating, calculate its change in density.

8. Viscosity υ has units of $(\text{length})^2/\text{time}$.
The molecular viscosity of water is about $\upsilon = 0.01\ cm^2/sec$.
A typical vertical eddy viscosity for the ocean is about $1\ cm^2/sec$

(a) Explain what eddy viscosity is, in contrast to molecular viscosity. (short answer – 1 to 2 sentences)

(b) The "Reynolds number" is

$$Re = UL/\upsilon.$$

where U is a typical horizontal velocity and L is a typical horizontal length scale for a given flow.
Re is a measure of the relative size of the viscosity and advection terms in the force balance. Flows with very large Reynolds number are turbulent.
Why do think this would be the case?

(c) What are typical horizontal length and horizontal velocity scales for the Gulf Stream? (i.e. give a typical U and L).

(d) For the Gulf Stream U and L, what size (order of magnitude) are the Reynolds numbers associated with molecular and eddy diffusivity?

Is the Gulf Stream viscous or turbulent based on these Reynolds numbers?

9. Suppose that the Mediterranean Overflow Water (MOW) in the North Atlantic occupies a layer that is 1000 m thick, 5000 km wide (east-west) and 2000 km in the north-south direction.

(a) Calculate the volume of this layer. (Watch your units.)

(b) If 1 Sv of MOW enters the North Atlantic at the Strait of Gibraltar, how long does it take to fill this volume? Consider this to be an approximate age or residence time of the layer.

(c) The other sources of North Atlantic Deep Water (NADW) have ages of about 30 years. If they occupy the same size volume as the MOW, estimate a formation rate for these other sources, using your answer to (b).

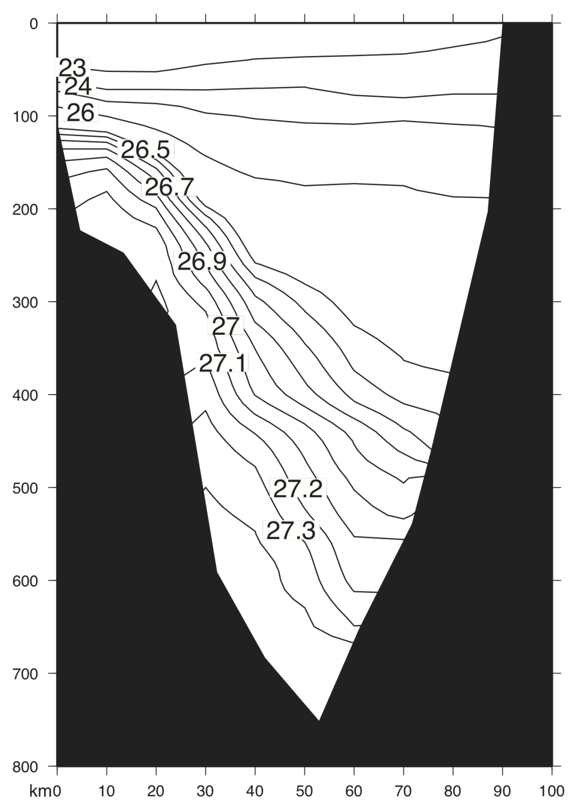
10. Geostrophic flow is the balance between pressure gradient force and Coriolis force.

(a) Which of the three momentum equations express this balance? (short answer)

(b) If the density of seawater were uniform (no variations), would there still be geostrophic flow?

