ASPECTS OF TURBULENCE SECOND MOMENTS IN THE UNSTABLE ATMOSPHERIC SURFACE LAYER ABOVE FLAT PINE FOREST AND HYDROLOGIC APPLICATIONS

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Abstract

Variances of vertical velocity w, temperature θ, and specific humidity q observed in the ASL over a flat maritime pine forest with an aircraft are used to investigate the applicability of the variance methods to inhomogeneous terrain. The variances of w and θ were found approximately to obey the universal function of Monin-Obukhov similarity (MOS), while that of q clearly does not. Further investigation suggested the possibility that the surface heterogeneity affected the fluctuation of q and that it also caused a breakdown of the similarity between scalars.

Several types of the variance method were tested and some of them were found to predict the surface flux of sensible heat with considerable accuracy. The latent heat flux estimates were in reasonable agreement when the dimensionless functions were calibrated locally.

1 INTRODUCTION

The variance method, or variance technique, utilizing the universal relationships between the flux and the variance, predicts fluxes from the measurements of variances. It was probably first proposed by Tillman (1972), and has been applied to observations by several researchers (e.g., Wesely, 1988; Weaver, 1990; Lloyd *et al.*, 1991; Albertson *et al.*, 1995; Katul *et al.*, 1995) with micrometeorological measurements. Especially, Wesely (1988) listed several possible variations of the variance method and investigated their physical basis. Since it is an indirect method with MOS relationships, one drawback of the variance methods is that it critically depends on the hypotheses that MOS is based on. More specifically, it is still not known whether MOS is extensible to a heterogeneous terrain, and, thus, the applicability of the variance methods to such a terrain is still not clearly established (Katul *et al.*, 1995).

In this study, several variations of the variance method based on the one-third power law for the standard deviations were tested against aircraft observations over inhomogeneous pine forest.

2 MONIN-OBUKHOV SIMILARITY AND VARIANCE METHODS

2.1 Monin-Obukhov Similarity and One-third Power Law

Monin-Obukhov Similarity (MOS) (e.g. Monin and Yaglom, 1971) predicts the variance of the vertical wind speed, σ_w, and the variance of a scalar, σ_c, over horizontally homogeneous terrain as follows.

$$\sigma_w/u_* = \phi_w(\zeta) \qquad \sigma_c/c_* = \phi_c(\zeta) \tag{1}$$

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where the ϕ's are universal functions to be determined empirically, u_* is the friction velocity, $c_* \equiv \overline{w'c'}_0/u_*$ the scale for the scalar concentration, $\zeta \equiv z/L$, where L is Obukhov's length defined as,

$$L \equiv -{u_*}^3/k\beta\overline{w'\theta_v'}_0 \tag{2}$$

and $\beta \equiv g/\theta_v$, g the acceleration of gravity, k the von Kármán constant which is assumed to equal 0.4 and subscript $_0$ denotes the value evaluated at the surface.

In the limit as $\zeta \to -\infty$, which is sometimes called "local free convection"(Wyngaard *et al.*, 1971; Monin and Yaglom, 1971), u_* can be dropped from the list of relevant parameters. This immediately results in,

$$\phi_w = C_w(-\zeta)^{\frac{1}{3}} \tag{3a}$$

$$\phi_c = C_c(-\zeta)^{-\frac{1}{3}} \tag{3b}$$

where C_w and C_c are universal constants, which do not, in principle, depend on stability, surface conditions, etc. Equations (3a) and (3b) embody the one-third power law of local free convection, which has been found to describe observations through many experimental studies (see, for example, Monin and Yaglom 1971, Kader and Yaglom 1990 for reviews). As shown by Kader and Yaglom (1990), the one-third power relationships between standard deviations and fluxes can also be obtained through directional similarity combined with a three-layered structure of the ASL.

2.2 Variance Methods

Using (3a) and (3b), it is possible to derive three types of variance methods, each of which corresponds to the classification by Wesely (1988). They are introduced below.

