Candidates are admitted to the examination room ten minutes before the start of the examination. On admission to the examination room, you are permitted 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 2009

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) Show that the zonal mean, time mean northward flux of a quantity H (i.e., $\left[\overline{vH}\right]$) can be written as:

$$\left[\overline{vH}\right] = \left[\bar{v}\right]\left[\bar{H}\right] + \overline{\left[v\right]'\left[H\right]'} + \left[\bar{v}^{*}\bar{H}^{*}\right] + \left[\overline{v'^{*}H'^{*}}\right]$$

[8 marks]

(b) The first term on the right hand side of the equation given in part (a) (i.e., $\left[\bar{v}\right]\left[\bar{H}\right]$) describes the poleward flux of H due to the advection of the zonal mean, time mean H by the zonal mean, time mean flow. Similarly, the second term describes the poleward flux due to temporally correlated fluctuations in the zonal mean v and H. Both these terms are important for transports by zonally symmetric circulations such as the Hadley cell. Provide a similar description of the remaining two terms and an example of a circulation feature where each term is important. [6 marks]

(c) Both Eulerian variance and feature tracking techniques can be used to investigate the mid-latitude storm tracks.

(i) Briefly explain how each method works and discuss their relative merits. [10 marks]

(ii) For each method, give one example of a physical quantity that could be used to diagnose a storm track. [2 marks]

(d) Describe the main characteristics of the northern hemisphere storm tracks in the lower troposphere and very briefly explain how the strength of the tracks changes through the annual cycle. [8 marks]

(e) The Northern Hemisphere's winter storm tracks display significant asymmetries. Discuss how the distribution of the storm tracks in the lower troposphere may be affected by asymmetries in the extratropical surface boundary conditions. [16 marks]

2.

(a) In the context of wave propagation, briefly describe the difference between phase velocity and group velocity. [4 marks]

(b) You are given that the dispersion relation for barotropic Rossby waves is given by:

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

where the notation is standard. Using this relationship, and taking the latitude to be 45°N, estimate the planetary wavenumber at which the zonal phase velocity is zero. You will need to provide an appropriate value for the zonal wind, $\bar{u}$, in the mid-latitude middle troposphere but may assume that $l=0$ and $\beta = 1.6 \times 10^{-11} s^{-1} m^{-1}$.

[12 marks]

(c) Explain the relevance of the estimate produced in part (b) to the movement of midlatitude cyclones and blocking anticyclones.

[4 marks]

(d) Use the dispersion relation given in part (b) to show that the group velocity of a stationary wave propagating in a beta-plane can be written:

$$\mathbf{c}_g = 2\bar{u}\hat{\mathbf{K}} \cos\alpha$$

where:

$$\hat{\mathbf{K}} = \left(\frac{k}{\sqrt{k^2 + l^2}}, \frac{l}{\sqrt{k^2 + l^2}} \right)$$

is the unit vector in the direction of propagation and α is the angle this makes with the x-axis. [10 marks]

(e) Consider a point source of stationary Rossby wave activity in the midlatitudes that is "switched on" in a uniform westerly flow at a time t=0. Draw a sketch diagram showing the region of space that can be impacted by the wave activity after a time t=T. [5 marks]

Question 2 continued overleaf

Question 2 cont'd

(f) Describe the physical processes by which upper tropospheric Rossby waves may be generated by large scale, quasi-stationary diabatic heating in the tropics. The explanation should include an appropriate discussion of vortex dynamics. [10 marks]

(g) Briefly explain why stationary Rossby wave activity generated in the Northern Hemisphere extratropics tends to have little direct impact on the flow in the Southern Hemisphere. [5 marks]

3.

(a) Draw a figure showing the time mean, zonal mean net northward heat transport by the climate system as a function of latitude and its partition between the atmosphere and ocean. You should indicate the scales on the axes. [8 marks]

(b) Briefly describe the thermohaline processes thought to be important in the meridional overturning circulation in the Atlantic ocean. [4 marks]

(c) Assuming that the Atlantic thermohaline circulation transports approximately 0.75PW of energy polewards in the North Atlantic, and that the temperature difference between the upper and lower limb is 10^{o}C, estimate the net northward mass flux in the upper limb. [8 marks]

(d) Draw a sketch of the streamlines that represent the major near-surface gyres in the Atlantic ocean. Your diagram should indicate the relative intensity, width and location of the northward and southward currents and also the flow in the region where the Atlantic Ocean meets the Southern Ocean. [10 marks]

Question 3 continued overleaf

Question 3 cont'd

(e) You are given that:

$$\mathbf{M}_{ek} = \int_{BL} \rho \mathbf{v}_{ek} dz = -\frac{1}{f} \mathbf{k} \times \boldsymbol{\tau}_s$$

where $\boldsymbol{\tau}_s$ is the surface stress exerted by the atmosphere onto the ocean and $\mathbf{M}_{ek}$ is the horizontal mass flux due to Ekman transport, integrated over the depth of the ocean's boundary layer, BL.

Using the bulk stress formula ($\boldsymbol{\tau} = \rho c_D \mathbf{v}|\mathbf{v}|$ where the dimensionless constant, $c_D = 10^{-3}$) and assuming that surface easterly wind speed is $10ms^{-1}$ at 10^o latitude both north and south of the equator, estimate the mean vertical velocity of water into the oceanic surface boundary layer between 10^oN and 10^oS. You may assume that the impact of the horizontal Ekman flow is completely compensated by vertical motion. Give your answer in terms of both ms^{-1} and the approximate number of metres per 90-day season. [14 marks]

(f) Explain why maps of sea surface temperature tend to show a cold tongue near the equator (e.g., in the East Pacific). What impact does this have on the atmospheric intertropical convergence zone? [6 marks]

(End of Question Paper)