THE RESPECTIVE EFFECTS OF WATER VAPOR AND TEMPERATURE ON THE TURBULENT FLUXES OF SENSIBLE AND LATENT HEAT

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(Received in final form 6 March, 1980)

Abstract. Various aspects of the Brook correction for the effects of moisture fluctuations or gradients on atmospheric specific heat and, consequently, on the vertical flux of sensible heat are discussed, and additional forms of the complete and approximate equations are derived. Corollary expressions for the influence of temperature fluctuations or gradients on vertical latent heat flux are presented. Errors due to neglecting these temperature and moisture effects on the respective fluxes are compared in terms of the Bowen ratio. Either of these normally neglected effects can change the direction (sign) and very substantively affect the magnitude of the corresponding flux. The effects sometimes compensate in the total, sensible plus latent, heat flux. Calculations include practical examples from the very different climates of the tropical Atlantic Ocean and the Great Plains of Nebraska.

1. Introduction

Water vapor fluctuations or gradients significantly affect the vertical turbulent flux of sensible heat in air. Brook (1978) has shown that this influence is predominantly due to the dependence of the specific heat of air on specific humidity, rather than the effects of water vapor on air density and buoyancy. Brook has derived eddy correlation and flux-gradient relationships for the sensible heat flux adjusted for the moisture effect. Thus,

\[ Q_s = \bar{\rho} C_{p_d} \bar{w} \bar{T}' + 0.84 C_{p_d} \bar{T} \bar{\rho} \bar{w}' q' = Q_d + M \]

\[ Q_s = \bar{\rho} C_{p_d} K_H \left( \frac{\partial \bar{T}}{\partial z} + \Gamma_d + 0.84 \bar{T} \frac{\partial \bar{q}}{\partial z} \right) = Q_d + M' \]

In (1), \( \bar{\rho} \bar{w}' q' = E \), the water vapor flux. Equation (2) is a simplified form of the flux-gradient equation derived by Brook. The quantities \( \rho, C_{p_d}, w, T, \) and \( q \) are air density, specific heat of dry air, vertical eddy motion, temperature and specific humidity, respectively. Bars and primes represent means and fluctuations, respectively.

Equations (1) and (2) are approximations, and are equivalent only if the assumption of equal eddy conductivities for heat and water vapor,

\[ K_H = K_E \]

is applied. Brook applied assumption (3) to Equation (1) to derive his flux-gradient
equation. The more direct derivation given below shows that assumption (3), while convenient in Brook's approach, is not required to establish (2). Also, the derivation in the simplified flux-gradient form parallels Brook's development of Equation (1). Therefore, the complete moisture corrections to the eddy and flux-gradient (or bulk aerodynamic) formulations may be explicitly compared, and limits of applicability of the main simplifying approximations can be readily determined. Retention of the secondary moisture correction terms provides a condition for equality of $K_H$ and $K_E$. The set of the different forms of the complete and approximate equations should be useful for intercomparing flux data gathered by different methods.

The obvious corollary to the Brook moisture correction to sensible heat flux is a correction for the effects of temperature fluctuations or gradients on the latent heat flux. Thus, the latent heat flux is derived with allowance for a varying, temperature-dependent latent heat of vaporization. The magnitude of this correction and its range of significance in terms of the Bowen ratio are analyzed and compared to the moisture correction to sensible heat. Practical examples are presented using field data from two very different climates.

2. The Flux-Gradient and Bulk Aerodynamic Equations for Sensible Heat Flux

Sensible heat flux and water vapor flux may be expressed in flux-gradient form as

$$Q_s = -\bar{\rho}K_H \frac{\partial(c_{pm}T + gz)}{\partial z}$$  \hspace{1cm} (4)

$$E = -\bar{\rho}K_E \frac{\partial q}{\partial z}$$  \hspace{1cm} (5)

Commonly, the less general form of (4), as presented by Priestley (1959) and Fleagle and Businger (1963), is used; i.e., the specific heat is regarded as a constant or given a mean value, such that

$$Q_d = -\bar{\rho}C_{pd}K_H \left( \frac{\partial T}{\partial z} + \Gamma_d \right)$$

for dry air, or

$$Q_m = -\bar{\rho}C_{pm}K_H \left( \frac{\partial T}{\partial z} + \Gamma_m \right)$$

for moist air ($\Gamma_m = g/\bar{C}_{pm}$). However, applying Brook's (1978) conclusion, the moisture effects can be properly accounted for only when $C_{pm} = C_{pd}(1 + 0.84q)$ is regarded as a variable and substituted into (4). Thus,

$$Q_s = -\bar{\rho}K_H \frac{\partial C_{pd}T + 0.84C_{pd}qT + gz}{\partial z}$$