On admission to the examination room, you should acquaint yourself with the instructions below. You must listen carefully to all instructions given by the invigilators. You may read the question paper, but must 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.

DO NOT REMOVE THIS QUESTION PAPER FROM THE EXAM ROOM.

April 2015 **MTMW20 2014/15 A001**

Answer Book

Data Sheet
Any bilingual English language dictionary permitted
Any non-programmable calculator is permitted

UNIVERSITY OF READING

Global Circulation of the Atmosphere & Oceans (MTMW20)

Two hours

Answer Question 1 and **either Question 2 or 3**.

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

1. This question is intended to test your general knowledge of the global circulation of the oceans and atmosphere.

(a) Draw a sketch map of the main *surface* ocean circulation in the Pacific, Atlantic and Southern Oceans. Your sketch should show the approximate locations of the main ocean basins and indicate the latitudinal extents of the various circulation features.

[8 marks]

(b) Temperature decreases with depth in the tropical ocean. With the aid of diagrams, explain how the process of Ekman pumping leads to an atmospheric tropical cyclone leaving a cold-water trail in its wake.

[12 marks]

(c) Explain what is meant by:

i) the “Thermohaline circulation” in the Atlantic Ocean

[4 marks]

ii) the “Hadley Cell” in the atmosphere

[5 marks]

(d) Draw a sketch map of the main extratropical storm track regions during wintertime, in both the northern and southern hemispheres. The sketch should indicate the location, spatial extent and orientation of the storm tracks.

[8 marks]

(e) Using a simple diagram, explain why transient Rossby waves propagating away from a meridionally-localised mid-latitude jet can act to enhance (rather than weaken) the jet.

[6 marks]

(f) 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]

2. You are given the barotropic vorticity equation in standard notation:

$$\left(\frac{\partial}{\partial t}+\mathbf{v}\cdot\nabla_h\right)\zeta=\zeta\frac{\partial w}{\partial z}$$

(a) For small perturbations on a beta-plane with uniform zonal background flow, show that the barotropic vorticity equation can be linearised as:

$$\frac{\partial \xi'}{\partial t}+\overline{u}\frac{\partial \xi'}{\partial x}+v'\beta=f\frac{\partial w'}{\partial z}$$

You should provide a brief explanation of why the other terms in the full barotropic vorticity equation are ignored.

[16 marks]

(b) Briefly explain the physical meaning of the 2nd and 3rd terms on the left-hand side of the linearised equation in part (a).

[6 marks]

(c) The right hand side of the equation represents a forcing term and, in regions remote from the forcing, this can be assumed to be negligible. By introducing a one-dimensional wave-like streamfunction,

$\psi'=\psi_0 e^{i(kx-\omega t)}$, where $\mathbf{v}'=\left(-\frac{\partial \psi'}{\partial y},\frac{\partial \psi'}{\partial x},\right)$:

i) Show that wave-like solutions exist for the unforced equation according to the dispersion relation $\omega=\overline{u}k-\left(\beta/k\right)$

ii) Show that the zonal group velocity for stationary Rossby waves is given by: $c_g=\partial\omega/\partial k=2\overline{u}$

[10 marks]

(d) Consider the atmosphere as a single layer of fluid of uniform depth *H* under a fixed horizontal lid. An isolated mountain of height *h* << *H* introduced at the lower boundary can be represented on the right-hand side of the linearised barotropic vorticity equation as follows:

$$\frac{\partial \xi'}{\partial t} + \bar{u}\frac{\partial \xi'}{\partial x} + v'\beta = -\frac{f}{H}\bar{u}\frac{\partial h}{\partial x}$$

The left-hand side of the equation can be interpreted as the circulation-response to the mountain. Insight into the response can therefore be gained by considering special situations in which one term on the left hand side "dominates" over the others (e.g., if it is known that |*term3*| >> |*term2*| >> |*term1*| then physical insight can be gained by considering the reponse implied by term 3 while neglecting terms 1 and 2).

Consider the following special situations:

i) the instantaneous vorticity tendency produced if the mountain forcing was suddenly "switched on".

ii) the equilibrium (i.e., steady state) response to the mountain forcing if short zonal-wavelengths dominate.

In each case, simplify the left hand side of the equation to show the dominant balance and sketch the resulting circulation response. You should explain your reasoning for the simplification in each case.

[18 marks]

3. (a) Draw a sketch of the latitudinal dependence of annual-mean zonal-mean evaporation minus precipitation. Mark on the location of the ITCZ, the extent of the Hadley Circulation and extratropical storm tracks, and give an indication of scales on the axes.

[14 marks]

(b) Assume that the area-average value of evaporation minus precipitation poleward of 30^{o}N is -0.5 mm day^{-1}. The surface area of the polar cap is πR_E^2 where R_E = 6.4 x 10^6 m is the Earth's radius.

i) Clearly explaining your reasoning, calculate the total poleward flux of water in the atmosphere across 30^{o}N.

[10 marks]

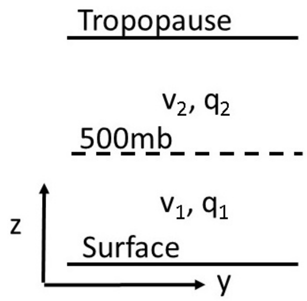
ii) Use *either* your numerical answer to part (i) *or* the approximate value of 10^9 kg s^{-1}, estimate the poleward transport of latent heat in the atmosphere across 30^{o}N. Give your answer in Petawatts (1PW = 10^{15} W).

[4 marks]

iii) Based on your knowledge of atmospheric energy transport, provide a brief justification as to whether or not you believe the estimate derived in part (ii) is physically reasonable.

[4 marks]

(c) Consider a two-layer model of the poleward atmospheric water vapour flux across 30^{o}N. v_i and q_i are the meridional wind and specific humidity in each layer *i*. *k* is a fixed integer zonal wave-number, λ is longitude (in radians) and δ is a constant phase offset between the wave-parts of v_i and q_i. *[ ]* and * denote zonal means and departures.



Where:

- $q_i = [q]_i + q_i^* \sin(k\lambda + \delta)$
- $v_i = [v]_i + v_i^* \sin(k\lambda)$

In the real atmosphere, the upper level transport, v_2q_2, can be neglected as the moisture content, q_2, is small. Hence show that the zonal average column-total poleward flux of water across 30^{o}N can be approximated by:

$$[vq] \approx \frac{1}{2\pi} v_1^* q_1^* \cos(\delta)$$

You should provide physical reasoning for each step – e.g., *why* $[v]_1[q]_1$, $v_1^*[q]_1$ and $[v]_1 q_1^*$ make no contribution. *You may find the following helpful:*

- $2\sin(a)\cdot\sin(b) = \left(-\cos(a+b) + \cos(a-b)\right)$
- *For any integer n:* $\sin(2n\pi + x) = \sin(x)$
- $\int_0^{2\pi} \cos(2k\lambda + \delta)\,d\lambda = \left[\frac{1}{2k}\sin(2k\lambda + \delta)\right]_{\lambda=0}^{\lambda=2\pi}$

[18 marks]

(End of Question Paper)