COMMENTS ON 'THE INFLUENCE OF WATER VAPOR FLUCTUATIONS ON TURBULENT FLUXES', BY BROOK

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Reinking (1980) presented an extension of the earlier analysis by Brook (1978) on the influence of water vapor and temperature fluctuations on the turbulent fluxes of sensible and latent heat. Brook concluded that density fluctuations caused by water vapor variations have an insignificant effect on the measured fluxes of other quantities. However, changes in specific heat capacity arising from fluctuations in specific humidity were thought by Brook to have a significant effect on the sensible heat flux. Reinking made the further assumption that fluctuations in the latent heat of evaporation of water caused by temperature fluctuations result in a flux of latent heat. We believe that the conclusions of both these authors are based on faulty reasoning, as this communication shows.

Consider first the effects of density fluctuations on measured fluxes. For the flux density of an entity with concentration $S(\equiv \rho_s/\rho)$ per unit mass of moist air, Brook used $F' = \overline{(\rho w)' S'}$ (his Equation (1)). While this is an acceptable definition of the 'turbulent flux', it is important to realize that it is not equal to the total flux. In most contexts the total flux is required, and for this one should write

$$F = \overline{\rho w S} \equiv \overline{\rho_s w} = \overline{\rho_s}\,\overline{w} + \overline{\rho_s' w'} \tag{1}$$

where, in general, $\overline{w}$ is not equal to zero (Webb *et al.*, 1980; hereafter WPL). Contrary to Brook's assertion, $\overline{w}$ is not zero, even at the lower boundary ($z = 0$), if there is an evaporative flux. To obtain the true value of $\overline{w}$, Webb and Pearman (1977) and WPL started from the fundamental proposition that there is no net flux of 'dry air' at the surface nor at any level in the atmosphere, i.e., $\overline{\rho_a w} = 0$, which immediately implies that

$$\overline{w} = -\overline{\rho_a' w'}/\overline{\rho_a} \tag{2}$$

where ρ_a is the density of dry air. WPL derived an equation (WPL Equation (9b)) for ρ_a' in terms of humidity and temperature fluctuations (strictly, absolute potential temperature). Using this expression for ρ_a', Equation (2) becomes

$$\overline{w} = \mu \overline{w'\rho_v'}/\overline{\rho_a} + (1 + \mu\sigma)\overline{w'T'}/\overline{T}, \tag{3}$$

with $\mu = m_a/m_v$, the ratio of the molecular masses of dry air and water, and $\sigma = \overline{\rho_v}/\overline{\rho_a}$. Clearly $\overline{w} \neq 0$ whenever there are fluxes of water vapor and/or sensible heat, and this vertical velocity, coupled with $\overline{\rho_s}$, results in a mean vertical flux of entity s. This effect is particularly significant for the measurement of carbon dioxide fluxes (WPL). Clearly, by considering only the turbulent flux F', Brook implicitly eliminated from his analysis the major effect of temperature and humidity fluctuations on the total flux density of another quantity.

We now consider the influence on the heat flux caused by changes in specific heat capacity which result from humidity fluctuations. Brook writes the flux density of sensible heat as

$$H = \overline{\rho}\, \overline{w'(c_pT)'} \tag{4a}$$

where $c_p = c_{pa}(1-q) + c_{pv}q$, and c_p, c_{pa}, and c_{pv} are the specific heats at constant pressure of the moist air, dry air and water vapor, respectively, and q is the specific humidity. We shall show that use of Equation (4a) leads to a fundamental problem concerning the relationship between the heat transported by a flux of mass. Equation (4a) may be formally expanded to

$$H = \overline{\rho}\, \overline{w'(c_pT' + c_p'T + c_p'T')} \tag{4b}$$

where $c_p' = (c_{pv} - c_{pa})q'$. We are particularly concerned with the second term in brackets ($\overline{\rho}\, \overline{w'c_p'}\, \overline{T} \equiv \overline{\rho}[c_{pv} - c_{pa}]\, \overline{w'q'}\, \overline{T}$) since Brook argues that this term has a major influence on the correct measurement of H. For an isothermal atmosphere, $T' = 0$, and the sensible heat flux, according to Equation (4b), is

