

Comment on “Determination of the Surface Sensible Heat Flux from Aircraft Measurements”

by S. Emeis, Beitr. Phys. Atmosph. **68**, 143–148

by U. SCHUMANN, DLR, Institut für Physik der Atmosphäre, Oberpfaffenhofen, D-82230 Weßling, Germany

A common procedure to determine surface fluxes of sensible heat in convective boundary layers from aircraft measurements is to extrapolate the heat flux profile measured within the mixed layer linearly to the ground. This linear profile is usually derived from the fact that the heating rate, which is given by the vertical gradient of the heat flux, must be vertically constant within the well mixed part of the convective boundary layer, because otherwise the shape of the temperature profile would vary with time. Such a linear profile can be expected only for quasi-steady state, homogeneous surfaces and small advective or radiative sources within the boundary layer. Comparisons between aircraft measurements and surface measured heat fluxes often show systematic differences, although not in all cases (Kelly, 1992). Several reasons for disagreements have been considered, such as horizontal and vertical advection, radiation heat sources, surface inhomogeneities, large scale trends, sampling errors, methods used for detrending and filtering, and insufficient number of surface stations (Kelly, 1992; Michels and Jochum, 1995). Significant disagreements were not found to vary systematically with time of day or average wind speed (Grossman, 1992; Kelly, 1992).

In a recent paper, Emeis (1995) proposes an alternative concept to explain systematic differences between airborne and surface heat flux measurements in the convective boundary layer. He suggests that the vertical heat flux profile deviates systematically from a linear profile, so that linear extrapolations from airborne measurements underestimate the heat flux at the surface. Combining the Monin-Obukhov profile functions with an empirical relationship for the mixing length, he derives a relationship for the vertical profile of the heat flux. This is an essential extension, since the Monin-Obukhov

theory is valid for stationary conditions, requires small variations in the fluxes, assumes that the profiles are dependent on height above ground, roughness length and Obukhov length only, and contains no predictions on the flux gradients. In the new relationship the vertical gradient of the heat flux profile is larger near the surface than in the mixed layer above a surface layer. This causes a nonzero divergence of the heat flux gradient. The resultant heating rate varies with altitude and, hence, changes the shape of the temperature profile. This contradicts the assumption of quasi-steady state. Emeis is aware of this fact but considers this to be unimportant except that he limits the result to the first half of a day during which a cooler surface layer adjusts to the mixed layer conditions. Finally, he has not applied the results to a specific case with surface and aircraft based flux measurements.

The purpose of this comment is to point out several deficiencies of the concept proposed by Emeis (1995). The concept implies large differences in the heating rates near the surface and in the mixed layer. Within a time period short compared to the time from sunrise to noon, the different heating rates would cause changes in the temperature differences between the surface and the mixed layer which may be larger than the vertical variations in temperature profile necessary to drive the vertical heat flux in steady state. Hence, the concept implies transient profiles which appear to be unrealistic and contradict the assumed steadiness of the Monin-Obukhov profile functions. Moreover, the concept is based on the assumption of convective conditions and cannot, therefore, be applied to the short period in the early morning when the surface layer may be much cooler than the air above. Finally, the concept defines a surface layer that is relatively thick so that

the applicability of the Monin-Obukhov theory becomes questionable.

To be specific, we illustrate the above statements for one of the cases which were considered by Emeis (1995). We select the case where the results are most obvious, i.e. for row 1 of his Table 1, which lists the parameters: Obukhov length $L_* = -250$ m, inversion height $z_i = 500$ m, asymptotic mixing length $\ell_\infty = 0.0586 z_i$, and depth of a surface layer $z_T = 0.284 z_i$. For this case, Emeis deduces that the linear extrapolation of the heat flux profile in the mixed layer underestimates the surface heat flux by a factor 0.56. For boundary layers with smaller L_*/z_i the factor is closer to one, and is less relevant in explaining deviations between various surface heat flux measurements for strongly convective cases, therefore.

