University College Dublin
An Coláiste Ollscoile, Baile Átha Cliath

SEMESTER II EXAMINATIONS – YEAR 2010/2011

ACM 40480

Climate Dynamics

Extern examiner: Dr. Peter Clark

Head of School: Dr. Mícheál Ó Searcóid

Examiner: Dr. Paul Nolan*

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 the examination.

Question 1

(a) *(8 marks)* Explain how the Earth's obliquity gives rise to the seasons.

(b) *(7 marks)* Show that for a planet devoid of an atmosphere, the global-mean surface temperature can be estimated as

$$T_S = \left(\frac{S(1-\alpha_S)}{4\sigma}\right)^{\frac{1}{4}}$$

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.

(c) *(15 marks)* Consider the simple model for the greenhouse effect in which the atmosphere is composed of two discrete layers, each transparent to solar radiation but a blackbody to longwave radiation. Derive the radiative equilibrium surface temperature for this model as a function of the insolation S and albedo α.

(d) *(20 marks)* Now consider the more realistic, vertically continuous model consisting of the Schwarzschild equations for a plane-parallel grey gas:

$$\frac{dF^{\uparrow}}{d\tau} = -F^{\uparrow} + \sigma T^4$$

$$\frac{dF^{\downarrow}}{d\tau} = F^{\downarrow} - \sigma T^4$$

where $F^{\uparrow}$ and $F^{\downarrow}$ are the upward and downward irradiance respectively and τ is the optical depth. Derive the radiative equilibrium surface temperature for this model.

Question 2

(a) *(7 marks)* Consider a vertically-continuous atmosphere in radiative-convective equilibrium. Explain, in qualitative terms, why atmospheric and surface temperatures increase when the infrared opacity of the atmosphere increases.

(b) *(8 marks)* Give a definition of the *atmospheric greenhouse effect* and a qualitative account of its basic mechanism. Use diagrams as necessary.

(c) *(10 marks)* Define the term *cloud radiative forcing.* Give a qualitative discussion of the radiative forcing due to high and low clouds.

(d) *(10 marks)* Explain the differences between *climate forcing* and *climate feedback*. Give three examples of climate feedback processes. Give a brief quantitative discussion of *water vapour feedback* in the atmosphere.

(e) *(15 marks)* Define the term *climate sensitivity*. Give a mathematical treatment showing how water vapour feedback affects climate sensitivity.

Question 3

(a) *(15 marks)* Sketch the structure of the zonal-mean overturning circulation in the atmosphere during boreal winter (December-February), clearly labeling the various cells and giving a rough indication of their latitudinal extent. Overlay on this picture a sketch of the zonal-mean zonal wind. On a separate diagram with latitude on the x-axis and precipitation amount on the y-axis, sketch a plot of the zonal-mean precipitation in the same season. Give a brief explanation of the processes leading to the local precipitation maxima and minima.

(b) *(15 marks)* Discuss 4 physical effects that play an important role in controlling the mean equator-pole surface temperature gradient. For each effect, state clearly whether it tends to increase or decrease the gradient.

(c) *(5 marks)* Give a simple, qualitative account of the mechanism that drives an overturning circulation in the presence of a horizontal temperature gradient, neglecting the effects of planetary rotation and friction.

(d) *(15 marks)* Given the equation expressing conservation of momentum

$$\frac{d\boldsymbol{u}}{dt} + 2\Omega \times \boldsymbol{u} = -\frac{1}{\rho}\nabla p - \nabla\Phi + F_u,$$

derive Kelvin's Circulation theorem

$$\frac{dC}{dt} = -\oint \frac{1}{\rho} dp$$

where $C = \oint \boldsymbol{u} \cdot d\boldsymbol{r}$ is the circulation around a closed loop, other symbols have their usual meaning, and both planetary rotation and friction have been neglected. Explain why Kelvin's theorem implies that a horizontal temperature gradient will drive an overturning circulation.

Values of physical constants

Note: This is a generic list. Some of the constants listed here may not be necessary for any of the exam questions.

Gravitational acceleration $g = 9.8\, ms^{-2}$
Earth's radius $a = 6.37 \times 10^6\ m$
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℃ $l_v = 2.5\ \times 10^6\ J\ kg^{-1}$
Stefan-Boltzmann constant $\sigma = 5.67 \times 10^{-8}\ W\ m^{-2}\ K^{-4}$