2.2.1 Power-law method

By assuming $\overline{w'\theta_v'}_0 = \overline{w'\theta'}_0$. one can rewrite (3a) and (3b) for θ with respect to the sensible heat flux $H = C_p\rho\overline{w'\theta'}_0$ (Tillman, 1972), where C_p and ρ are the specific heat and the density of the air, respectively,

$$H = C_p\rho\left(\frac{\sigma_w}{C_w}\right)^3\frac{1}{\beta k z} \tag{4a}$$

$$H = C_p\rho\left(\frac{\sigma_\theta}{C_\theta}\right)^{\frac{3}{2}}(\beta k z)^{\frac{1}{2}} \tag{4b}$$

This is a simplified version of the normalized standard deviation method of Wesely (1988), and is attractive among others because single measurements of σ_w or σ_θ enable us to estimate the heat flux. Especially, (4b) has been applied to observations by many (e.g. Lloyd *et al.*, 1991; Katul *et al.*, 1995).

2.2.2 Correlation method

Combining (3a) and (3b) to eliminate ζ, and applying them to θ and q with (1), one gets

$$H = C_p\rho\frac{\sigma_w}{C_w}\frac{\sigma_\theta}{C_\theta} \qquad LE = L_e\rho\frac{\sigma_w}{C_w}\frac{\sigma_q}{C_q} \tag{5}$$

where L_e is the heat of evaporation.

Equations (5) are a consequence of the one-third power law for both σ_w and σ_c, and they are closely related to the correlation coefficient method, the second category of Wesely's(1988) classification.

2.2.3 *Standard-Deviation Ratio Method (SDRM)*

Taking the ratio of (3b) for θ and (3b) for q, one can estimate the Bowen ratio, Bo, with the measurements of σ_θ and σ_q as follows,

$$Bo \equiv \frac{H}{LE} = \frac{C_p}{L_e} \frac{\sigma_\theta / C_\theta}{\sigma_q / C_q}. \tag{6}$$

This can be regarded as an extension of the Bowen ratio method to the variance method, and either of the fluxes, $\overline{w'\theta'}_0$ or $\overline{w'q'}_0$, can be obtained by combining SDRM with any other methods, such as the energy budget or the power law methods.

3 ANALYZED DATA

The data used in the analysis are the turbulence statistics measured by the NCAR King Air aircraft over the flat Landes forest during HAPEX-Mobilhy (hereafter, HAPEX) (André *et al.*, 1986) in 1986, in southwestern France. The Landes forest consists of 65 % flat maritime pine stands with heights ranging from 10 to 20 m, and 35 % clearings with linear sizes of the order of 10^2 to 10^3 m. Therefore, the region can be regarded as "heterogeneous" over the 10 km flight path of the NCAR King Air. Moreover, as the sensible heat flux from the forest canopy was usually quite large (e.g. André *et al.*, 1990), the turbulent time scales associated with this strong buoyancy tended to be relatively small; thus, it is probably safe to assume that the turbulence field was very nearly steady.

Detailed information on the data acquisition, data processing, and flight logs of the NCAR King Air aircraft during HAPEX are available elsewhere (Hildebrand, 1988). Briefly, turbulence measurements over the flight path (150 km) were filtered with a 15 km high pass filter, and block averaged for every 10 km intervals. To allow comparison with ground based measurements, out of the turbulence statistics calculated in this way, only those for the closest point to a micrometeorological tower (Gash *et al.*, 1989) in the Landes forest were used in the analysis.

Analysis of the radiosounding profiles of θ, q and u (Parlange and Brutsaert, 1993, and papers cited therein) provides the roughness and the displacement height of the terrain. Moreover, following these studies, the vertical extent of the ASL, where MOS is valid, was assumed as $49 \leq z \leq 156$ m, and only the flight data in this range were subjected to the analysis.

4 RESULTS

Table 1: Constants used in the variance methods. The uncalibrated constants were chosen from available experimental values found in the literature (Wyngaard *et al.* (1971) and Högström and Smedman-Högström (1974)). The calibrated constants were calculated from the data using aircraft surface fluxes. The standard deviations are also presented in the brackets.

	C_w	C_θ	C_q
uncalibrated	1.8	0.99	1.04
calibrated	1.76	0.92	1.42
	(±0.15)	(±0.14)	(±0.38)

