11A.2 # CANOPY DYNAMICS AND THE SURFACE ENERGY BALANCE

Ian N. Harman* and John J. Finnigan
CSIRO Marine and Atmospheric Research, Canberra, Australia

1. INTRODUCTION

We have long known that conventional surface layer theory fails to predict the relationship between the mean profiles of wind speed or scalar concentrations and the fluxes of those quantities within and just above tall canopies (e.g. Chen and Schwerdtfeger, 1989). This layer of the boundary layer is known as the roughness sublayer (RSL). However, surface layer theory is still widely used within numerical weather prediction (NWP) and general circulation (GCM) models as part of their surface energy balance and surface exchange schemes.

It is now widely understood that one of the reasons for the failure of such standard relationships is the existence of coherent turbulent structures in the flow over canopies which are unlike those in rough wall boundary layers (Raupach et al. 1996) and upon which the standard relationships are based. Harman and Finnigan (2007) were able to incorporate the impacts of the coherent structures and the canopy dynamics on the mean wind speed within and over tall canopies as modifications to surface layer theory. Recently, this approach has been extended so as to apply to the scalar concentration and temperature profiles (Harman and Finnigan, 2008). There are two key advantages of this approach, over the many alternatives. First, this approach couples the profiles within and above the canopy, with the consequence of reducing the level of empiricism required. Second, this approach could be incorporated into the surface layer theory based approaches used within NWP models.

However, this approach does represent an increase in complexity to the surface scheme within most NWP and GCM models. Such an additional complexity would only be merited if there were significant differences when this approach is adopted. Here we investigate this issue by considering the impacts of the Harman and Finnigan approach on the evolution of a coupled surface energy balance and boundary layer model in an idealised case.

**Corresponding author address:* Ian Harman, CSIRO Marine and Atmospheric Research, GPO Box 3023, Canberra, ACT, 2601. Australia.
e-mail: ian.harman@csiro.au

2. MODEL

The model used here is comprised of two components. First is the multi-level boundary layer model of Busch et al. (1976). This is a first-order closure, mixing-length based, model for the vertical profiles of the wind vector, potential temperature and water vapour concentration over a horizontally homogeneous surface. Similar models for the boundary layer are used within many NWP and GCM models.

The second component is a simple model for the surface energy balance of a homogeneous, dense canopy. The canopy is represented by a single heat capacity, C_g, and temperature, T_c. The canopy is coupled to the underlying substrate solely by radiative transfer as shown schematically in Figure 1a. The evolution of the temperature of the canopy is then governed by an energy balance, namely

$$\frac{\mathrm{d}(\Delta C_g T_c)}{\mathrm{d}t} = S - \hat{S} + L^{\downarrow} - L^{\uparrow} - \Delta L - H - \lambda E$$

where S and $\hat{S}$ are the downwelling flux densities of shortwave radiation at canopy top and at the ground, respectively, H is the flux density of sensible heat and λE the flux density of latent heat. The longwave radiation terms are comprised of $L^{\downarrow}$ the downwelling radiation, $L^{\uparrow}$ the total outgoing radiation and ΔL the net longwave radiative exchange between the canopy and the substrate. $L^{\downarrow}$ is given by the boundary layer model, the other radiative terms are given by the canopy model of Watanabe (1994) and are dependent on canopy height, leaf area index and the temperatures of the canopy and substrate.

The evolution of the temperature profile within the ground is given by the heat conduction equation with the surface flux of heat, G, given by

$$G = \hat{S} + \Delta L$$

The turbulent fluxes of heat and water vapour act to couple the boundary layer and surface energy balance components of the model. Resistance forms are used to determine these fluxes (see below). It is the formulation of these resistances, in terms of known variables, which is considered here.

