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 2013

Answer Book
Data Sheet
Any bilingual English language dictionary permitted
Only Casio-fx83 calculators are permitted

Final Examination for MSc

Course in Applied Meteorology
Course in Atmosphere, Oceans and Climate
Course in Data Assimilation and Inverse Modelling in Geosciences
Course in Applied Meteorology and Climate with Management

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. Its magnitude can be estimated from the balance between absorbed solar radiation (ASR) and outgoing longwave radiation (OLR). Approximate latitudinal profiles are given by:

$\mathrm{ASR}(\phi) = 175 + 125\cos 2\phi$ W m^{-2}, $\mathrm{OLR}(\phi) = 200 + 50\cos 2\phi$ W m^{-2},

where ϕ is the latitude. Sketch these profiles, and explain why both ASR and OLR are largest in the tropics. State the constraint on ASR(ϕ) and OLR(ϕ) that is required if the Earth system is assumed to be in energy balance, and show that it is satisfied by these particular profiles. This identity may be useful:

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

[7 marks]

(b) You may assume the flux-source relationship in the form

$$F(\phi) = -\iint S\, a^2 \cos\phi \, d\theta \, d\phi \,,$$

where $F(\phi)$ is the northward heat flux into a cap around the Earth's north pole bounded at latitude ϕ, θ is the longitude, a is Earth's radius, S is the source of heat from exchange with space (S is negative in the case of a sink), and the integral is taken over the cap. Using the profiles above, 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).

[10 marks]

(c) Draw a sketch graph of the mean northward heat transport in the climate system as a function of latitude from the south pole to the north pole. You should draw three curves: one for the atmospheric component, one for the oceanic component, and one for the total energy transport. The sketch should show how the relative importance of the atmospheric and oceanic transports varies with latitude. It should also show the approximate magnitude and latitudinal position of the peak transport associated with each curve.

[12 marks]

Question 1 continues overleaf

Question 1 continued

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

[7 marks]

(e) With reference to the Hadley cell in the atmosphere, consider a parcel of air that is initially at the equator, at rest with respect to the ground, and is then transported northwards. Assuming the parcel's angular momentum is conserved, show that its westward velocity u at latitude ϕ is given by $u = a\Omega \sin^2\phi / \cos\phi$, where Ω and a are the Earth's rotation rate and radius, respectively.

[7 marks]

(f) 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 the type discussed in (d) 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) Two different physical arguments lead to the notion of the westward movement of patterns when the Coriolis parameter increases linearly with latitude — the basis of Rossby waves. These arguments are based on consideration of:

(i) mass conservation for a pressure perturbation independent of y;

(ii) vorticity conservation for a vorticity perturbation independent of y.

Briefly discuss the arguments for westward movement in the two cases.

(12 marks)

Question 2 continues overleaf

Question 2 continued

The dispersion relation for barotropic Rossby waves in a zonal flow *u* may be written

$$\omega = uk - \frac{\beta k}{k^2 + l^2} \quad ,$$

where ω is the frequency, *k* and *l* are the zonal and meridional wavenumbers, and β is the latitudinal gradient of the Coriolis parameter.

(b) Show that stationary Rossby waves are possible in a westerly flow but not in an easterly flow.

[5 marks]

(c) Estimate the zonal wavelength (in km) for stationary Rossby waves where $\beta = 1.75\times10^{-11}\ \text{m}^{-1}\text{s}^{-1}$. You may assume the waves propagate zonally (i.e. $l=0$) on a background westerly flow of $u = 20\ \text{m s}^{-1}$.

[6 marks]

(d) Show that the group velocity of stationary waves may be written $\mathbf{c}_g = 2u \cos\varphi\, \boldsymbol{K}$, where $\boldsymbol{K}$ is a unit vector in the direction of phase propagation and φ is the angle this makes with the eastward direction.

[14 marks]

(e) Describe the physical mechanisms through which a stationary large-scale diabatic heat source in the tropics may generate upper-tropospheric Rossby waves in the extratropics. You should sketch diagrams where appropriate to illustrate the processes involved.

[10 marks]

(f) Briefly explain why stationary Rossby wave activity generated in the extratropical Northern Hemisphere tends to have little direct impact on the flow in the Southern Hemisphere.

[3 marks]

Question 3 begins overleaf

3. You are given the horizontal momentum and mass conservation equations for a uniform, incompressible, steady ocean:

$$\rho f\boldsymbol{k}\times\mathbf{v} + \nabla p = \partial\boldsymbol{\tau}/\partial z, \qquad \nabla\cdot\boldsymbol{u} = 0,$$

where $\boldsymbol{v}$ is the horizontal velocity, $\boldsymbol{u}$ is the three-dimensional velocity, f is the Coriolis parameter, p is pressure, $\boldsymbol{k}$ is a unit vector in the direction of the vertical coordinate z, $\boldsymbol{\tau}$ is the viscous stress, and the density ρ is assumed constant.

(a) Assuming that the ocean has a uniform depth H, show that the vertically integrated mass transport in the y direction, V, is given by

$$\beta V=\boldsymbol{k}\cdot(\nabla\times\boldsymbol{\tau}_{\mathrm{s}}),$$

where $\boldsymbol{\tau}_{\mathrm{s}}$ is the stress at the upper surface of the ocean, and it has been assumed that the bottom stress is zero.

[12 marks]

(b) For the case of an anticyclonic wind-stress curl, give a physical interpretation of the result given by this equation in terms of Ekman convergence and the Sverdrup relation.

[8 marks]

(c) Using the bulk formula $\boldsymbol{\tau} =\rho c_{\mathrm{D}}|\boldsymbol{v}|\boldsymbol{v}$ and typical values that you should state, use the equation derived in (a) to estimate the equatorward mass transport per metre of longitude in the subtropical oceans. Use this mass transport to produce an estimate of a typical equatorward flow speed.

[10 marks]

(d) Briefly discuss theories for where the return flow occurs when an anticyclonic wind stress curl acts on a closed ocean basin, and draw a sketch showing the circulation of the ocean.

[10 marks]

Question 3 continues overleaf

Question 3 continued

(e) Consider now the equatorial ocean. Using your general knowledge of the tropical atmospheric circulation, Ekman pumping, and the temperature structure of the oceans, explain why a cold tongue is often seen in sea surface temperatures along the equator (e.g. in the East Pacific). You should draw a sketch diagram to illustrate this process, clearly indicating the nature of the atmospheric circulation and the Ekman flows it produces in both the atmosphere and ocean.

[10 marks]

[End of Question paper]