University College Dublin
An Coláiste Ollscoile, Baile Átha Cliath

SEMESTER II EXAMINATION 2007/2008

MAPH 40250

Climate Dynamics

Extern examiner: Prof. Keith Shine

Head of School: Prof. Sean Dineen

Examiner: Dr. Rodrigo Caballero*

Time Allowed: 3 hours

Instructions for Candidates

Answer **four (4)** of the following five questions. Each question carries 25 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*) The observed height of the 500 hPa surface presents significant zonal variations in the northern hemisphere midlatitudes, even in the long-term mean. Account for the existence of these climatological stationary wave perturbations in terms of forcing by permanent zonal asymmetries at the Earth's surface.

b) (*5 marks*) Explain what is meant by an atmospheric *teleconnection pattern*, and name 2 examples of such patterns.

c) (*10 marks*) Define the North Atlantic Oscillation (NAO), and describe its regional impacts on the climate of Europe and North America/Greenland. Give a brief theoretical interpretation of the NAO in terms of eddy momentum fluxes.

Question 2

a) (*5 marks*) Give a succinct statement of the *Central Limit Theorem* of statistics, and a simple example of its application.

b) (*10 marks*) Give an outline of the structure and logic of a *statistical hypothesis test*.

c) (*10 marks*) A dice is thrown 5 times, giving the following sequence of outcomes:

1 2 3 2 2.

The manufacturer claims that the dice is true, i.e. that the probability distribution of the outcomes is perfectly uniform. Given the above outcomes, use a two-sided Student's t test to assess this claim. Recall that Student's t statistic is defined as

$$t = \frac{\hat{\mu} - \mu_0}{\hat{\sigma}},$$

where μ_0 is the population mean under the null hypothesis, $\hat{\mu}$ is the sample mean, and $\hat{\sigma}$ is the sample standard deviation. The following table lists the quantiles t_p for a given probability p (that is, $p = \int_{-\infty}^{t_p} P(t)dt$, where $P(t)$ is Student's probability distribution):

p	0.9	0.95	0.975	0.99	0.995
t_p	1.48	2.20	2.57	3.36	4.03

Question 3

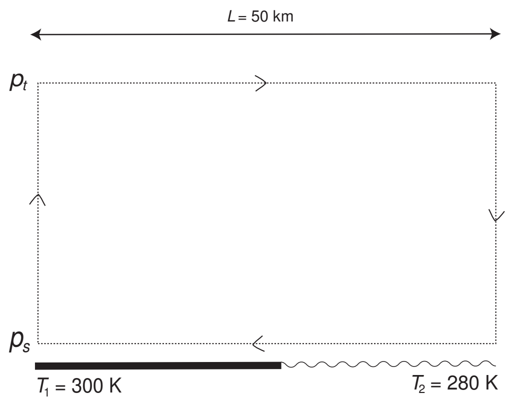

Figure 1:

a) (*7 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.

b) (*8 marks*) Given the equation expressing conservation of momentum,

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

derive Kelvin's theorem

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

where $C = \oint \mathbf{u} \cdot d\mathbf{r}$ 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.

c) (*10 marks*) Consider a sea-breeze cell, as pictured in Fig. 1. Solar heating raises the land temperature to 300 K, while the ocean temperature remains at 280 K; the resulting temperature gradient drives a circulation in which air rises over land from the surface at pressure p_s to a level $p_t = 0.9\,p_s$, moves horizontally for a distance of 50 km, and then subsides over the ocean and returns to the starting point along the surface. The motion is inviscid everywhere except for the surface branch, where a frictional force $F_u = -ru_s$ acts on the flow, with u_s the surface wind speed and $r = 2.4 \times 10^{-3}$ m^{-1} a frictional constant. Assuming that all vertical motions are dry-adiabatic and horizontal motions are isobaric, estimate the mean surface wind speed in steady state. Neglect any difference between surface temperature and near-surface air temperature.

Question 4

a) (*5 marks*) Give a definition of the *atmospheric greenhouse effect*, and a qualitative account of its basic mechanism. Use diagrams as necessary.

b) (*10 marks*) Explain the difference between *climate forcing* and *climate feedback*. Cite 3 examples of climate feedback processes. Provide a formal treatment showing how feedback processes affect climate sensitivity.

c) (*10 marks*) Consider a cloudless atmosphere in radiative-convective equilibrium, with an insolation of 300 W m^{-2}, a constant lapse rate of 6 K km^{-1} and zero planetary shortwave albedo. Suppose that the outgoing longwave radiation (OLR) may be written as $OLR = \sigma T(z_e)^4$, where T is atmospheric temperature and z_e is an effective emission level. If the surface temperature is 300 K, compute z_e. Now suppose a cloud is inserted into the atmosphere, with its top 3 km above z_e. The cloud is completely opaque to longwave radiation, and after it is inserted, the planetary shortwave albedo is 0.3. Compute the surface temperature after the system comes into equilibrium in the presence of the cloud. Assume that atmospheric opacity and lapse rate remain unchanged.

Question 5

a) (*5 marks*) Give a brief observational characterization of the Hadley cell and the climatological features associated with it.

b) (*10 marks*) Explain the presence of a subtropical jet at the poleward margin of the Hadley cell. Assuming the Hadley cell to be perfectly inviscid, and assuming that the rising branch is at the equator while the poleward margin is at 30° latitude, estimate the wind speed in the core of the jet. Explain why this value is different from the observed climatological value.

c) (*10 marks*) Write down simplified equations showing the dominant balance in the maintenance of the zonal-mean zonal wind and potential temperature in the midlatitude troposphere. Give a physical interpretation of each term in the equations. Make a sketch of the observed zonal-mean fluxes of momentum and heat, and explain why these fluxes imply the existence of an indirect meridional overturning circulation in midlatitudes.

oOo

Values of physical constants

Gas constant for dry air $R_d = 287$ J K^{-1} kg^{-1}
Specific heat capacity of dry air at constant pressure $c_{pd} = 1004$ J K^{-1} kg^{-1}
Stefan-Boltzmann constant $\sigma = 5.67\times10^{-8}$ W m^{-2} K^{-4}
Earth's radius $a = 6.37\times10^{6}$ m
Earth's rotation rate $\Omega = 2\pi/86400$ s^{-1}