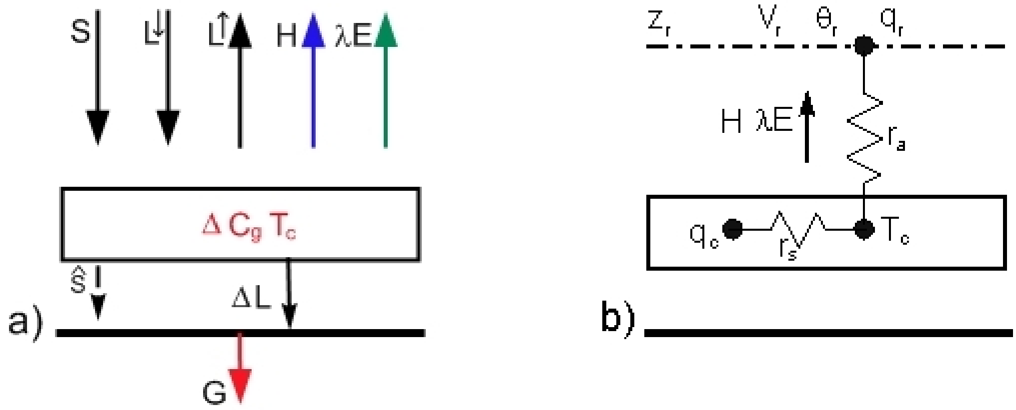

Figure 1. a) Schematic of the canopy energy balance model, the arrows indicate the direction of a positive value for the flux density. The symbols are introduced in the text. b) Schematic of the resistance network used to determine the flux densities of sensible and latent heat. The sensible heat flux is (partially) controlled by the aerodynamic resistance, r_a, whereas the latent heat flux is (partially) controlled by the combination of the aerodynamic and stomatal resistances, r_a+r_s .

Resistance forms are adopted to determine the turbulent fluxes i.e.

$$H = \rho c_p V_r \left(T_c - \theta_r\right) / r_a = \rho c_p C_H V_r \left(T_c - \theta_r\right)$$

$$E = \rho V_r \left(q_c - q_r\right) / \left(r_a + r_s\right) = \rho \lambda V_r C_E \left(q_c - q_r\right)$$

where ρ is the mean density of air, c_p the heat capacity of air, λ the latent heat of evaporation, V_r the wind speed at a reference height, z_r, in the boundary layer (usually the lowest level of the boundary layer model), θ_r is the potential temperature at the reference level, and q_r and q_c are the water vapour concentrations at the reference level and in the sub-stomatal cavities of the leaves respectively. r_a and r_s denote the aerodynamic and stomatal resistances to transfer respectively. The stomatal resistance is assumed independent of the turbulent properties of the boundary-layer, but controlled by the physiological characteristics of the canopy and dependent on solar radiation, temperature and the boundary layer water vapour deficit (Jacquemin and Noilhan, 1990). Conversely the aerodynamic resistance quantifies the turbulent aspect of the transfer and depends on the assumed relationship between the mean profiles and the fluxes.

The form for r_a consistent with surface layer theory is

$$r_a = \left[\ln\left(\frac{z-d}{z_0}\right) - \Psi_m\right]\left[\ln\left(\frac{z-d}{z_{0h}}\right) - \Psi_h\right] \Big/ \kappa^2$$

where d, z_0 and z_{0h} are the canopy displacement height and canopy roughness lengths for momentum and heat. κ is von Karman's constant. The influence of stability (and indeed other processes) is captured through the use of the integrated forms of the generalised similarity functions, Ψ_m and Ψ_h. In many NWP and GCM models the parameters d, z_0 and z_{0h} are prescribed according to vegetation type and/or canopy height – this methodology takes no account of the profiles within the canopy.

Harman and Finnigan (2007; 2008) introduce simple forms for the profiles within a canopy. With this approach the canopy is characterised by two leaf-level properties; a length scale which quantifies the ability of the canopy to exert drag, L_c which is related to the leaf area index, and the leaf-level Stanton number, r. The displacement height is given a physical meaning to be the location of the turning moment associated with the drag on the canopy (Jackson, 1981). Coupling the profiles within the canopy to the above canopy (surface layer type) profiles provides a set of conditions which L_c, r, d, z_0 and z_{0h} must satisfy. Since the leaf-level processes are unlikely to be influenced by the larger scale diabatic stability the parameters L_c and r are considered invariant. The immediate consequence is that d, z_0 and z_{0h} vary with stability. Conceptually d, z_0 and z_{0h} quantify the bulk characteristics of the canopy – any process which influences the profiles and/or sources and sinks within the canopy then impacts on these parameters.

