Reply

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In my paper (Sorbjan 1995, hereafter referred to as S95), I described a simple algorithm to calculate the vertical distribution of turbulent fluxes (as well as some other related characteristics) in the atmospheric boundary layer. The method was assumed to be valid for horizontally averaged scalars (such as the potential temperature or the specific humidity) in cases where there is no horizontal advection, and also when radiative fluxes, as well as water phase changes, can be neglected. I provided an example (day 33 of the Wangara experiment) showing that the method could be useful even without horizontal averaging.

In his comment (hereafter referred to as H96), Hibberd discusses some difficulties that arise in applying the S95 algorithm to "real-world data." Even though I agree with most of the author's comments, I find his evaluation of the method perhaps a little too harsh. One has to keep in mind that relative errors in other indirect methods applied presently in the estimation of surface fluxes are also not small (see, e.g., Vogel et al. 1995).

In Fig. 1b of H96, Hibberd integrates the Wangara temperature profiles to level h (where the turbulent flux is assumed to vanish) to obtain almost identical results to those in S95. In addition, the author integrates the Wangara temperature profiles above $z = h$—that is, above the boundary layer—and shows that this can lead to spurious results. This is not surprising. One should not extend the algorithm above the boundary layer height h. Nevertheless, I agree that this procedure demonstrates that the effects of gravity waves contribute to an error in the estimation of h. Generally, nonzero temperature fluxes for $z > h$, such as those shown in Fig. 1b of H96, could be caused not only by gravity waves but also by such factors as subsidence, horizontal advection, the presence of a cumulus cloud in the way of a radiosonde, etc. I would also like to add that the positive temperature fluxes at $z > z_i$ in Fig. 4 of S95 were caused by truncation errors of the numerical scheme, and that temperature profiles in Fig. 2 of S95 were averaged horizontally and in time.

The described difficulties with the evaluation of h were also encountered by Hibberd in his saline laboratory simulation of the convective boundary layer (Hibberd and Sawford 1994). As stated on page 240 in the quoted paper, "the exact height of zero flux had to be determined by eye from preliminary calculations for each profile." Certainly, such a subjective approach could also be applied in the S95 method in an attempt to reduce errors in the estimation of h.

In Fig. 1b of H96, Hibberd presents four temperature profiles obtained during the 1989 CADS experiment in Australia. The first two profiles (at 0930 and at 1143 CST) in this figure imply the presence of cold advection above the mixed layer during the first interval. For example, at $z = 1500$ m, there is about a 1.5-K decrease of temperature during a 2-h interval. Assuming 5 m s^{-1} wind at this level, this yields a potential temperature horizontal gradient of about 4.5 K (100 km)$^{-1}$. Since the case is nonhomogeneous, the S95 algorithm should not be applied, unless advection is taken into consideration. [This would require the modification of $\partial\theta/\partial t$ in Eq. (1) of H96, as discussed below.] Moreover, because the first two profiles do not cross each other above 1100 m, h cannot be found. The author does not include any correction for baroclinicity. In addition, his assumption that $h = 1200$ m is taken out of the blue (even though it leads to a reasonable result on the surface). Consequently, his first flux profile is totally incorrect.

The other two curves (1143–1400 and 1400–1623 CST) in Fig. 2b of H96 show more reasonable behavior. As can be seen in Fig. 2a of H96, this is because the effects of horizontal advection vanish after 1143 (probably due to a shift in wind direction). Nevertheless, a warmer layer appears from $z = 400$ m to $z = 700$ m in the third profile at 1400 CST in Fig. 2a of H96. Without additional information, it is difficult to judge if this effect is real or spurious. Nevertheless, the disturbance causes the surface heat flux in the second interval (1143–1400) to increase by about 1 K × 250 m/8400 s = 0.03 K m s^{-1} and to decrease in the third interval (1400–1623) by the same amount.

