You are allowed ten minutes before the start of the examination to acquaint yourself with the instructions below and to read the question paper.

Do not write anything until the invigilator informs you that you may start the examination. You will be given five minutes at the end of the examination to complete the front of any answer books used.

April 2010

Answer Book
Data Sheet

Any bilingual English language dictionary permitted
Calculators and programmable calculators are permitted

THE UNIVERSITY OF READING

MSc/Diploma
Course in Atmosphere, Oceans and Climate

Course in Mathematics
and Numerical Modelling of the Atmosphere and Oceans

MTMW20

Global Circulation of the Atmosphere & Oceans

Two hours

Answer **ANY TWO** questions

The marks for the individual components of each question are given in [ ] brackets. The total mark for the paper is 100

1.

(a) The poleward transport of energy is a fundamental property of the climate system and its magnitude can be estimated from the balance between absorbed solar radiation (ASR) and outgoing long wave radiation (OLR). The latitudinal profiles of these are given by:

- ASR(ϕ) = 175 + 125 cos 2ϕ Wm^{-2}
- OLR(ϕ) = 200 + 50 cos 2ϕ Wm^{-2}

where ϕ is the latitude.

You may assume the flux-sources relationship in the form:

$$F(\phi) = \int_{\phi}\int_{\theta} \langle S \rangle a^2 \cos\phi \, d\theta \, d\phi,$$

where F(ϕ) is the northward flux into a cap around the Earth's North pole bounded at latitude ϕ, θ is the longitude, *a* is the Earth's radius, and $\langle S \rangle$ is the source term. The identity:

$$3\int_0^{\phi} \cos\phi \cos 2\phi \, d\phi \equiv -2\sin^3\phi + 3\sin\phi,$$

is given to help. Using these profiles, calculate:

i. The latitudinal position of the peak northward heat flux
ii. The magnitude of the peak northward heat flux (give your answer in petawatts)

[17 marks]

(b) Using your estimate in (a), or otherwise, draw a sketch graph of the mean northward heat transport in the climate system as a function of latitude. You should draw three curves, one each for: the atmospheric component, the ocean component, and their combined energy transport. The sketch should show how the dominance of the atmosphere and ocean transports varies at different latitudes. It should also show the approximate magnitude and latitudinal position of the peak transport associated with each curve.

[12 marks]

Question 1 continues overleaf

Turn over

Question 1 continued.

(c) Using your general knowledge of the equation of state for sea-water, explain why changes in evaporation and precipitation over the tropical oceans have less affect on local ocean convection than a similar magnitude change would have at high-latitudes.

[7 marks]

(d) With reference to the Hadley cell in the atmosphere, consider a parcel of equatorial air, initially at rest with respect to the ground which is transported northwards. Use angular momentum conservation to show that its westward velocity at latitude ϕ is given by:

$$u = a\Omega \frac{\sin^2\phi}{\cos\phi},$$

where Ω and a are the Earth's rotation rate and radius, respectively. You are given that angular momentum $M \equiv (u + a\Omega\cos\phi)a\cos\phi$.

[7 marks]

(e) Very briefly (giving just one or two sentences for each part):

(i) Explain why angular momentum conservation makes it impossible for a "Hadley cell" of this type to extend all the way from the equator to the poles

(ii) Identify the latitude to which the Hadley cell typically extends in the real atmosphere

(iii) Name the dominant dynamical processes that occur in the atmosphere on the poleward side of the Hadley Cell to continue the poleward transport of heat

[7 marks]

2.

(a) Consider flow on a beta-plane in which the relative vorticity is zero everywhere (i.e., $\zeta = f(y) = f_0 + \beta y$). With the aid of a simple sketch diagram and vorticity conservation arguments, explain why a small vorticity perturbation to this field will propagate westward relative to the background flow.