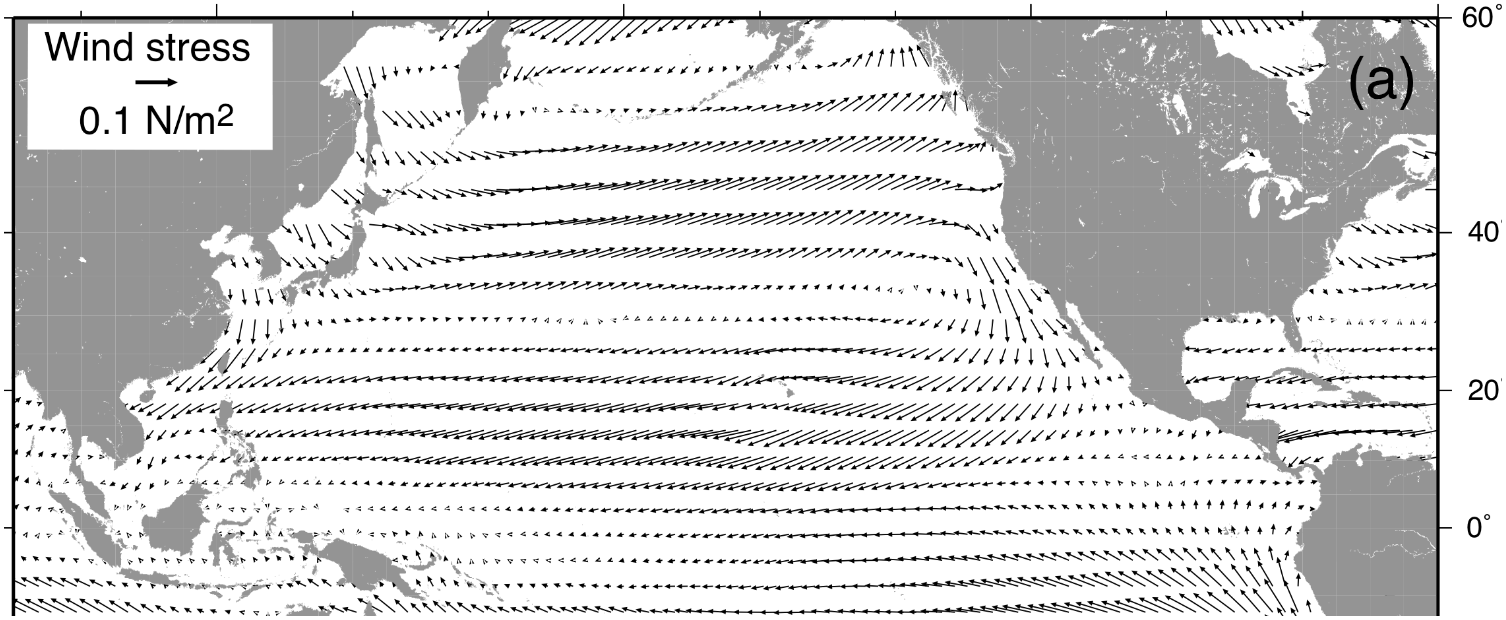
(c) For this potential density section, the geostrophic flow is strongest at the surface. Which direction is the flow at the surface (to the right, to the left, into the page, or out of the page)? ___________

Sketch the sea surface height for this section.



Longer problems (30 points total)

11. This is a map of the annual mean wind stress in the North Pacific Ocean.



(a) On the map, mark the *westerlies* and *trade winds*

(b) Draw the direction of Ekman transport that you expect in these regions of westerlies and trades. (You can simplify, just be clear).

(c) Explain the relation between the Ekman transport and the surface flow due to Ekman.