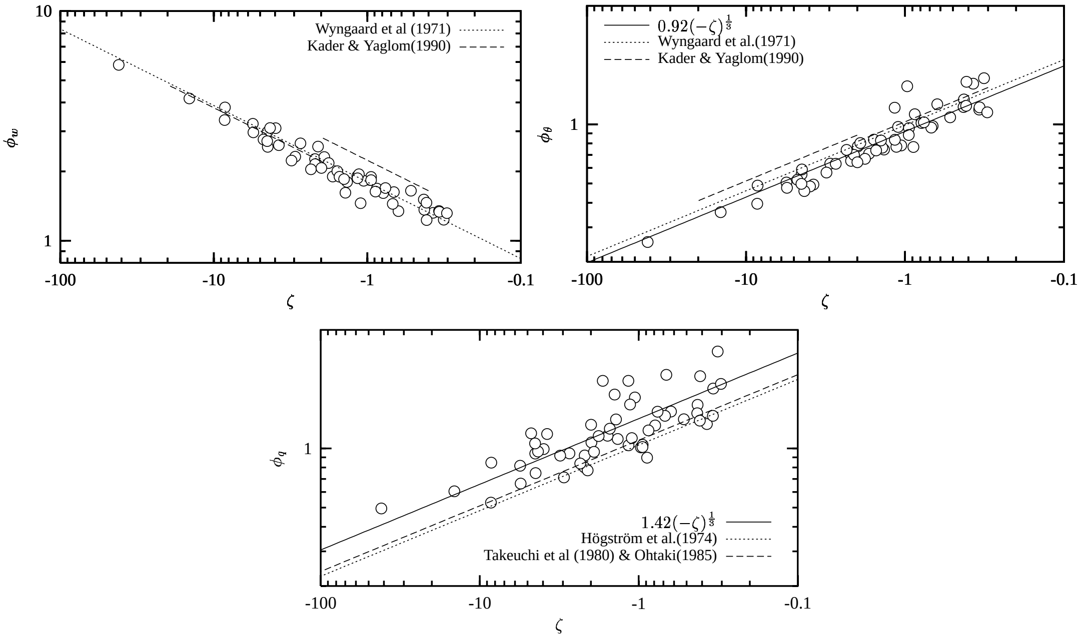


Figure 1: Dimensionless standard deviation, ϕ_w, ϕ_θ and ϕ_q as a function of ζ. The circles are the observations in HAPEX, and the solid lines are the fitted lines to the data. The dotted and broken lines are empirical functions from the literature.

In this section, the three kinds of variance methods described above are applied to the measurements of standard deviations and they are compared with the surface fluxes measured with the aircraft.

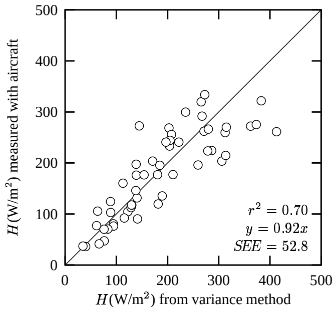
4.1 Values of the Constants

Before using (3a) and (3b) for both θ and q, the constants, C_w, C_θ and C_q, C_c for θ and q respectively, must be determined. Two sets of values were used in this study. The constants in the first set, the "uncalibrated constants", were chosen from available experimental values found in the literature, namely the well-known results by Wyngaard *et al.* (1971) from the Kansas experiment, $C_w = 1.8$ and $C_\theta = 0.99$ (adjusted for $k = 0.4$), and that obtained by Högström and Smedman-Högström (1974), $C_q = 1.04$. The second set, the "calibrated constants", was determined so that (3a) and (3b) fit the data in HAPEX with the aircraft surface flux. The results are listed in Table 1, and the fitted equations are plotted with the HAPEX data in Figure 1. The fitted results for C_w and C_θ are close to those selected from the literature, while the values of C_q are quite different. This problem will be visited later in this study.

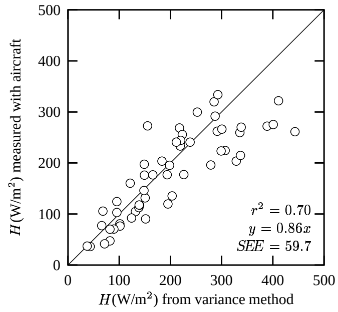
4.2 Power-Law Method

The results of the power-law method are shown in Figure 2 with some relevant statistics. These results can be considered fairly good with a squared correlation coefficient $r^2 = 0.70$. The data show a larger scatter for larger flux values. This is probably due to the fact that the heat flux is proportional to the third power of the observed σ_θ in (4a). Even when the calibrated constant is used, this inherent limitation cannot be eliminated as shown in Figure 2(b).