$$H = \overline{\rho}(c_{pv} - c_{pa})\overline{w'q'}\,\overline{T}. \tag{5}$$

As $c_{pv} \neq c_{pa}$, this equation implies that the flux of water vapor carries with it a heat flux proportional to the total energy relative to zero energy content at 0 K. This is not correct, as can be shown by considering an isobaric, adiabatic container consisting of two chambers in thermal equilibrium. The chambers contain dry and moist air, respectively, and the two mixtures obviously have different heat capacities. We remove the partition between the chambers and allow the gases to mix. There is a mass flux of water vapor across the plane of the partition and also a redistribution of heat capacity, but there is no flux of heat in this system (Kestin, 1966, p. 334), i.e., $c_{pv} \neq c_{pa}$, $\overline{w'q'} \neq 0$, but $H = 0$. The incorrect idea that heat has flowed arises from the supposition that we can define the 'total heat content' of a gas. Unlike mass, total heat content cannot be defined as an absolute quantity; this is an experimental fact and is fundamental to thermodynamic theory (Resnick and Halliday, 1966, p. 560). It is possible only to define fluxes of sensible heat in relation to *temperature differences* between two bodies. Thus, fluctuations in heat capacity at constant temperature do not result in a transport of heat.

When considering rates of heat transfer across a particular horizontal *plane* in the atmosphere, we are implicitly assuming certain features of the *volume* of air contained beneath the plane (see e.g., Tanner, 1960). Allow the volume of air to have its base at the Earth's surface and assume for simplicity that the flux of heat and mass entering the lower surface equals that which leaves the upper surface. The mass flux density through both these planes is simply the mass of water evaporated from the lower surface per unit area and time. How much heat does this mass flux carry with it through the upper surface? Let the air at the lower ('base') and upper surfaces be T_b and T, respectively. The energy per unit volume required to change the temperature of the water vapor which is passing *through* the volume is $c_{pv}\rho_v(T - T_b)$. The average flux density of sensible heat through the upper plane in excess of that at the lower surface resulting from evaporation is thus $c_{pv}\overline{\rho_v w(T - T_b)}$. A similar argument can be developed for dry air. However, there is no net mass flux of dry air at either the upper or lower surfaces, and heat transfer across the upper plane occurs by the turbulent interchange of air parcels which on average have differing temperatures according to the direction of air movement.

The correct expression for the transport of sensible heat is given (WPL) as

$$H = c_{pa}\,\overline{w\rho_a(T - T_b)} + c_{pv}\,\overline{w\rho_v(T - T_b)}\,. \tag{6}$$

Recognizing that $\overline{\rho_a w} = 0$, the first term of Equation (6) reduces to $c_{pa}\,\overline{\rho_a}\,\overline{w'T'}$. WPL show that all terms arising from the expansion of the second term of Equation (6) are small, except for $c_{pv}\,\overline{\rho_v}\,\overline{w'T'}$, and that the flux density of sensible heat is given, to a close approximation, by

$$H = c_p\,\bar{\rho}\,\overline{w'T'}\,. \tag{7}$$

Thus no correction to the covariance is required to measure correctly the sensible heat flux.

Reinking (1980) made the same erroneous assumptions as Brook in his extended analysis of the influence of heat capacity fluctuations on the measured flux of sensible heat. Reinking made a further error when he assumed that latent heat is transported by a term of the type $\overline{w'L'}$, where L is the latent heat of evaporation. The energy associated with evaporation is simply the water vapor flux E multiplied by the value of L appropriate to the temperature *at the site of evaporation*. Variations in L in the atmosphere are irrelevant to the latent heat flux if no phase changes (such as droplet evaporation) occur within the volume beneath the measurement plane. Both Brook and Reinking have made incorrect assumptions concerning the relationship between heat flux and the heat content of mass flux.

A recently completed experiment (Leuning *et al.*, 1982) on the flux density of carbon dioxide over an arid surface confirms the conclusions of WPL concerning the relationships between density effects and flux measurements.

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