You are allowed ten minutes before the start of the examination 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 2003 **9XMMT567 2002/3 A 001**

1 x Answer Book
Data Sheet
Calculators and programmable calculators are permitted

THE UNIVERSITY OF READING

MSc/Diploma
Course in Applied Meteorology
Course in Weather Climate and Modelling

MSc in Mathematics and Numerical Modelling of the Atmosphere and Oceans

PAPER MTMG49

Boundary Layer Meteorology and Micrometeorology

One and a half 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) Explain the meaning of all the symbols in the surface energy balance equation

$$R_n - G = H_s + \lambda E \, .$$

[5 marks]

(b) Explain how the diurnal variation of the surface energy balance for short grass drives the diurnal variation in the atmospheric boundary layer under ideal cloudless conditions. Use a sketch diagram with axes of time and height to illustrate this cycle, annotating your sketch diagram with typical values of the boundary layer depth. Explain briefly the differences that would be expected over dry bare soil.

[15 marks]

(c) Describe the turbulent structures that control the thermodynamic structure and evolution of the convective boundary layer. Hence describe carefully the assumptions made to derive the Carson model for the variation of the height, *h*, of the convective boundary layer, namely

$$h(t) = \left\{ \frac{2(1+2E)}{\rho c_p \gamma} \int_0^t H_s(t')\,dt' \right\}^{\frac{1}{2}}$$

If $H_s = 350\,\mathrm{Wm}^{-2}$, which remains constant, and $E = 0.2$, $\gamma = 6.5\,\mathrm{K\,km}^{-1}$, calculate the depth of the convective boundary layer 6 hours after sunrise.

[15 marks]

(d) Describe the dynamical and chemical processes that control the concentration of ozone near the ground over a diurnal cycle of a polluted boundary layer.

[15 marks]

2.

(a) Describe the role of turbulence in the atmospheric boundary layer, describing (i) the meaning turbulence and why is it 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

$$-\overline{u'w'} = K_m \frac{dU}{dz}, \quad \text{where} \quad K_m = l_m^2 \left\{ \left(\frac{dU}{dz} \right)^2 - 4 \frac{g}{\theta_s} \frac{d\theta}{dz} \right\}^{\frac{1}{2}} \qquad (2.1)$$

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) By writing the expression for K_m given in equation (2.1) in terms of the Richardson number

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

give a physical interpretation of the model for K_m in convective, neutral and stable boundary layers.

[10 marks]

(d) Explain, with a suitable sketch diagram, how K_m would vary over a diurnal cycle at two suitably chosen heights within the boundary layer.

[10 marks]

3.

(a) The Ekman model of boundary layer flow is defined by the following equations:

$$-f\left(v - V_g\right) = K_m \frac{\partial^2 u}{\partial z^2}, \qquad f\left(u - U_g\right) = K_m \frac{\partial^2 v}{\partial z^2} \quad (3.1)$$

Explain the meaning of all the symbols. State the three assumptions that have been used to obtain these simplified equations. State the boundary conditions required for u and v at the top and bottom of the atmospheric boundary layer.

[10 marks]

(b) The solutions for the Ekman layer are

$$u = U_g\left[1 - \exp\left(-z/h\right)\cos\left(z/h\right)\right], \quad v = U_g \exp\left(-z/h\right)\sin\left(z/h\right),$$

with $h = \left(2K_m/f\right)^{\frac{1}{2}}$. What does h represent physically? Sketch the hodograph of the solution with u against v through the boundary layer. Calculate the angle between the geostrophic and surface winds. Critically discuss how these model predictions compare with observations.

[20 marks]

(c) Explain the physical processes that control turbulence in the boundary layer following night fall, under clear skies. How can the Ekman equations (3.1) be changed to model these conditions. Sketch on a hodograph the evolution of the wind speed and direction at two suitably chosen heights indicating the key features of the evolution.

[20 marks]

End of Question Paper