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.

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April 2009

<div align="right">

Answer Book
Data Sheet
Figure(s)
Any bilingual English language dictionary permitted
Calculators and programmable calculators are permitted

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THE UNIVERSITY OF READING

MSc/Diploma
Course in Applied Meteorology
Course in Atmosphere, Ocean and Climate

MSc in Mathematics and Numerical Modelling of the Atmosphere and Oceans

PAPER MTMG49

Boundary Layer Meteorology and Micrometeorology

One and a half hours

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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 surface energy balance can be written as,

$$R_n - G_0 = H + \lambda E$$

where R_n is the net radiation, G_0 is the ground heat flux, H is the sensible heat flux and λE is the latent heat flux.

Define the Bowen ratio, B_0, and derive an expression for the sensible heat flux in terms of R_n-G_0 and B_0.

Give typical values of B_0 for the following surfaces, (i) Ocean, (ii) rural, (iii) urban and (iv) desert.

[10 marks]

(b)   In the Carson model for the development of the convective boundary layer depth, $h(t)$, is given by,

$$h(t) = \sqrt{\frac{2(1 + 2A)}{\rho\, c_p\, \gamma} \int_0^t H(t)dt}$$

where $H(t)$ is the surface sensible heat flux as a function of time.

Estimate the depth of the boundary layer for a rural site and an urban site given that $\int_0^t R_n(t)dt = 4.1$ MJ m^{-2} and an initial lapse rate, $\gamma=3.8$ K km^{-1}. Assume that at the rural site there is sufficient water for the vegetation to transpire freely. State any further assumptions you have to make in the calculation.

[10 marks]

Question 1 continued overleaf

Question 1 cont'd.

(c)   Show that

$$w_* = \left(\frac{g}{\theta} \overline{w'\theta'}_0 \, h\right)^{1/3}$$

Is the velocity scale for turbulent <u>eddies</u> in convective boundary layer. $w'\theta'_0$ is the surface kinematic heat flux.

[13 marks]

(d)   Over a rural site $h = 950$ m and over an urban site $h = 1600$ m. The net radiation at both sites is $R_n = 600$ Wm^{-2}. Calculate the convective velocity scale for the rural and urban sites stating any assumptions you make.

Based on your calculations describe how the dispersion of a pollutant emitted from the chimney of a power station would differ at the rural and urban sites.

[17 marks]

2.

(a) The structure of the surface layer is determined by the following parameters: the friction velocity, u_*, the kinematic heat flux, $\overline{w'\theta'}$, the parameter g/θ and the height above the surface, z.

Show that the parameter z/L is non-dimensional, where L is the Obukhov length defined as

$$L = -\frac{u_*^3}{\kappa \, g/\theta \, \overline{w'\theta'}}$$

Explain how z/L relates to turbulence production mechanisms.

State how the parameter z/L differs from the static stability parameter.

[14 marks]

(b) The turbulence kinetic energy budget is

$$\frac{\partial E}{\partial t} = -\overline{u'w'}\frac{\partial U}{\partial z} + \frac{g}{\theta}\overline{w'\theta'} + T - \epsilon$$

where T represents the transport term.

Describe each of the terms in the budget.

State which terms in the turbulent kinetic energy budget can be neglected in stable conditions.

[12 marks]

Question 2 continued overleaf

Question 2 cont'd.

(c)   The wind-shear in the surface layer in stable conditions is given by,

$$\frac{\partial U}{\partial z} = \frac{u_*}{\kappa z}\left(1 + 5\frac{z}{L}\right)$$

Assuming that conditions are steady use the TKE budget to calculate the dissipation rate at 3m if $u_* = 0.1$ ms^{-1} and $\overline{w'\theta'} = -10^{-2}$ ms^{-1} K. State any assumptions you make.

Calculate the flux Richardson number. Comment on how stable the conditions are by referring to the value of the flux Richardson number.

[11 marks]

(d)   Sketch the spectrum of fluctuations of the wind in terms of wave-number. Mark on your sketch the important regions of the spectrum explaining what they represent.

What information about turbulence does the spectrum give?

Which part of the spectrum has the form $E(k) = \alpha \epsilon^{2/3} k^{-5/3}$ where k is wave-number? Explain how this spectral form arises by referring to the turbulent processes.

[13 marks]

Turn over

3.

(a) Make a sketch of the diurnal variation of the boundary layer under clear sky conditions. Mark on your sketch the significant layers, their stratification and the processes that occur in them.

[13 marks]

(b) The Ekman wind profile is given by,

$$\overline{u} = u_g(1 - \exp(-az) \, \cos(az))$$

$$\overline{v} = u_g \exp(-az) \sin(az)$$

where $a = \sqrt{f / (2 \, K_m)}$

Sketch a hodograph of the Ekman wind profile in the Northern hemisphere. Mark the significant features of the profile.

State any ways in which the Ekman profile differs from observed boundary layer wind profiles in neutral, barotropic conditions.

[15 marks]

(c) Give two examples of internal boundary layers.

Sketch the main features of both examples.

[8 marks]

(d) Describe the dynamical and chemical processes that control the concentration of ozone near the ground in the polluted urban boundary layer.

[14 marks]

(End of Question Paper)