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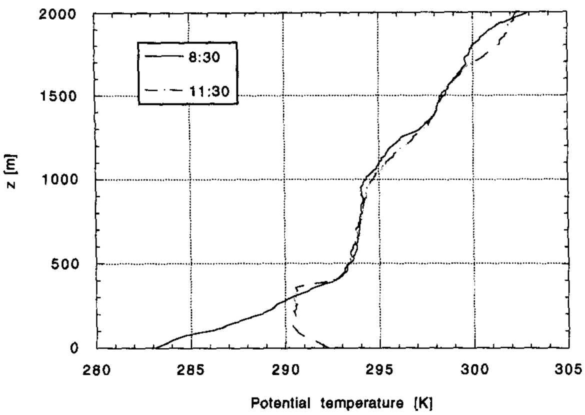

FIG. 1. Soundings obtained at site b1 at 0830 and 1130 CST 6 November 1994.

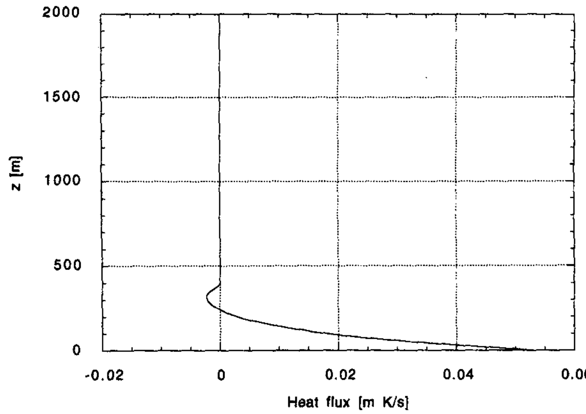

FIG. 2. The heat flux calculated from profiles in Fig. 1.

Regarding Eq. (2) of H96, Hibberd makes three statements. The first one is that Eq. (2) can be corrupted by the effects of advection. This statement is correct. The presence of advection requires $\partial\theta/\partial t$ to be adjusted in Eq. (2) of H96. In the second statement, Hibberd shows that Eq. (2) does not work in the late afternoon. This statement is also correct. Equation (2) should not work well in the early morning and in the late afternoon. Finally, Hibberd argues that the surface heat flux cannot be reliably estimated from Eq. (2) because large temperature fluctuations in the surface layer make the detection of θ, and consequently $\partial\theta/\partial t$, difficult. It is enough to examine trends in the diurnal variation of the averaged (running average in time) air temperature in the surface layer [see, e.g., Fig. 5.6 in Arya (1988), p. 63, or Fig. 1.2 in Sorbjan (1989), p. 3] to see that this statement is exaggerated.

For further discussion of the considered method, I will present several radiosoundings collected in 1994 as a part the ongoing Atmospheric Radiation Measurement (ARM) project in Oklahoma and Kansas. The ARM sondings were performed every 3 h at three sites: b1, b4, and b5, located in corners of an equilateral triangle with sides of about 300 km. Sites b4 and b5 are situated in Oklahoma, while b1 is in Kansas.

Figure 1 presents soundings obtained at site b1 on 6 November 1994. As seen in the figure, at 0830 CST a nocturnal inversion layer is intact. At 1130, a 400-m mixed layer develops with a sharp 2-K temperature jump at the top. Above the 400-m level, a nearly isothermal layer (remnants of the mixed layer from a day before) extends to the level of about 1000 m. Both temperature profiles nearly coincide above 400 m, which indicates that there is no temperature advection. The Oklahoma mesonet stations reported variable winds of about 3–5 m s^{-1} at the same time, with no signs of temperature advection. Wave motions seem to be weak below 1600 m in Fig. 1. The heat flux obtained from profiles in Fig. 1 is shown in Fig. 2. The flux profile is not linear, due to the transition from the stable to the convective state. As a result, the entrainment flux H_i is equal to 6% of the surface flux, which is below the expected 20%.

