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 2014 **MTMW15**

Answer Book
Data Sheet
Only Casio-fx83 calculators are permitted

UNIVERSITY OF READING

Extra-tropical weather systems (MTMW15)

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) Draw diagrams showing the vertical coupling between Rossby waves at the ground and tropopause in baroclinic systems.

[12 marks]

(b) The quasi-geostrophic omega equation can be written in the form

$$N^2\nabla_h^2 w + f_0^2\frac{\partial^2 w}{\partial z^2} = \underbrace{f_0\frac{\partial}{\partial z}\left(\mathbf{v_g}\cdot\nabla\xi_g\right)}_{A} - \underbrace{\nabla_h^2\left(\mathbf{v_g}\cdot\nabla b'\right)}_{B} + \underbrace{\beta f_0\frac{\partial v_g}{\partial z}}_{C}$$

Draw a diagram showing a wave in vorticity. Mark on this diagram the direction of the geostrophic wind, regions of ascent and descent and the signs of term A and the vorticity advection.

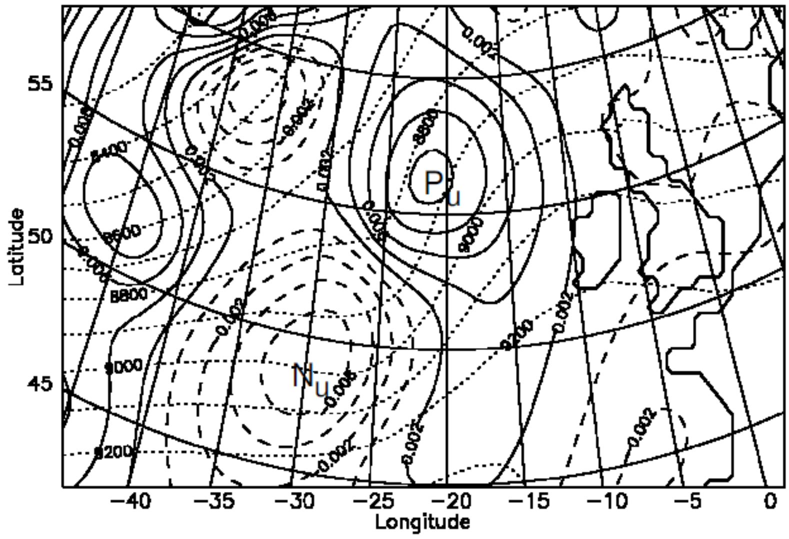
Now draw a diagram showing a thermal wave. Mark on this diagram the direction of the geostrophic wind, regions of ascent and descent and the signs of term B and the thermal advection.

Using scaling analysis, explain how you related the signs of terms A and B to the corresponding signs of the vertical velocity.

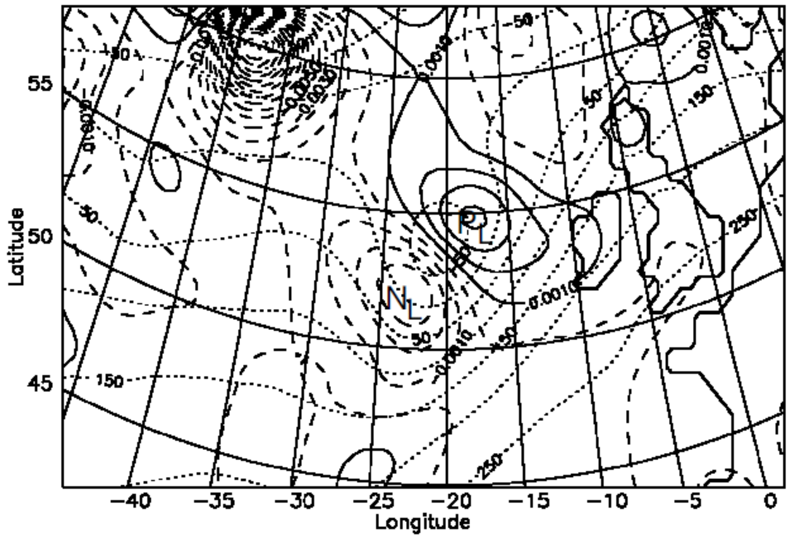
[12 marks]

Use the figure below to answer the rest of this question. It shows analysis of model output at a particular time and is from a paper by Deveson et al. (2002) (which you are not expected to have read).

(a)



(b)



(a) Vertical velocity at 700 hPa forced from upper levels (650-50 hPa), with solid contours for ascent and dashed contours for descent at intervals of 0.002 ms^{-1}, overlaid with 300 hPa geopotential height (dotted contours). (b) Vertical velocity at 700 hPa forced from lower levels (1050-750 hPa) with solid contours for ascent and dashed contours for descent at intervals of 0.002 ms^{-1}, overlaid with 1000 hPa geopotential height (dotted contours). PU, NU and PL, NL represent the locations of the ascent and descent maxima at 700 hPa forced from upper and lower levels, respectively.

(c) State (giving reasons) whether the vertical structure in geopotential height is consistent with the structure predicted from barolinic instability theory.

[2 marks]

(d) The Eady model of baroclinic instability predicts the wavelength at which the maximum growth rate of cyclones occurs. Using typical midlatitude scalings for the latitude at which this cyclone occurs estimate this wavelength and compare the predicted scale of the cyclone with that determined from the figure.

Give two reasons why the predicted and measured scales might differ.

[16 marks]

(e) The vertical velocity at 700 hPa determined by solving the omega equation for this cyclone is also plotted in the figure. Forcing from upper levels only is used to derive the vertical velocity in panel (a) and that from lower levels only is used to derive the vertical velocity in panel (b). Assume that the upper-level forcing is dominated by term A and the lower-level forcing is dominated by term B. Do the patterns of vertical velocity agree with that predicted by the omega equation (assume the cyclone is travelling eastwards)? Give your reasoning.

