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 **MTMG49/ 2014/15/ A001**

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

UNIVERSITY OF READING

Boundary Layer Meteorology and Micrometeorology (MTMG49)

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 surface energy balance can be written as

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

where R_n is the net all-wave radiation, G is the ground heat flux, H is the turbulent sensible heat flux and λE is the turbulent latent heat flux.

Define the Bowen ratio, B, and derive an expression for the sensible heat flux in terms of R_n, G and B.

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

[10 marks]

(b) In the Carson (1973) model for the development of the convective boundary layer depth, $h(t)$ is given by

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

where $H(t)$ is the surface sensible heat flux as a function of time, and E is the entrainment coefficient.

Estimate the depth of the boundary layer for a rural site and an urban site given that $\int_0^t R_n(t)dt = 5$ MJ m^{-2} and the initial lapse rate is $\gamma = 4$ K km^{-1}. Assume that the ground heat flux G is zero. State any further assumptions you have to make in the calculation.

[10 marks]

(c) Show using dimensional analysis that

$$w_* = \left[\frac{g}{\theta_0} \left(\overline{w'\theta'} \right)_0 h \right]^{1/3}$$

is the velocity scale for turbulent eddies in the convective boundary layer, where $\left(\overline{w'\theta'} \right)_0$ is the surface kinematic heat flux.

[14 marks]

(d) Over a rural site h = 950 m and over an urban site h = 1600 m. The net all-wave radiation at both sites is R_n = 600 W m^{-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.

[16 marks]

2.

(a) The following equation describes radiative processes at the Earth's surface

$$R_n = S_\downarrow (1-\alpha) + \varepsilon (L_\downarrow - \sigma T_S^4).$$

Explain the meaning of all the symbols on the right-hand side of the equation.

[6 marks]

(b) Measurements of R_n are made at the same time in a city and in a rural area nearby. By considering the properties of the surface and air for both the urban and the rural areas, explain the differences in magnitude over each surface of each quantity on the right-hand side of the equation above.

Is there a significant difference in the overall magnitude of R_n? Briefly justify your answer.

[12 marks]

(c) Air is flowing from a rural to an urban surface. The change in surface roughness leads to the growth of an internal boundary layer over the urban surface. Estimate the maximum depth h_i of the urban internal boundary layer using

$$\frac{h_i}{z_0} = 0.72\left(\frac{x}{z_0}\right)^{0.8}$$

where z_0 is the roughness length and the fetch of the urban surface is x = 8 km. Use a reasonable estimate of the urban roughness length.

The flow then adjusts back to a rural surface. Calculate the fetch of rural surface required to grow an internal boundary layer to the same depth as the urban internal boundary layer.

[10 marks]

(d) Explain the processes leading to the Urban Heat Island phenomenon, and how it might be quantified. Include references to the evolution of the phenomenon, the surface energy balance, and differences between the urban and surrounding rural surface. When is the effect at its maximum during a diurnal cycle?

[12 marks]

(e) What were the chemical processes and meteorological conditions leading to the “London Smog” events of December 1952? Consider the main pollutant sources at the time in your answer.

Which key measures were implemented in the Clean Air Act to avoid recurrence of such smog events?

[10 marks]

3.

(a) Given the role of turbulence in the atmospheric boundary layer, describe:

(i) the meaning of turbulence and why it is so important in boundary layer meteorology;

(ii) the two main physical processes causing turbulence in the atmospheric boundary layer;

(iii) the main purpose of a turbulence closure scheme.

[15 marks]

(b) A model for the boundary layer has a simple first-order mixing length closure scheme given by

$$-\overline{u'w'} = K_m \frac{dU}{dz} \quad \text{where} \quad K_m = l_m^2 \left[\left(\frac{dU}{dz} \right)^2 - 4 \frac{g}{\theta_0} \frac{d\theta}{dz} \right]^{1/2}$$

Describe an experiment that could determine the variation of the mixing length l_m with height, including a careful explanation of:
(i) selection of the site,
(ii) the instruments required and
(iii) their deployment.
Sketch the variation of l_m with height that you would expect to find from such an experiment.

[15 marks]

(c) Write the expression for K_m given in the equation in question 3(b) in terms of the Richardson number

$$Ri = \frac{(g/\theta_0)d\theta/dz}{(dU/dz)^2}.$$

Give a physical interpretation of K_m, explaining how this quantity varies with l_m, dU/dz and Ri in convective, neutral and stable boundary layers.

[10 marks]

(d) Using the equations in questions 3(b) and 3(c) and also noting that in the surface layer

$$\frac{dU}{dz} = \frac{u_*}{\kappa z}\phi_m\left(\frac{z}{L}\right)$$

obtain an expression for l_m in the surface layer in terms of z, ϕ_m and *Ri*. Estimate the value of l_m in a neutral boundary layer at a height of 10 m.

[10 marks]

[End of Question Paper]