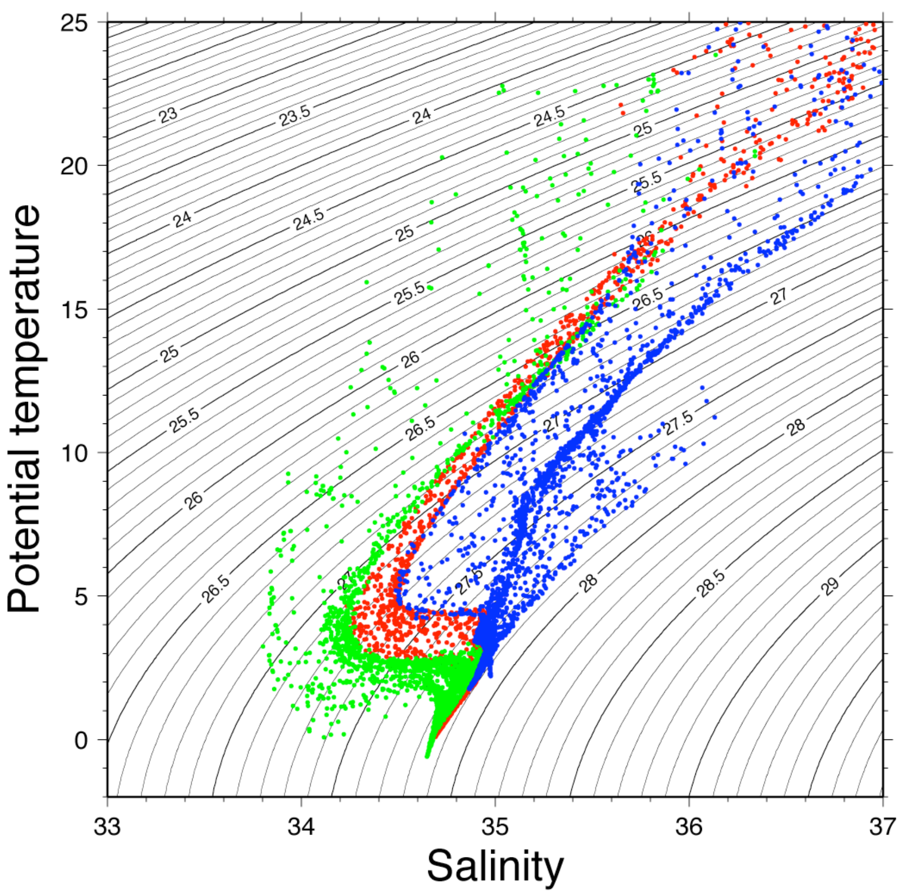
(d) What is the force balance in an Ekman layer? (based on the "useful expressions" at the top of the exam)

(e) Between 20°N and 40°N in the open ocean, would you find upwelling or downwelling, based on these winds? Why?

(f) Based on these winds, in what large regions would you expect to find high nutrients near the sea surface? Why?

(g) Along the coast of California and Baja California, the wind stress follows the coastline. Based on this wind stress, is there upwelling or downwelling along the California coast? Why?

12. The attached figure is a potential temperature-salinity diagram for the South Atlantic Ocean.



(a) Which of the profiles comes from the North Atlantic and which from the South Atlantic (indicate roughly on the plot)? How do you know?

(b) Indicate roughly where Mediterranean Overflow Water and Antarctic Intermediate Water appear on this plot.

(c) Superimposed on the plot are the potential density contours relative to the sea surface, σ_θ. Sketch schematically the contours of potential density relative to 4000 dbar, σ_4. (Just make sure the sense of the contours is correct relative to the σ_θ contours.)

(d) In terms of σ_θ, the deep water (colder than about 3°C) appears to be statically unstable (light water below is denser). Explain how this situation can exist in a steady state. (Assume that if there is an inversion in density, the water will overturn instantaneously.)

12. Suppose the vertical velocity at the sea surface due to effects described in problem 11 is

$$w = 1x10^{-6} \text{ m/sec}$$

(a) If this velocity is applied for 1 year, and is downward, how much would a water column be "squashed" in that year?

(b) If a water column is subjected to this kind of squashing, what do you expect it to do in the mean? Use the concept of potential vorticity conservation, and explain.

(c) Using potential vorticity conservation, calculate the change in latitude that would result from this "squashing". Assume that relative vorticity is negligible. (Look at the "useful" expressions above; "PV" means potential vorticity.)

12. (a) On the map, which shows steric height at the sea surface in the Indian Ocean, locate a high pressure zone. (Mark it on the map).

(c) In this box, sketch the sea surface