The RSL is included in this coupling methodology by modifying the assumed flux-gradient relationship above the canopy, namely

$$\frac{\mathrm{d}V}{\mathrm{d}z} = \frac{u_*}{\kappa(z-d)}\Phi_m = \frac{u_*}{\kappa(z-d)}\phi_m\hat{\phi}_m$$

and similarly for temperature and water vapour. ϕ is the standard rough wall similarity function which quantifies the impact of diabatic stability on the flux-gradient relationships.

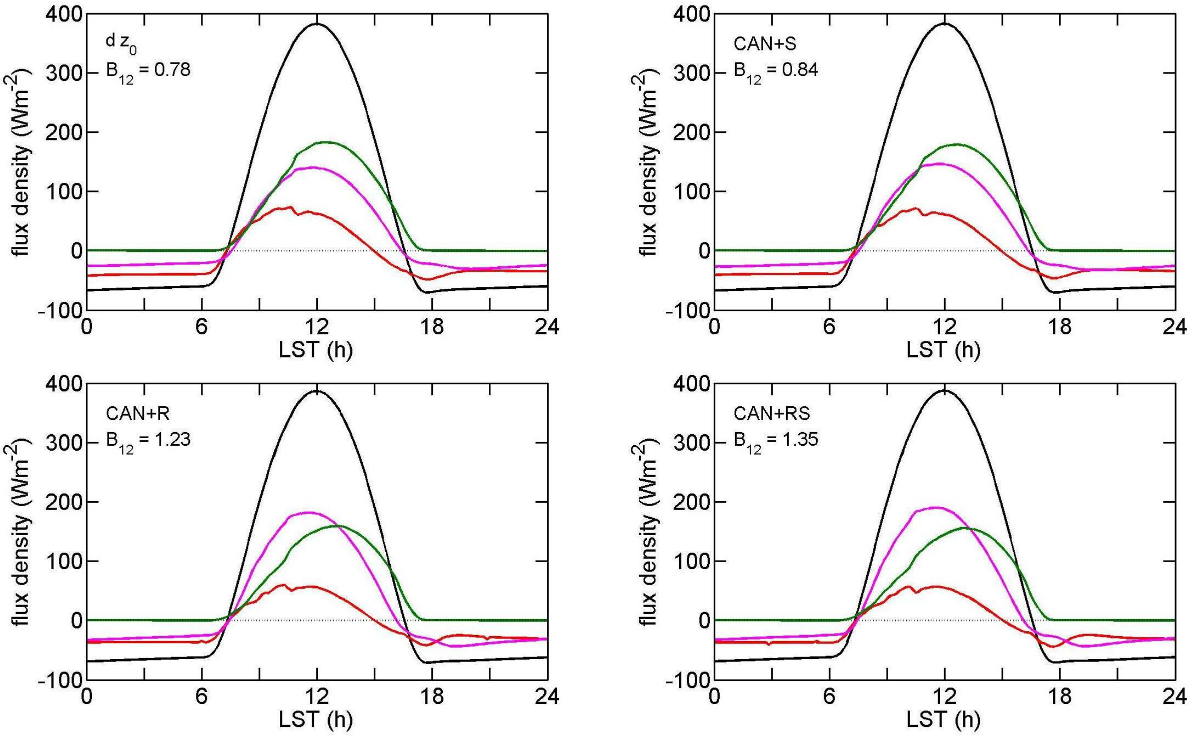

Figure 2. Diurnal variation of the energy balance at canopy top from the simulations with the four alternate forms of the aerodynamic resistance. In each panel the black line is the flux density of net radiation, the green line the flux density of latent heat, the magenta line the flux density of sensible heat and the red line the flux density of energy into heat storage within the canopy or into the substrate.