[10 marks]

(b) Briefly describe, with the aid of diagrams, the vertical structure of the horizontal circulation that you would expect to see in the troposphere if you were looking at a positive relative vorticity anomaly at the surface that was:

(i) barotropic
(ii) equivalent barotropic
(iii) baroclinic (first mode)

[7 marks]

(c) Briefly explain, with the aid of diagrams, the difference between the concepts of *phase velocity* and *group velocity* for waves.

[4 marks]

(d) The dispersion relationship for barotropic Rossby waves is:

$$\omega = \bar{u}k - \frac{\beta k}{k^2 + l^2},$$

where the notation is standard. For stationary plane waves with no meridional variation show that the group velocity is zero and that its magnitude is

$$c_g = 2\bar{u}.$$

[8 marks]

Question 2 continues overleaf

Turn over

Question 2 continued.

(e) Consider a simple model of the ocean in which it is represented by a single layer of fluid, of depth H_e. A height perturbation to the fluid, h, satisfies the shallow water equations on a beta-plane:

$$\frac{\partial u}{\partial t} - fv + g\frac{\partial h}{\partial x} = 0,$$

$$\frac{\partial v}{\partial t} + fu + g\frac{\partial h}{\partial y} = 0,$$

$$\frac{\partial h}{\partial t} + H_e\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) = 0.$$

Show that on long time-scales (i.e., where $T \gg f^{-1}$), the motion is approximately geostrophic. Using this relationship demonstrate that the height equation can be rewritten as a one-dimensional wave equation with a (Rossby wave) phase speed of c_{RW}, where

$$c_{RW} = -\frac{\beta}{f^2} gH_e.$$

[14 marks]

(f) Taking H_e as 0.3m (equivalent to the first baroclinic mode), use the above expression for c_{RW} to estimate the phase speed of oceanic Rossby waves in midlatitudes. Briefly explain why this is relevant to decadal-scale variability in the climate system.

[7 marks]

3.

(a) For eddy activity in the mid-latitude storm tracks, describe, with the help of sketch diagrams:

(i) how midlatitude eddies act to transport heat polewards

(ii) how the meridional propagation of eddies out of a strong jet region acts to re-enforce the jet through momentum transports.

[12 marks]

(b) Using your knowledge of Ekman pumping, explain why increases in surface drag will act to weaken a midlatitude storm moving eastward from an ocean into a continent. You should include sketch diagrams indicating how both the horizontal and vertical circulations are affected. You should also clearly explain how the surface signal is communicated upwards into the free troposphere.

[11 marks]

(c) In addition to increased surface drag, give one additional reason why a midlatitude storm track would be weaker over a large *flat* continent than over the ocean?

[2 marks]

Question 3 continues overleaf

Question 3 continued

(d) Use the Ekman pumping relationship:

$$\rho_{ocean} w_{ek}\big|_{BBL} = \mathbf{k} \cdot \left(\nabla \times \frac{1}{f} \boldsymbol{\tau}_s \right),$$

(where BBL indicates the bottom of the ocean's boundary layer and $\boldsymbol{\tau}_s$ is the surface stress) to estimate the wind-driven vertical velocity in the ocean's subtropical gyre. You may assume that the storm tracks drive surface westerly winds of $10\,\mathrm{ms}^{-1}$ at 30^{o}N, and that the surface wind is $-10\,\mathrm{ms}^{-1}$ (easterly) at the equator. You may further assume that the wind strength varies linearly between 30^{o}N and the equator and that the bulk formula for surface drag is given by: $\boldsymbol{\tau}_s = \rho C_D |v| \mathbf{v}$ where the dimensionless drag coefficient, C_D, is 10^{-3}. Give the magnitude (in ms^{-1}) and the direction of the velocity in your answer.

[10 marks]

(e) Explain how the existence of equatorward flow throughout the top few 100m of the tropical ocean is consistent with the direction of the vertical motion obtained in (d). Why is this equatorward flow relevant to the formation of western boundary currents in the upper ocean?

[8 marks]

(f) Very briefly say how the surface western boundary current in the subtropical North Atlantic Ocean may affect the wintertime North Atlantic atmospheric storm track.

[7 marks]

(End of Question Paper)