TURBULENT HEAT TRANSFER FROM A SPARSELY VEGETATED SURFACE: TWO-COMPONENT REPRESENTATION

(Research Note)

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...you know not the way of the wind...
Ecclesiastes, Ch. XI, verse 5

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Abstract. The conventional calculation of heat fluxes from a vegetated surface, involving the coefficient of turbulent heat transfer, which increases logarithmically with surface roughness (commonly taken as about 0.12 of the plant height), appears inappropriate for highly structured surfaces such as desert-scrub or open forest. An approach is developed here for computing sensible heat flux from sparsely vegetated surfaces, where the absorption of insolation and the transfer of absorbed heat to the atmosphere are calculated separately for the plants and for the soil. This approach is applied to a desert-scrub surface for which the turbulent transfer coefficient of sensible heat flux from the plants is much larger than that from the soil below, as shown by an analysis of plant, soil and air temperatures measured in an animal exclosure in the northern Sinai. The plant density is expressed as the sum of products (plant-height) \times (plant-diameter) of plants per unit horizontal surface area (the dimensionless silhouette parameter of Lettau). The solar heat absorbed by the plants is assumed to be transferred immediately to the airflow. The effective turbulent transfer coefficient $k_{g, eff}$ for sensible heat from the desert-scrub/soil surface computed under this assumption increases sharply with increasing solar zenith angle, as the plants absorb a greater fraction of the incoming irradiation. The surface absorptivity (the co-albedo) also increases sharply with increasing solar zenith angle, and thus the sensible heat flux from such complex surfaces (which include open forests) is a much broader function of time of day than when computed under constant $k_{g, eff}$ and constant albedo assumptions. The major role that desert-fringe plants play in the genesis of convection and advection cannot be evaluated properly in the conventional calculations.

1. Introduction: the Nature of the Problem

The planetary boundary layer (PBL), especially under clear conditions, is heated predominantly through daytime turbulent transfer of sensible heat from the surface. The sensible heat flux can exceed 500 W m$^{-2}$ over dark, rocky desert, but it is much smaller over ocean or irrigated field at the same latitude, time of day and season.

The surface sensible heat flux $H$ is conventionally expressed as a product of a coefficient of turbulent transfer for sensible heat, $k_g$, and the surface-to-air temperature difference $\Delta T_{sfc-a}$:

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\[ H = k_g \Delta T_{\text{sfca}}. \]  

(1)

The coefficient \( k_g \) is a complex function of turbulence. It is usually evaluated based on the first-order turbulence closure scheme (see Chapter 7 in Pielke, 1984). This formulation has been used to calculate surface sensible heat flux within mesoscale atmospheric models (Pielke, 1984; Anthes, 1984), and also applied in global models of the general circulation for climate studies (Sud et al., 1980) and numerical weather prediction (Blondin, 1991). Based on close correspondence between the momentum transfer and heat transfer, and under various approximations, first-order turbulence closure leads to an expression for \( k_g \) of the form:

\[ k_g = \rho c_p \kappa^2 u(z) \left[ \ln \left( \frac{z}{z_0} \right) \right]^{-2}, \]  

(2)

where \( \rho \) is air density, \( c_p \) is the specific heat capacity of dry air at constant pressure, \( \kappa \) is von Kármán's constant \((-0.4)\), \( u(z) \) is the horizontal wind speed at height \( z \), and \( z_0 \) is the surface roughness height. In the context of Equation (1), \( z \) represents the height of the surface layer. Differences between momentum and heat transfer processes (form drag and mixing-length scale), effects of turbulent mixing below the top of the ground cover (zero plane displacement), and corrections for buoyancy effects have been neglected. Full discussion of the necessary simplifications and the different formulations may be found in Thom (1971), Garratt and Hicks (1973), Brutsaert (1975; 1982), Stathers et al. (1988) and Stull (1988). An approximate rule for estimating \( z_0 \) for a rough surface is to assume that it is about 1/8 the height of the roughness elements (plant height in the case of vegetation); see Chamberlain (1968), Lettau (1969) and Brutsaert (1982).

The plant height is the sole surface parameter controlling this coefficient (by controlling \( z_0 \)). We raise the question whether the conventional approach, based on this form of \( k_g \), is appropriate for evaluating the sensible heat flux (or the latent heat flux) from two-component surfaces where the area-to-mass ratio is much larger for one component (the canopy) than for the other component (the soil). Consider two structurally-identical surfaces, but where in one case the canopy is completely transparent to the solar radiation, while in the other it is fully absorbing. The momentum transfer coefficient will be the same in these two cases. Should the coefficient \( k_g \) also be the same? We discuss this question for desert-fringe surface, where evaporation during the dry season is very low. Our questioning applies also to the latent heat flux, where green vegetation will evapotranspire freely when solar heat is absorbed. In the case of such a green canopy, the area-to-mass ratio will tend to be smaller, however, than in the case of our desert-fringe plants.