Figure 3 shows two soundings collected at site b4 on 25 October 1994. The profile at 0830 CST depicts a shallow morning mixed layer about 200 m thick. At 1130, the mixed layer is well developed and extends up to the level of about 700 m. Above this level, both temperature profiles nearly coincide, which indicates no temperature advection. This agrees with surface observations from the Oklahoma mesonet stations, which detected weak south-southwest winds of about 2.5 m s^{-1} at the same time, as well as almost no horizontal differences in temperature over northern Oklahoma. Effects of gravity waves cannot be seen in Fig. 3. The calculated heat flux is shown in Fig. 4. The flux profile is nonlinear, due to the fact that the temperature profile in the stable layer at 0830 is also nonlinear. The entrainment flux H_i is equal to 17% of the surface flux, which is close to the expected value. The first two ex-

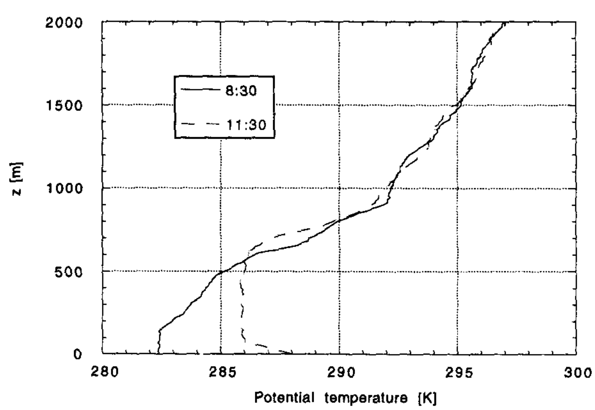

FIG. 3. Soundings obtained at site b4 at 0830 and 1130 CST 25 October 1994.

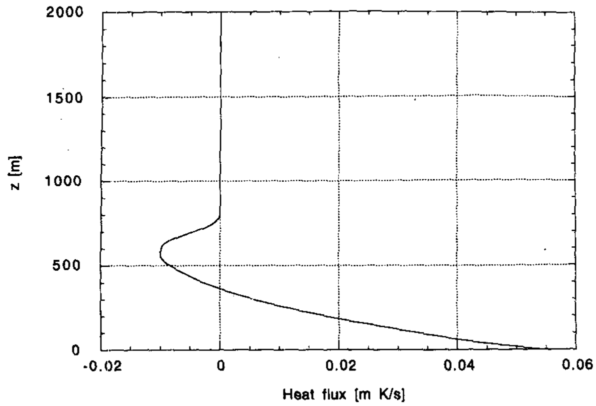

FIG. 4. The heat flux calculated from profiles in Fig. 3.

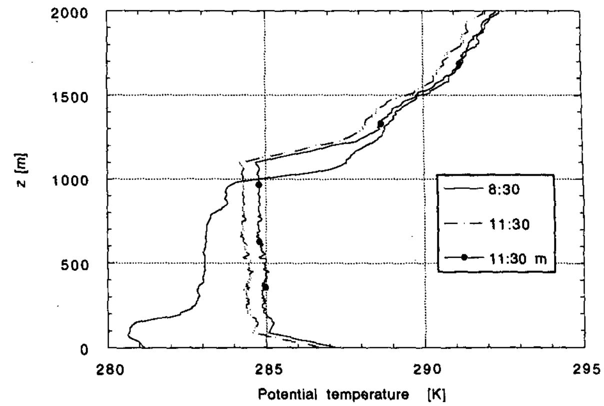

FIG. 6. Soundings obtained at site b1 at 0830 and 1130 CST 25 October 1994. The dotted line (1130—modified) was obtained by adding 0.5 K to observations at 1130.

amples confirm that the S95 method can be applied without spatial or temporal averaging.

Soundings in Fig. 5 were obtained at site b4 on 5 November 1994. In both cases, at 1130 and 1430 CST the mixed layers are well developed, with sharp temperature jumps at the top. The temperature crossover height h is about 600 m. Integration down from this level produces a linear heat flux (not shown), with the surface flux H_0 = 0.085 m K s^{-1}. The resulting entrainment flux H_i is 0.0075 m K s^{-1}, which constitutes 9% of the surface flux. This value is smaller than the expected 20% and indicates an error in the evaluation of the temperature crossover height h. The error is caused by the wave effects, which are clearly visible in the inversion layer in Fig. 5. The considered example demonstrates the fact pointed out by Hibberd that the effects of gravity waves at the top of the mixed layer can sometimes seriously affect the retrieved values of the heat fluxes. The effects of gravity waves could be filtered by applying spatial or temporal averaging. Unfortunately, a lack of observations is an obstacle to such averaging in the considered cases.