After an obvious correction of Eq. (6) of Emeis (1995), which misses the factor ℓ_∞^{-1} , one deduces from his theory heating rates $-\partial H(z)/\partial z$ at the surface ($z = 0$) and at the top of his surface layer ($z = z_T$). The different heating rates cause changes in the temperature difference $\Delta\Theta = \Theta(z = 0) - \Theta(z = z_T)$ with time,

$$\frac{\partial \Delta\Theta}{\partial t} = -\frac{\kappa u_* \theta_*}{\ell_\infty} \left[1 - 4 \left(1 + \frac{\kappa}{\alpha} \frac{z_i}{\ell_\infty} \right)^{-2} \right]. \quad (1)$$

Here, $\kappa = 0.4$ is the von Karman constant and $\alpha \approx 1.4$ accounts for the increase in heat flux gradient in the mixed layer due to the entrainment heat flux at the top of the mixed layer.

For quantitative evaluations, we assume a surface heat flux of about 100 W m^{-2} , or kinematic flux of $H(z = 0) = -u_* \theta_* = 0.1 \text{ K m s}^{-1}$, and a surface roughness height of $z_0 = 0.1$ m, i.e., typical values. As a consequence of the definition of the Obukhov length, for a potential temperature of 300 K and gravity of 9.81 m s^{-2} , one computes $u_* = 0.69 \text{ m s}^{-1}$, and $\theta_* = -0.145 \text{ K}$. For these values one computes $\partial \Delta\Theta/\partial t = 4.5 \text{ K h}^{-1}$, or a change of temperature of 27 K within the about six hours from sunrise till noon of a typical day. This is a large temperature change which implies strong deviations from steady state. For otherwise constant parameters, even larger temperature changes result for larger surface heat fluxes.

For comparison, the difference between the mean temperatures at the bottom (at roughness height) and at the top of the surface layer under steady state conditions would be $\Theta(z_0) - \Theta(z_T) = 2.2 \text{ K}$. This

result follows from the Monin-Obukhov profile function (if applicable) in integral form (see Paulson, 1970) for the specified case. Hence, within about half an hour, the variable vertical profile of the heat flux causes a temperature change larger than the steady state temperature difference between top and bottom of the surface layer. This shows that the variable heat flux profile would quickly cause very large changes in the shape of the temperature profile.

Hence, the concept proposed by Emeis (1995) cannot be correct. The basic reason for failure comes from the assumption of validity of the Monin-Obukhov profiles over a substantial fraction of the boundary layer depth. The Monin-Obukhov theory is valid only for $z \ll z_i$ (Tennekes, 1981, p. 50). In the present application, the theory is applied for $z_T = 0.29 z_i$. At such large altitudes turbulent mixing depends not only on z/L_* but also on z/z_i . Finally, the assumed relationship for the asymptotic length scale, Eq. (11) in Emeis (1995), which scales with the Rossby number, ignores the scaling of the mixed layer with the boundary layer depth (e.g., Holtslag and Nieuwstadt, 1986).

Hence, the Monin-Obukhov theory was applied outside the range of its validity. The results are inconsistent with the assumptions of a convective boundary layer and quasi-steady temperature profile, and cannot be used, therefore, to explain observed differences between airborne and surface measurements of heat fluxes.

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Reply

by S. EMEIS, Fraunhofer-Institut für Atmosphärische Umweltforschung, Kreuzeckbahnstr. 19,
82467 Garmisch-Partenkirchen, Germany

I thank Schumann for his comment on my paper. First of all he is right when he states that the factor ℓ_∞^{-1} is missing in Eq. (6). The correct equation must read

$$\frac{\partial}{\partial z} H(z) = \frac{\kappa u_* \theta_*}{\ell_\infty \left(1 + \frac{\kappa z}{\ell_\infty} \right)^2}$$

Schumann is also right when he inserts the values from row 1 of Table 1 and yields a difference in heating rates between the surface ($z = 0$) and the top of the surface layer ($z = z_T$) of about 4.5 K h^{-1} . But he has taken the extreme value for an early morning condition. During the morning the boundary layer is growing and we rapidly get the conditions in the subsequent rows of Table 1. In the following Table the difference in the heating rate between $z = 0$ and $z = z_T$ (Δ_0) and the difference between $z = 10 \text{ m}$ and $z = z_T$ (Δ_{10}) for all rows of Table 1 in Emeis (1995) is given:

