Boundary Layer Heat Budgets from Wind Profiler/Radio Acoustic Sounding Systems Data: A Feasibility Study

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Radar wind profilers (WP) and radio-acoustic sounding systems (RASS) are now available commercially and offer the promise of improving our knowledge of processes in the lower atmosphere on scales that were until now unresolved spatially and/or temporally. Plans to install a network of boundary layer WP/RASS within two or three years are now under discussion in the U.S. Department of Energy's ARM (Atmospheric Radiation Measurement) Program and in other national programs. The new devices raise the prospect of gaining better insight into planetary boundary layer processes. With this background in mind, we re-evaluate some classical methods for the calculation of kinematic and dynamic quantities using measurements from these new remote sensing devices.

In this paper, we restrict our study to the evaluation of the heat budget equation (e.g., Pielke 1984) for the atmospheric volume dV defined by a triangular array of vertically pointing WP/RASS:

$$\iiint \underbrace{\bar{\rho}\, c_p \nabla \bullet (\overline{v'\theta v'})}_{A}\, dV = -\iiint \left[\underbrace{\bar{\rho}\, c_p \frac{\partial \bar{\theta}v}{\partial t}}_{B} + \underbrace{\bar{\rho}\, c_p \nabla \bullet (\overline{v}\overline{\theta}v)}_{C} + \underbrace{\nabla \bullet \bar{R}}_{D} \right] dV$$

where ρ = air density

c_p = specific heat at constant pressure

v = vector wind

θv = virtual potential temperature

R = vector net radiation

and the overbars and primes indicate a Reynolds decomposition of the individual terms over a suitable averaging period. The four terms of the heat budget equation are A: turbulent virtual potential temperature flux divergence, B: time rate of change of heat storage, C: mean virtual potential temperature flux divergence, and D: net all-wave radiative flux divergence.

Our goal is to determine the sensitivity of the heat budget calculations to WP/RASS wind and temperature measurement uncertainties. This can be done, in a first step, with a Monte Carlo-type model. For this purpose we define a hypothetical triangular array of WP/RASS with a distance between stations on the order of 30 km, and a height range of 2 km resolved into 100-m-deep layers. Mean profiles of wind and virtual temperature are assumed, and the WP/RASS measurement errors are added as perturbations to these mean profiles. These errors are simulated by randomly sampling from Gaussian distributions with standard deviations corresponding to measurement precisions obtained from the scientific literature. Evaluation of the heat budget terms for a large number of randomly perturbed profiles yields a distribution of values from which basic statistical quantities such as standard deviations can be calculated. These standard deviations are regarded as confidence limits and are used to estimate the effect of the measurement uncertainties on heat budget terms for individual height layers.

The results presented here are based on the assumptions of 1) ideally flat terrain; 2) horizontally homogeneous meteorological conditions, i.e. no horizontal gradients in wind, temperature, and radiation, no time change in temperature; and 3) dry atmosphere with no phase changes or clouds. The radiation profiles have been extracted from climatological data of Grand Junction, Colorado (McKee

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(a) On leave from Paul Scherrer Institute (PSI), Villigen, Switzerland.

and Whiteman 1977). Values varied linearly from 90 W/m^2 at the surface to 116.7 W/m^2 at the top. The turbulent sensible heat flux term in the equation was calculated as a residual of all other terms. We assumed a wind speed of 10 ms^{-1} for all levels and stations, thus having a non-divergent wind situation. Temperature was assumed to decrease linearly with height with a lapse rate of 0.005 Km^{-1}. Surface temperature was 19.1°C.

The precisions of 915 MHz WP/RASS have been taken from values published by Neff and Wilczak (1992) and Martner et al. (1993). Wind errors can be considered to be less than 1 ms^{-1} under ideal conditions, while temperature measurement errors are less than 1 K. These values are valid for 1-hour averages. To account for errors in the net radiation profiles, we used a standard deviation of 15 W/m^2, which corresponds to a relative error of approximately 15%.

Figure 1 shows the mean values and standard deviations of the turbulent sensible heat flux divergence term as a function of height for three different temperature measurement standard deviations. We selected this term because it shows the largest standard deviation of all terms, a fact that clearly emerges from the calculation of the term as a residual. The mean values are distributed around zero, as expected for a horizontally homogeneous situation. The peaks in the curves are a result of the random number generator. The resulting standard deviations increase with increasing measurement standard deviations. To evaluate this result, a comparison with typical observed values proves useful. For convective situations, maximum daily values reach 0.2 to 0.25 W/m^3, which is about half the standard deviation for a temperature error of 1 K.

The situation for wind measurement uncertainties is presented in Figure 2. The effect of wind measurement uncertainties differs strongly from the effects of temperature measurement uncertainties. The standard deviations increase with height for values larger than 1 ms^{-1}. This behavior reflects the accumulation of errors that are due to the integration of the vertical velocities computed from mass conservation. Thus an error in the mass balance is always propagated to the next level, where another error can be added, and so on. The 0.2 ms^{-1} curve suggests that only little can be gained by improving wind measurements, while a great deal could be gained by improving temperature measurements.

