Physics 3340. Environmental Physics
Final Examination

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Duration of the exam: 120 min. All the questions have equal value of 25%. You are expected to solve the last problem 6 and three problems from the problems (1)-(5).

Problem (1).

Suppose that the Earth's rotation axis were normal to the Earth-Sun line. The solar flux, measured per unit area in a plane normal to the Earth-Sun line is S_0. The 24hr-averaged solar flux per unit area of the belt on the Earth surface bounded by latitudes $(\phi, \phi + d\phi)$ is:

$$S = \frac{S_0}{\pi} \cos \phi$$

(a) By using the single layer atmospheric model determine how the surface temperature varies with latitudes.

(b) Calculate the surface temperature at the equator, 30^o, and 60^o latitude if Earth albedo is 30% and $S_0 = 1367 W m^{-2}$.

Hint: Replace in the equation of the single layer atmospheric model S_0 with S from the formula above.

Problem (2).

(a) Define the **lapse rate** and distinguish between dry adiabatic, wet adiabatic and environmental lapse rates.

(b) Describe stable, unstable and neutral atmospheric conditions in terms of the definitions given in (a).

(c) Describe how atmospheric stability and inversions affect air pollution dispersion.

(d) Name and explain three forces that determine wind direction and speed within the earth's friction layer.

(e) Using the thermal wind relation explain the physical mechanism of formation of the jet stream in the upper troposphere.

Problem (3) Consider the Atlantic Ocean to be a rectangular basin, centered on latitude $\phi = 35^o$N of longitudinal width L_x=5000km and latitudinal width L_y=3000km.

The ocean is subject to a zonal wind stress if the form:

$$\tau_x = -\tau_s \cos\left(\pi \frac{y}{L_y}\right)$$

$$\tau_y = 0$$

where $\tau_s = 0.1 N m^{-2}$. Assume a constant value of $\beta = 2 \times 10^{-11} s^{-1} m^{-1}$, and that the ocean has uniform a density 1000 $kg m^{-3}$.

(a) From the Sverdrup relation, determine the magnitude of the depth integrated southward flow velocity in the interior of the ocean.

(b) If the southward transport

$$T_I(y) = (L_x - L_b) V(y)$$

in the interior of the ocean is balanced by a return northward flow at the western boundary, i.e. $T_I = -T_B$, where

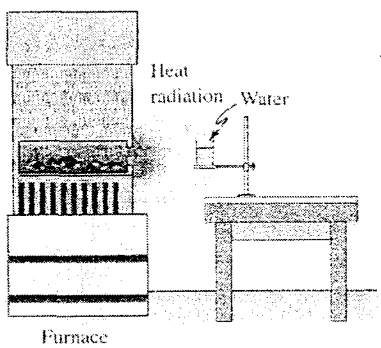
$$T_B(y) = L_b V_b(y)$$

which is confined to a width of $L_b = 100km$, determine the magnitude of the depth integrated flow V_b in this boundary current.

(c) If the flow is confined to the top 400m of the ocean (and is uniform with the depth in this layer), determine the northward components of flow velocity in the interior, and in the western boundary current (Gulf Stream).

Problem (4).

(a) Consider that radiation is emitted from a furnace through a hole with an area of $1cm^2$. Assume that all the radiation is absorbed by a beaker holding 5kg of water. Given specific heat of water - 4810 $Jkg^{-1}K^{-1}$ how long will it take for the beaker to reach 80°C if the furnace is at 2000°C? Does the radiative loss of heat by the beaker matter (provide a calculation to estimate what this loss per m^2 would be)? Assume that the surrounding room is at 20°C.



(b) Using radiative arguments, and commenting on the structure of the real atmosphere, draw a diagram and explain what regulates the radiative heat balance of a planet. Treat the problem as one-dimensional, referring to processes of heat conduction and radiation, but also consider such effects as clouds and ice.

Problem (5)

(a) If a wind turbine has a radius a, air has density ρ and the wind speed is u then derive the equation to show how much power is available to be extracted from the air that passes the turbine.

(b) The equation that defines the Betz limit is

$$P = \rho A u^3 (1-a)^2 a$$

Explain the role of each of the variables in this equation and in particular explain how the potential power of a wind turbine depends on the (probability) distribution of wind velocities.

Problem (6) Discuss in detail one of the following subjects. Be sure to present at least 6-7 key points to bolster your presentation. Remember that this is physics and you need to present scientific arguments and analysis to justify your viewpoint. There is no maximum or minimum length to this presentation but you should expect to write something like 2 pages.

Either

Present the scientific case for (and possibly against) global warming and the role of humanity in changing the climate over the past few centuries. What is the evidence? What are the scientific interpretations of the evidence and what are the projections for the future? How much certainty is there associated with different aspects of the case?

Or

Presently, we rely heavily on fossil fuels for our energy supply. Present three other sources of energy and indicate their likelihood for further development and the strengths and weaknesses of each. How much progress has been made in each in overcoming the technological challenges? Make the case for one that is most likely to supplant fossil fuels, when and if, we run out of oil.