The last example in Fig. 6 illustrates the effects of temperature advection. The soundings in the figure were obtained at the Kansas site b1 on 25 October 1994. The profile at 0830 CST depicts a shallow morning mixed layer about 150 m thick. A nearly isothermal layer, which is a remaining portion of the mixed layer from a day before, extends to the level of about 800 m. At 1130 CST, the mixed layer is about 1100 m deep. Above the 1200-m level, the 1130 temperature profile seems to be shifted uniformly to the left with respect to the 0830 profile. This fact indicates a presence of cold advection. Its strength can be estimated from Fig. 6 as 0.5 K (3 h)$^{-1}$ in the layer above 1200 m. Since the wind velocity (not shown) in the layer 100–2000 m in the interval from 0830 to 1130 CST stays quite uniform (8–12 m s^{-1}), I assumed that the strength of advection was also equal to the same 0.5 K (3 h)$^{-1}$ below 1200 m.

To compensate for the effects of advection, the 1130 profile was translated by +0.5 K uniformly to the right, resulting in the dotted line in the figure. As a result of

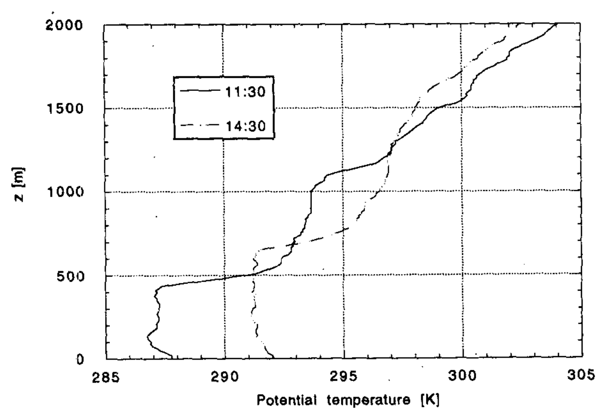

FIG. 5. Soundings obtained at site b4 at 1130 and 1430 CST 5 November 1994.

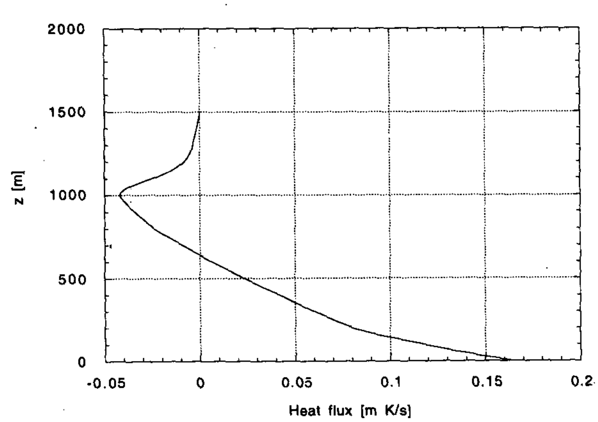

FIG. 7. The heat flux calculated from profiles in Fig. 6.

this translation, the temperature profiles above 1500 m approximately coincide. Comparing the dotted line and the 0830 profile allows one to estimate the modified temperature crossover height as equal to 1500 m. Integrating the difference between the dotted line and the 0830 profile yields the heat flux profile in Fig. 7. The resulting entrainment heat flux H_i is equal to 25% of the surface flux, which agrees with our expectations.

In conclusion, it could be stated that the S95 method can provide useful information about the boundary layer from the analysis of radiosondings. Nevertheless, potential users of the method should be aware that it cannot be "mechanically" employed. Consequently, the effects of advection, gravity waves, and clouds should be carefully examined. As indicated in H96, the time intervals between sondings should not be too short. Obviously, the most reliable results can be expected if the scalar profiles are averaged horizontally (in this case several instantaneous sondings have to be performed over a small, flat, horizontal area) or in time (this requires a few soundings with short intervals between each other).

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