University College Dublin
An Coláiste Ollscoile, Baile Átha Cliath

SEMESTER II EXAMINATION 2008/2009

MAPH 40250

Climate Dynamics

Extern examiner: Prof. Keith Shine

Head of School: Dr. Mícheál Ó Searcóid

Examiner: Dr. Rodrigo Caballero*

Time Allowed: 2 hours

Instructions for Candidates

Answer **two (2)** of the following 3 questions. Each question carries 50 marks.
A list of values of physical constants can be found on the last page.

Instructions for Invigilators

Non-programmable calculators may be used during this examination.

Question 1

a) (*10 marks*) Show that for a planet devoid of an atmosphere, the global-mean surface temperature can be estimated as

$$T_s = \left(\frac{S(1-\alpha_s)}{4\sigma} \right)^{1/4}, \tag{1}$$

where S is the solar irradiance, α_s is the surface albedo and σ is the Stefan-Boltzmann constant. Clearly state any assumptions you are making.

b) (*20 marks*) Show that if the atmosphere is treated as a single layer with uniform temperature, transparent to solar radiation and with longwave emissivity ϵ, then the surface temperature becomes

$$T_s = \left(\frac{S(1-\alpha_s)}{(4-2\epsilon)\sigma} \right)^{1/4}. \tag{2}$$

Provide an example where this formula can successfully match the observed surface temperature. Provide another example in which the formula is *not* successful, and briefly explain the reason for this failure.

c) (*20 marks*) Define the term *cloud radiative forcing*. Give a qualitative discussion of the radiative forcing due to high and low clouds. Briefly describe how the Walker cell of the equatorial Pacific affects cloud formation. Explain why the total cloud radiative forcing in the rising branch of the cell is close to zero, while in the subsiding branch it is strongly negative (cooling).

Question 2

a) (*10 marks*) In a lake or other body of fresh water subjected to surface cooling, a layer of ice can form at the surface while the bulk of the water remains at temperatures close to 4°C. Explain why this is.

b) (*20 marks*) In the oceanic Ekman layer, the dominant balance in the momentum equation can be written

$$f\mathbf{k} \times \mathbf{u} = -\nu \frac{\partial^2 \mathbf{u}}{\partial z^2}, \tag{3}$$

where f is the Coriolis parameter, $\mathbf{k}$ is a vertical unit vector, $\mathbf{u} = (u, v)$ is the horizontal velocity, ν is the viscosity and z indicates depth. At the surface ($z = 0$), the windstress $\boldsymbol{\tau}$ acts on the ocean through the boundary condition

$$\nu \frac{\partial \mathbf{u}}{\partial z} = \frac{\boldsymbol{\tau}}{\rho}, \tag{4}$$

where ρ is the density of ocean water. Use these equations to derive an expression for the vertically-integrated flow in the Ekman layer, and discuss how it is oriented with respect to the windstress $\boldsymbol{\tau}$. Discuss the implications this orientation has for climate and biology in the eastern subtropical oceans.

c) (*20 marks*) Give a qualitative account of the phenomenon known as the El Niño/Southern Oscillation (ENSO) and its impacts on tropical and extratropical climate.

Question 3

a) (*10 marks*) The general circulation of the atmosphere and ocean accomplishes a large transport of energy from the tropics to the poles. Derive a formula which permits this poleward energy transport to be evaluated given the net (longwave+shortwave) top-of-atmosphere radiative flux. State clearly any assumptions you make.

b) (*20 marks*) The energy per unit mass of a parcel of air can be written

$$E = \frac{1}{2}u^2 + c_v T + gz + \ell_v q, \tag{5}$$

where u is the windspeed, c_v is the specific heat at constant volume, g is the gravitational acceleration, z is height above the surface, ℓ_v is the latent heat of vaporization and q is specific humidity. The first law of thermodynamics (conservation of energy) can be expressed as

$$\rho \frac{dE}{dt} + \nabla \cdot (p\mathbf{u}) = Q, \tag{6}$$

where ρ is density, p pressure, $\mathbf{u}$ is the vector wind and Q represents all diabatic processes. Show that Eq. (6) can be rewritten in the approximate form

$$\frac{\partial}{\partial t}(\rho E) + \nabla \cdot (\rho h \mathbf{u}) = Q, \tag{7}$$

where $h = c_p T + gz + \ell_v q$ is the moist static energy, with c_p the specific heat at constant pressure. Sketch the vertical profile of moist static energy and of its 3 component quantities in the tropics, and explain how the Hadley cell accomplishes a net transport of energy from the equator to the subtropics.

c) (*20 marks*) Suppose that the time- and spatial-mean precipitation rate in the latitude band 0°–30°N is 3.5 mm day^{-1}, while the surface evaporation rate is 4.5×10^{-5} kg m^{-2} s^{-1}. Compute the atmospheric poleward latent heat flux across 30°N. Assume there is no latent heat flux across the equator. Note that the latitude band in question occupies 1/4 of the Earth's total surface area.

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Values of physical constants

Note: This is a generic list; some of the constants here may not be necessary for any of the questions in this exam.

Gravitational acceleration $g = 9.8$ m s^{-2}
Earth's radius $a = 6.37\times10^{6}$ m
Earth's rotation rate $\Omega = 2\pi/86400$ s^{-1}
Gas constant for dry air $R_d = 287$ J K^{-1} kg^{-1}
Gas constant for water vapour $R_v = 462$ J K^{-1} kg^{-1}
Specific heat capacity of dry air at constant volume $c_{vd} = 717$ J K^{-1} kg^{-1}
Specific heat capacity of dry air at constant pressure $c_{pd} = 1004$ J K^{-1} kg^{-1}
Latent heat of vaporisation at 0°C $\ell_v = 2.5\times10^{6}$ J kg^{-1}
Stefan-Boltzmann constant $\sigma = 5.67\times10^{-8}$ W m^{-2} K^{-4}