The function $\hat{\phi}_m$ quantifies the influence of the canopy dynamics and coherent structures on the profiles above the canopy. The form of $\hat{\phi}_m$ used is

$$\hat{\phi} = 1 - c_1 \exp\left\{-c_2 (z-d)/L_c\right\}$$

where c_1 and c_2 are (stability dependent) parameters, again obtained by reference to the within canopy solutions. The resultant profiles of wind speed and scalar concentration are shown to agree with observations in Harman and Finnigan (2007; 2008). Revised forms for Ψ_m, Ψ_h, and r_a can then be calculated numerically.

4. RESULTS

The diurnal evolution of the surface energy balance and boundary layer is considered for four alternate forms for the aerodynamic resistance, r_a. The four cases are

dz0 r_a is given by standard surface layer theory forms. *d* and z_0 are constant and determined from L_c in neutral conditions and the RSL is ignored. This methodology is the default used in many NWP models.

CAN+S r_a is determined by the coupled canopy-boundary layer profiles. The RSL is ignored in the coupling - *d* and z_0 vary with stability.

CAN+R r_a is determined by the coupled canopy-boundary layer profiles. The RSL is included but is invariant with stability - *d* and z_0 vary with stability.

CAN+RS r_a is determined by the coupled canopy-boundary layer profiles. The full stability dependent RSL is used.

Simulations are shown for a dense canopy of moderate height (h_c=15m, L_c=30m) in a dry mid-latitude climate (60N) on the equinox.

Figure 2 shows the diurnal variation of the energy balance at canopy top from the four simulations. The four simulations show a number of common traits. The radiative control on the stomatal resistance ensures that only very small latent heat fluxes are possible during the night in all the simulations. The phasing of the terms is similar, with the ground and sensible heat fluxes peaking around one hour before the net radiation and the latent heat approximately 2 hours after the net radiation. The unsteadiness in the energy balance in the morning is due to