FORMULAE

(1) The Black body spectrum:

$$I(\gamma) = \frac{2\pi hc^2}{\lambda^5\left[\exp\left(\frac{hc}{\lambda kT}\right) - 1\right]} Wm^{-2}$$

$$I(\nu) = \frac{2\pi h\nu^3}{c^2\left[\exp\left(\frac{h\nu}{kT}\right) - 1\right]} Wm^{-2}$$

$$I = \int_{-\infty}^{\infty} I(\nu)d\nu = \sigma T^4 Wm^{-2}$$

$\sigma = 5.67 \times 10^{-8} W.m^{-2}K^{-4}$.

(2) Radiation balance:

$$\frac{S_0(1-\alpha)}{4} = \sigma T_e^4$$

where $S_0 = 1367 Wm^{-2}$.

(3) A one layer greenhouse model:

$$A\uparrow = \frac{S_0(1-\alpha)}{4}$$

$$S\uparrow = \frac{S_0(1-\alpha)}{4} + A\downarrow$$

$$A\uparrow = A\downarrow = \sigma T_a^4 \quad S\uparrow = \sigma T_s^4$$

(4) A leaky greenhouse model:

$$A\uparrow + (1-\epsilon)S\uparrow = \frac{S_0(1-\alpha)}{4}$$

$$S\uparrow = \frac{S_0(1-\alpha)}{4} + A\downarrow$$

$$A\uparrow = A\downarrow = \sigma T_a^4 \quad S\uparrow = \sigma T^4$$

$$T_s = \left(\frac{2}{2-\epsilon}\frac{S_0(1-\alpha)}{4\sigma}\right)^{\frac{1}{4}} \quad and \quad T_a = \left(\frac{1}{2-\epsilon}\frac{S_0(1-\alpha)}{4\sigma}\right)^{\frac{1}{4}}$$

For the present climate $\epsilon = 0.77$.

(5) Hydrostatic and geostrophic balance of the atmosphere:

$$\frac{\partial p}{\partial z} = -g\rho \quad , \quad p(z) = p_s exp\left(- \int_0^z \frac{g}{RT} dz' \right) \quad , \quad \rho(z) = \frac{p_s}{RT} exp\left(- \int_0^z \frac{g}{RT} dz' \right)$$

$$\mathbf{u}_g = \hat{z} \times \frac{\nabla_H (p)}{f\rho} \Leftrightarrow (u_g, v_g) = \left(-\frac{1}{f\rho}\frac{\partial p}{\partial y}, \frac{1}{f\rho}\frac{\partial p}{\partial x} \right)$$

(6) Thermal wind relation:

$$f\left(\frac{\partial u_g}{\partial z}, \frac{\partial v_g}{\partial z} \right) = \frac{\alpha \rho}{T} \left(-\frac{\partial T}{\partial y}, \frac{\partial T}{\partial x} \right)$$

(7) The Brunt-Vaisala frequency:

$$N^2 = -\frac{g}{\rho_0}\frac{\partial \rho}{\partial z}$$

(8) Hydrostatic and geostrophic balance of the ocean:

$$p(z) = p_s + \int_z^\eta g\rho dz, \quad \mathbf{u}_g = \frac{1}{f\rho_0} \hat{\mathbf{z}} \times \nabla_H(p) \Leftrightarrow (u_g, v_g) = \left(-\frac{1}{f\rho}\frac{\partial p}{\partial y}, \frac{1}{f\rho}\frac{\partial p}{\partial x} \right)$$

(9) Ekman pumping:

$$w_{ek} = \frac{1}{\rho_0} \left(\frac{\partial \tau_y}{\partial x} - \frac{\partial \tau_x}{\partial y} \right)$$

(10) The Sverdrup balance:

$$V = \frac{1}{\beta\rho_0} \left(\frac{\partial \tau_y}{\partial x} - \frac{\partial \tau_x}{\partial y} \right), \quad V = \int_{-H}^{-\delta} v dz$$

and δ is the thickness of Ekman layer.

(11) Buoyancy:

$$b = -g\frac{\rho - \rho_0}{\rho_0}$$

(12) Buoyancy flux:

$$B = \frac{g}{\rho_0} \left(\frac{\alpha_t}{c} Q_{net} - \rho_0 \beta_s S(E - P) \right)$$

$$Q_{net} = Q_{sw} + Q_{lw} + Q_s + Q_L$$

where Q_{sw} is short wave radiative heat flux, Q_{lw} is long wave radiative heat flux, Q_s is sensible heat flux, Q_L is latent heat flux.

(13) Heat transfer:

(a) Convection:

$$q = hA(T_s - T_\infty)$$

(b) Radiation:

$$q = A\sigma(T_s^4 - T_\infty^4)$$

(c) Conduction

$$q = -kA\frac{\Delta T}{\Delta x}$$

Table 1: Some key ocean numbers.

surface area	$3.61 \times 10^{14} m^2$
mean depth	3.7 km
mean density	$1.035 \times 10^3 kg\ m^{-3}$
specific heat	$4.18 \times 10^3 J\ kg^{-1} K^{-1}$
density of fresh water	$0.999 \times 10^3 kg\ m^{-3}$
kinematic viscosity	$10^{-6} m^2 s^{-1}$