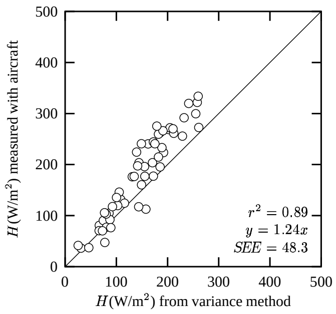
In Figure 2(d) shows a bias even with the calibrated constant. This is partly attributable to the assumption $\overline{w'\theta'_{v0}} = \overline{w'\theta'}_0$ in the derivation of equation (4a) and (4b) (Asanuma, 1996).



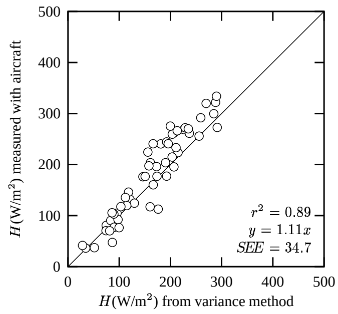
(a) (4a), uncalibrated



(b) (4a), calibrated



(c) (4b), uncalibrated



(d) (4b), calibrated

Figure 2: Sensible heat flux estimated by the power-law method, (4a) for (a) and (b) and (4b) for (c) and (d), compared with the aircraft surface values. Fluxes were calculated either with the uncalibrated constants (left panels) or with the calibrated constants (right panels). The correlation coefficient r^2, the fitted line for linear regression forced through the origin and the standard estimate of error, *SEE* in W/m^2 are also shown.

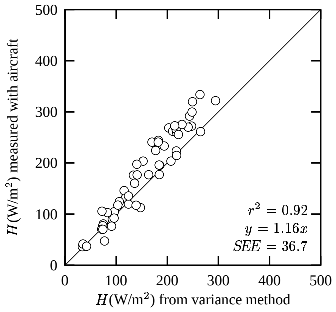
4.3 Correlation Method

The correlation method, (5), was applied to θ and q, and the resulting flux values are compared with the observations in each panel of Figures 3. The first of (5) works well, except that there is a small bias that is attributable again to the uncalibrated value of C_w and C_θ. This is improved when the calibrated constants are used; the line fitted to the data with forced origin has a slope which is quite close to unity (Figure 3(b)). An advantage of this method is that it does not directly depend on the power law, but merely on some type of similarity of the ϕ-function in (1). Figure 3(c) displays considerable scatter and a strong bias which is, again, attributable mainly to the value of C_q. This bias was eliminated when the calibrated constants were used (Figure3(d)).

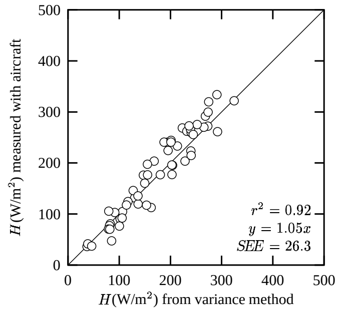
4.4 Standard-Deviation Ratio Method (SDRM)

The Bowen ratio's calculated with (6) are compared with the measured values in Figure 4. Again, the underestimate with the uncalibrated constant can be attributed to the value of C_q that is evidently inappropriate for the present data. This is improved when the calibrated values were used.

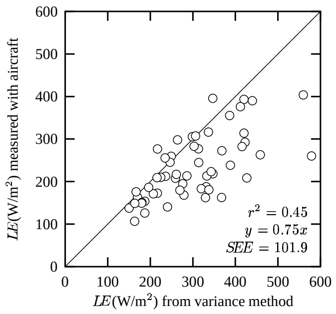
Once *Bo* is known, it can be used together with any other method to calculate the surface flux. One possibility is a combination with the power-law method. Combining (6) with (4a)



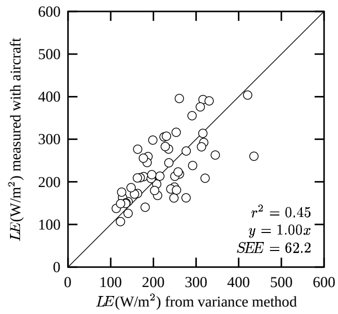
(a) (5) for H, uncalibrated



(b) (5) for H, calibrated



(c) (5) for LE, uncalibrated



(d) (5) for LE, calibrated

Figure 3: Same as Figure 2 but by the correlation method, the first equation of (5) for (a) and (b), and the second equation of (5) for (c) and (d).