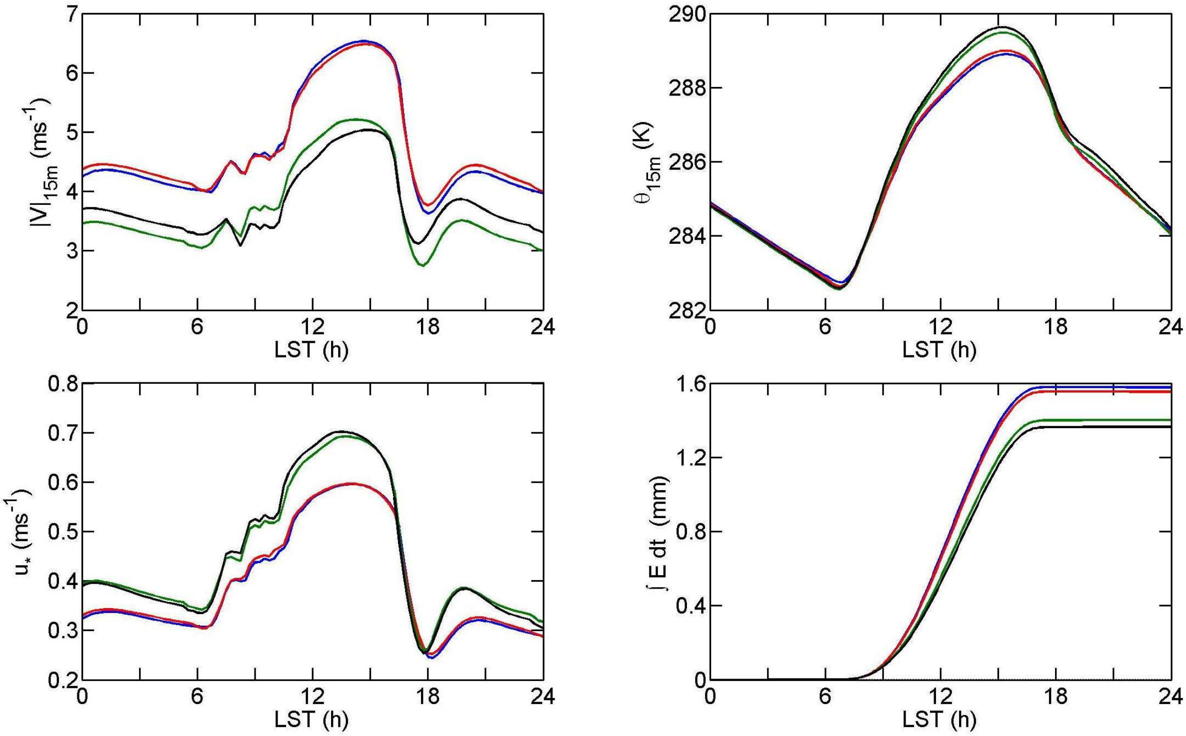

Figure 3. Diurnal variation of the 15m wind speed (top left), 15m potential temperature (top right), friction velocity (bottom left) and integrated evaporation (bottom right) for the simulations with the four alternate forms of the aerodynamic resistance. Blue line is the case dz0, red line the case CAN+S, green line the case CAN+R and black line the case CAN+RS. Unsteadiness in *V* and u_* in morning is due to the rapid growth of the convective boundary layer into overlying stable air.

the rapid and unsteady growth of the new convective boundary layer into the overlying atmosphere.

More important are the differences between the simulations – these occur mainly during the daytime. Most noticeable is that when the RSL is included in the coupling there is a significant change in the balance of the terms. More energy is released as sensible heat with less released as latent heat or stored within the canopy or substrate. There is a similar, but smaller, absolutely and relatively, shift to more negative sensible heat fluxes during the night.

The second difference is that when the coupling of the within and above canopy profiles accounts for the variation in stability (i.e. dz0 to CAN+S or CAN+R to CAN+RS), the promotion of sensible heat is reinforced. Together these effects imply that the midday Bowen ratio, B_{12}, is almost doubled between the dz0 and CAN+RS simulations. This suggests that assuming the bulk parameters *d* and z_0 to be fixed within NWP/GCM models misses an important aspect of the flow and exchange processes over canopies.

Alternative values of *d* and z0 can be found which result in closer, but non-exact, simulations to the CAN+RS simulations. However in doing so the characteristics of the canopy are altered. .

Accompanying the changes to the energy balance are changes in the boundary layer and in other aspects of surface exchange. Figure 3 shows the diurnal variation of the near-surface wind speed, near-surface temperature, friction velocity and integrated evaporation from the four simulations. The simulations that include the RSL have a marked decrease in near-surface wind speed yet an increase in the friction velocity. In essence the RSL forms are able to quantify the increase in efficiency of transport of momentum to the surface which occurs because of the different turbulence over canopies.

There are also changes in the near-surface potential temperature (~1K) which would be significant in NWP and changes (~20%) in the integrated evaporation from the surface which would be significant in hydrological process models.

The underlying reason for these changes can be found by considering how the aerodynamic and stomatal resistances vary during the course of the day as shown in reciprocal form in Figure 4. In these simulations $r_s > r_a$ and, since the stomatal resistance depends only on the mean conditions, the transfer coefficient for water vapour, C_E, is similar between the four simulations.