[4 marks]

(f) Estimate the magnitude of term A using the peak magnitude of vertical velocity plotted in panel (a), typical midlatude scalings for the latitude at which the cyclone occurs and the scale of the cyclone.

[4 marks]

2. (a) Under what assumptions does quasi-geostrophic theory apply in the atmosphere?

Using typical numerical values show that it is appropriate for midlatitude synoptic-scale weather systems.

[9 marks]

(b) Consider a developing cyclone in the midlatitudes.

The relative vorticity at the cyclone centre at a height of 5 km is 10^{-4} s^{-1} with a horizontal gradient of -10^{-4} s^{-1}/500 km towards the east, ahead of the cyclone. The relative vorticity is increasing at a rate of 0.5×10^{-4} s^{-1}/12 hours and the background wind is westerly at 30ms^{-1}. Assume that the vertical velocity and background wind are zero at the ground. Assume typical midlatitude scalings.

Use the quasi-geostrophic vorticity equation

$$D_g \zeta_g = f_0 \frac{\partial w}{\partial z}$$

to estimate the horizontal divergence ahead of the cyclone at 5km height.

[10 marks]

(c) Calculate the vertical velocity at 2.5 km using your answer from part (b). Assume a sinusoidal variation in vertical velocity with height with zero values at the ground and at 5km.

[5 marks]

(d) The quasi-geostrophic thermodynamic equation is given by

$$D_g b' + N^2 w = 0.$$

Derive the expression for conservation of the quasi-geostrophic potential vorticity, q, where

$$q = \zeta_g + f_0 \frac{\partial}{\partial z}\left(\frac{b'}{N^2}\right)$$

using the quasi-geostrophic vorticity and thermodynamic equations. Note the assumptions you make.

[12 marks]

(e) The relative vorticity anomaly for the cyclone in part (b) is associated with an anomaly in q. Estimate this q anomaly given that the vertical gradient in perturbation potential temperature is 30K/5km.

[8 marks]

(f) Explain the concepts of action-at-a-distance and invertibility associated with quasi-geostrophic potential vorticity anomalies.

[6 marks]

3. The Q-vector version of the quasi-geostrophic Omega equation is given by

$$N^2\nabla_h^2 w + f_0^2 \frac{\partial^2 w}{\partial z^2} = 2\nabla_h \bullet \mathbf{Q} \qquad (1)$$

in which the Q-vector may be expressed in natural coordinates as

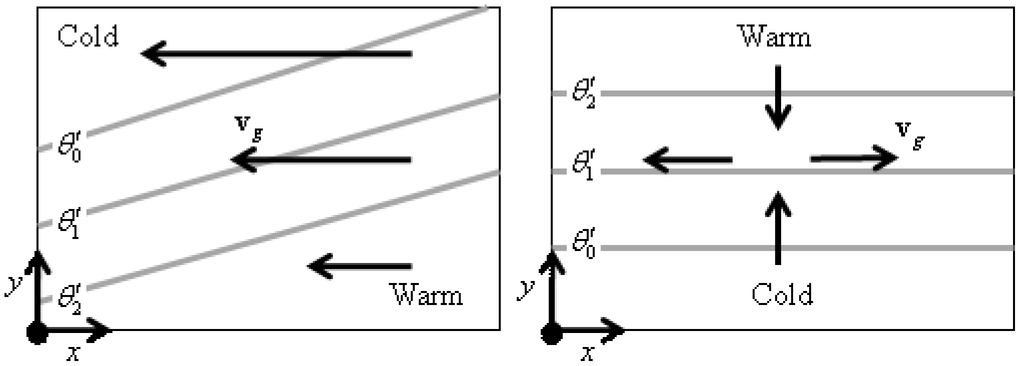
$$\mathbf{Q} = -\left|\nabla_h b'\right| \hat{\mathbf{k}} \times \frac{\partial \mathbf{v}_g}{\partial s} \qquad (2)$$

where, as usual, bold font indicates a vector quantity.

(a) Describe the recipe for determining the magnitude and direction of the Q-vector from equation (2) above.

[8 marks]

(b) Two hypothetical flows have the following v_g and θ' fields where $\theta'_2 > \theta'_1 > \theta'_0$



Copy the above diagrams into your answer books. Using the Q-vector recipe from part (a), determine the Q-vector direction at the centre of both figures and add it to the sketch (show your working).

[10 marks]

(c) Determine the regions of ascent and descent implied by the two diagrams and clearly mark them on your sketches.

Explain whether the resulting circulations are thermally direct or thermally indirect.

[10 marks]

(d) A front is aligned in the $\hat{\mathbf{s}}$ direction with no temperature gradient along its axis. Frontogenesis occurs when the buoyancy gradient increases with time. Using the quasi-geostrophic thermodynamic equation given by

$$D_g b' + N^2 w = 0,$$

show that the total geostrophic time derivative of the buoyancy gradient in the $\hat{\mathbf{n}}$ direction, $D_g\left(\partial b'/_{\partial n}\right)$, *at the surface* is given by

$$D_g \frac{\partial b'}{\partial n} = -\frac{\partial v_g}{\partial n}\frac{\partial b'}{\partial n}$$

[Hint: determine the relationship between $D_g \frac{\partial b'}{\partial n}$ and $\frac{\partial}{\partial n} D_g b'$]

[14 marks]

(e) It can be shown that an equivalent way of expressing the necessary condition for frontogenesis is that

$$\hat{\mathbf{n}} \cdot \mathbf{Q} < \mathbf{0}.$$

Explain whether each of the flows shown in (b) is undergoing frontogenesis or frontolysis.

[8 marks]

(End of Question Paper)