Table 1 Difference in heating rates of the surface layer between $z = 0 \text{ m}$ and $z = z_T$ (Δ_0) and between $z = 10 \text{ m}$ and $z = z_T$ (Δ_{10}) in K h^{-1} for values of the boundary layer height z_i , the asymptotic mixing length ℓ_∞ and matching heights z_T as given in Table 1 of Emeis (1995).

z_i m	ℓ_∞ m	z_T m	Δ_0 K h^{-1}	Δ_{10} K h^{-1}
500	29.3	142.0	4.3	3.0
700	39.6	200.2	3.2	2.6
800	57.7	213.6	2.1	1.8
900	84.2	216.0	1.3	1.1
1000	179.0	133.0	0.3	0.3
1200	315.6	33.6	0.1	0.1
2000	472.0	124.0	0.1	0.1

We see that the difference in the heating rate between the surface (or $z = 10 \text{ m}$) and the top of the surface layer decreases rapidly. This describes the rapid warming of the lower part of the surface layer in the first morning hours until the inverse vertical temperature gradient vanishes. In the following hours the lower part of the surface layer becomes even slightly warmer than the upper part of the surface layer. Taking each of the first six rows of the Table representative for one hour in the morning then by adding up these six values for Δ_{10} we get a warming of the air near the surface at $z = 10 \text{ m}$ of 8.9 K in 6 hours which does not seem unreasonable. Now to the more basic considerations brought forward by Schumann. He is right when he states that the Monin-Obukhov theory has been derived under a quasi-steady state assumption with an empirical relationship for the vertical profile of the mixing length. In Emeis (1995) only one change in the assumptions have been made: the mixing length is no longer growing linearly with κz . As stated by Schumann the mixing length scales with the boundary layer height. Therefore its growth has been limited by an asymptotic value ℓ_∞ which depends on the state of the boundary layer. It could be discussed whether there are better parameterizations of ℓ_∞ than Eq. (11) in Emeis (1995) which also include z_i . But this does not change the basic idea expressed in Emeis (1995): Limiting the growth of the mixing length with height by an asymptotic value (a procedure commonly used in numerical models) yields a height-dependent heat flux in the surface layer. The resulting heat flux profiles, which are no longer stationary then, fit with data e.g. published by Kaimal et al. (1976) and Caughey (1982) (see also rightmost profiles in Figure 1 of Emeis (1995)). The proposed formulation converges against the original Monin-Obukhov theory for $z \rightarrow 0$ and $\ell_\infty \rightarrow \infty$. So it does not contradict to the measurements which have led to the formulation of this

theory. These measurements have been made mainly within the first 10 or 20 m above ground, and have been interpreted under the assumption of an unlimited growth of the mixing length with height. In the formulation of Emeis (1995) the deviation from the vertically constant heat flux in these heights is within a few percent and thus within the accuracy of measurements. See the comparison with data from Högström (1988) in Emeis (1995).

The last argument in Schumann's comment is not correct. I have not extended the validity of the Monin-Obukhov profiles over a substantial fraction of the boundary layer depth. On the contrary, I have changed the formulation for the mixing length in order to be able to extrapolate the heat flux profile to heights greater than 10 or 20 m above ground. It is this change in the formulation which makes it possible to match the heat flux profile in the surface layer with the respective profile in the well-mixed layer. And we now have an expression for the vertical divergence of the heat flux which explains the warming of the surface layer in the first half of the day. When u , θ , changes sign at the surface in the late afternoon also the cooling can be described.

Finally, it can be stated: Introducing an asymptotic value for the growth of the mixing length with height changes the steady-state formulation by Monin and Obukhov to a transient-state formulation. This new formulation reproduces heat flux profiles published earlier (see references) and offers an explanation for the underestimation of the surface heat flux from airborne measurements.

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