and (4b), one can write

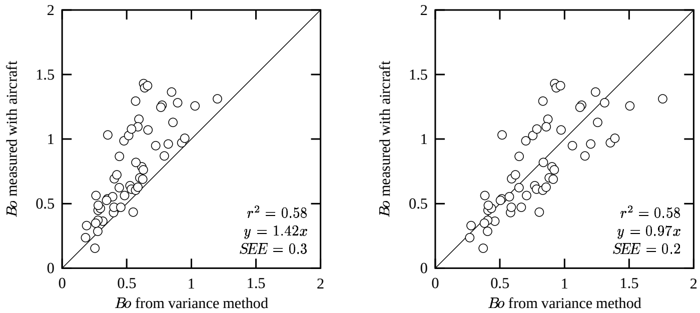
$$LE = L_e\rho\left(\frac{\sigma_w}{C_w}\right)^3\left(\frac{\sigma_\theta}{C_\theta}\right)^{-1}\left(\frac{\sigma_q}{C_q}\right)\frac{1}{\beta kz} \qquad LE = L_e\rho\left(\frac{\sigma_\theta}{C_\theta}\right)^{\frac{1}{2}}\left(\frac{\sigma_q}{C_q}\right)(\beta kz)^{\frac{1}{2}} \tag{7}$$

The other possibility of utilization of (6) is to combine (6) with the energy budget equation, so that one can compute either sensible heat or latent heat flux. This is an extension of the energy budget with Bowen ratio method (EBBR) (Brutsaert, 1982, Chapter 10) to the variance measurement. The results of (7) are presented elsewhere(Asanuma, 1996).

5 CONCLUSIONS

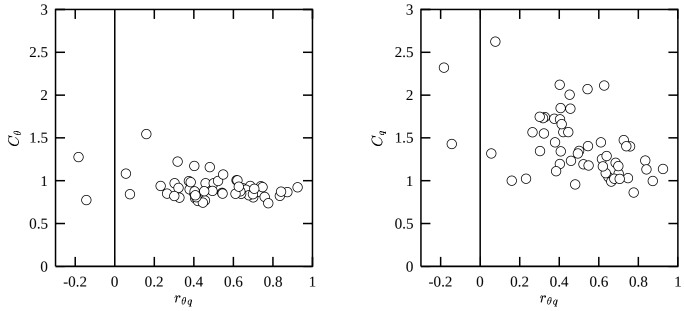
In summary, the variance methods with σ_θ show acceptable accuracy while those with σ_q give a marked bias with the uncalibrated constant, but not with the calibrated constant. The significant difference between the two values of C_q in addition to the difference between calibrated C_θ and C_q obtained herein bring out some unexpected features of σ_q in HAPEX. The fact that $C_\theta = C_q$ was not satisfied indicates that there was a dissimilarity between θ and q in HAPEX. This violates one of the implications of MOS, namely the similarity between scalars (Hill, 1989).

The possible reason for this violation of MOS can be attributed to the violation of either or both of two major prerequisites of MOS; the steadiness and homogeneity. As unsteadiness would influence both of θ and q in a similar way, inhomogeneity of the surface is probably the cause of the unusual behavior of σ_q in HAPEX. This notion is strongly supported by Figure 5, where the value of C_θ and C_q calculated for each point of Figure 1 is plotted against $r_{\theta q}$, the correlation coefficient of θ and q. Note that $r_{\theta q}$ is an indicator of the similarity between θ and



(a) uncalibrated (b) calibrated

Figure 4: Same as Figure 2 but for Bowen ratio estimated by SDRM, (6). *SEE* are dimensionless.



(a) (b)

Figure 5: Values of C_θ and C_q versus $r_{\theta q}$. Circles are the values over the Landes forest.

q, and that $r_{\theta q} = \pm 1$ is equivalent to the perfect similarity (see Dias and Brutsaert, 1995, for detailed discussion). Figure 5 shows striking features; (i) C_θ and C_q behave differently when $|r_{\theta q}|$ is small, and (ii) both of them tend to converge to unity as $r_{\theta q} \to 1$. The latter feature makes the possibility of the measurement error causing unusual values of σ_q highly unlikely.

Katul *et al.* (1995) already mentioned that the ϕ_q function becomes larger over non-uniform terrain, and the findings in this paper are not inconsistent with this. The present paper, however, suggests the existence of other possible factors governing the value of C_q (dimensionless standard deviation) as C_q does not simply increase.

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