Simulations for different averaging times suggest that a minimum averaging time of 6 h is required to get standard deviations less than 0.2 W/m^3 for quasi-stationary conditions. The disadvantage of time averaging is to lose resolution of diurnal variations (if we average over six consecutive hours) or resolution of synoptic weather events (if we average over the same hour of six consecutive days). The size of the triangular area affects the standard deviations inversely. Larger triangle sizes give smaller standard deviations and vice versa. This beneficial effect of larger triangle size is countered, however, by expected deviations from our assumption of linear variation in the meteorological fields as triangle size is increased.

We conclude that atmospheric heat budget terms are rather strongly affected by present-day measurement uncertainties even under favorable weather conditions, although time and space averaging brings some improvement. The calculation method itself still has important shortcomings, however, which may prove unresolvable in practice. On the other hand, some of the terms in the budget equation, such as the time rate of change of heat storage, can be calculated with acceptably small error bars, thus opening the perspective of obtaining longer term, climatological statistics of quasi-continuous temperature and wind measurements in the atmospheric boundary layer.

In the future the, method will be applied to data gathered during the WISP[(a)]/ARM/ASCOT[(b)] 91 experiment in Colorado's Denver/Boulder area, as this dataset is the only one currently available with three non-collinear 915-MHz WP/RASS stations.

Acknowledgments

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(a) Winter Icing and Storm Program.

(b) Atmospheric Studies in Complex Terrain Program.

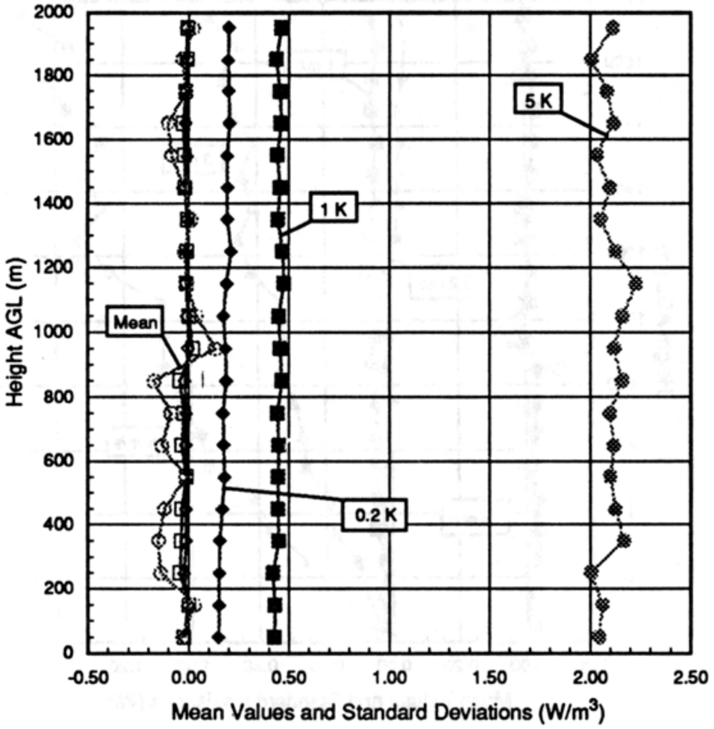

Figure 1. Monte Carlo simulations of the effects of temperature measurement errors on the standard deviations of turbulent sensible heat flux divergence calculated as a residual in the atmospheric heat budget equation. Solid symbols: standard deviations; outline symbols: mean values.

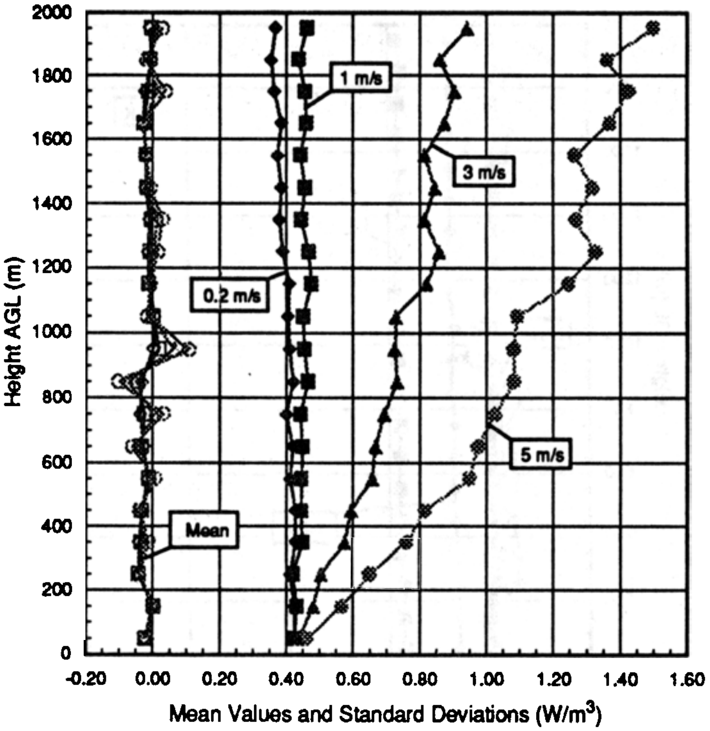

Figure 2. Monte Carlo simulations of the effects of wind measurement errors on the standard deviations of turbulent sensible heat flux divergence calculated as a residual in the atmospheric heat budget equation. Solid symbols: standard deviations; outline symbols: mean values.

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