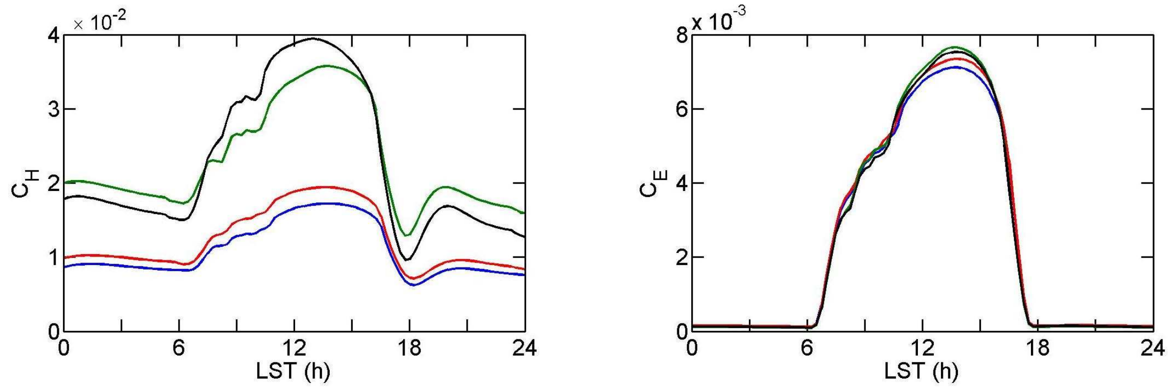

Figure 4. Diurnal variation of the transfer coefficients $C_H=1/r_a$ and $C_E=1/(r_a+r_s)$. Lines as in Figure 3.

However, the aerodynamic resistance depends directly on the assumed properties of the turbulence and the within-canopy profiles. Hence this resistance differs substantially between the four simulations – notably, the inclusion of the RSL and its variation with stability both act to decrease the day time resistance and to promote the release of sensible heat over that of latent heat. The difference in how the resistances behave between the four simulations leads directly to the differences in the energy balance and boundary layer state.

The control of the transfer of water vapour by stomatal processes, not by the turbulence, whereas heat transfer is a common trait of many biomes. Hence the results shown here could generalise to many bioclimatic regions.

5. CONCLUSIONS

While many NWP and GCM models rely on surface layer theory to determine the surface exchange processes, this theory has long been known to fail near to and within canopies. Here we show that the details of the surface exchange scheme, such as whether an RSL model is explicitly included, can result in differences in the predicted evolution of the surface energy balance and boundary layer state, which would be significant in many applications.

More fundamentally, the Harman and Finnigan approach succeeds because information on the flow, temperature and scalar concentration profiles and their sources and sinks within the canopy are used within the RSL calculations. This also implies that many parameters in surface layer theory, which quantify the bulk character of a canopy as viewed by the overlying boundary layer, should vary with any process which affects the profiles or sources and sinks within the canopy. A direct consequence of this is that the parameters d and z_0 vary with stability (i.e. on a diurnal time scale). Here we have shown that the differences between assuming these parameters are constant or not (within the coupled framework) can lead to significant differences in the boundary layer and surface states.

6. REFERENCES

Busch, N.E., Chang, S.W. and Anthes, R.A., 1976: A multi-level model of the planetary boundary layer suitable for use within mesoscale dynamic models. *J. Appl. Meteor.*, **15**(9), 909-919.

Chen, F. and Schwerdtfeger, P., 1989: Flux gradient relationships over tall plant canopies. *Quart. J. R. Meteor. Soc.*, **58**, 93-117.

Harman, I.N. and Finnigan, J.J., 2007: A simple unified theory for flow in the canopy and roughness sublayer. *Bound.-Layer Meteor.* **123**, 339-363.

Harman, I.N. and Finnigan, J.J., 2008: Scalar profiles in the canopy and roughness sublayer. submitted to *Bound.-Layer Meteor.*

Jackson, P.S., 1981: On the displacement height in the logarithmic velocity profile. *J. fluid Mech.*, 111, 15-25.

Jacquemin, B. and Noilhan, J., 1990: Sensitivity study and validation of a land surface parameterization using the Hapex-Mobilhy data set. *Bound.-Layer Meteor.*, **52**, 93-134

Raupach, M.R., Finnigan, J.J. and Brunet, Y., 1996: Coherent eddies and turbulence in vegetation canopies: The mixing layer analogy. *Bound.-Layer Meteor.*, **78**, 351-382.

Watanabe, T., 1994: Bulk parameterization for a vegetated surface and its application to a simulation of nocturnal drainage flow. *Bound.-Layer Meteor.*, **70**, 13-35.