6.11 DETERMINATION OF TURBULENT PARAMETERS IN THE ATMOSPHERIC BOUNDARY LAYER WITH AN UHF WIND PROFILER. COMPARISON WITH IN SITU MEASUREMENTS.

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1. INTRODUCTION

UHF wind profilers have shown to be very useful tools for the investigation of the convective Atmospheric Boundary Layer (ABL) with a high temporal and vertical resolution. Previous studies have demonstrated its ability to retrieve the wind velocity field and the height of the ABL (Zi).

Methodologies to determine three turbulent parameters (turbulent kinetic energy dissipation rate, momentum fluxes and sensible heat fluxes) with UHF radars are proposed in this study. To validate these methods, the results are compared with in situ measurements made by an aircraft during TRAC-98 experiment.

The originality of the methods proposed in this work to calculate the turbulent kinetic energy dissipation rates and the momentum fluxes is based on the determination of the Doppler spectral width associated to small-scales turbulence within the resolution volume measured by the UHF profilers. The sensible heat fluxes are deduced from the simplified turbulent kinetic energy (TKE) balance equation after calculation of the dissipation rate and the mechanical production.

2. TRAC-98 EXPERIMENT

The TRAC-98 campaign (Turbulence Radar Aircraft Cells) took place over the Beauce plain (France) during summer 1998 (15 June until 05 July 1998). This experiment was devoted to study coherent structures within convective ABL over very flat and homogeneous land surface (Campistron et al., 1999). To satisfy this objective in situ (aircrafts and ground stations) and remote sensing instruments (an UHF wind profiler, the Ronsard C-band radar and a sodar) were deployed to create a large database.

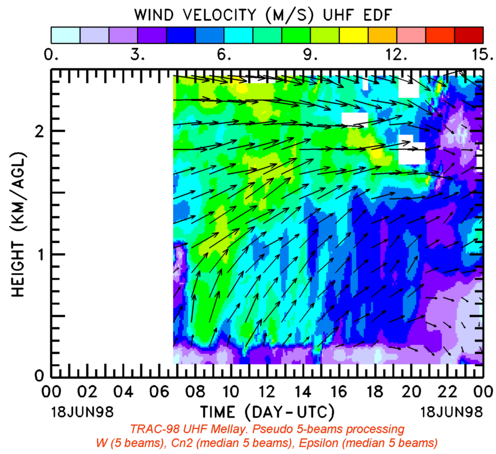
2.1. Merlin IV aircraft

Airborne data measured with the aircraft Merlin IV from Météo-France during 3 days (18, 19 and 23 June 1998) are used in this study. All these measurements were collected between 1100 to 1330 UTC when the turbulence can be considered as stationary. Each flight were constituted of two vertical explorations (only one exploration on 23 June 1998) within the ABL with 4 horizontal legs at about 0,1Zi, 0.4Zi, 0.6Zi and 1Zi. Turbulent moments were calculated at each horizontal leg using eddy-correlation method with a high pass filtering to remove large scales drifts higher than 5 km (for more details see Bernard-Trottolo, 2004).

2.2. UHF wind profiler

The UHF wind profiler used during TRAC-98 was developed by Degréane Horizon. It is a 1.238 GHz radar constituted of one vertical and four off-zenith beams with a 8.5° beamwidth. The four off-zenith beam have an elevation angle of 73° and are in quadrature in azimuth. The temporal resolution is 5 minutes and the vertical resolution is 75 m, from 75 m up to 2-3 km.

UHF wind profilers are useful instruments to retrieve wind field from the Doppler effect and the top of the ABL (Zi) from high backscattering echoes (Angevine et al., 1994). Fig. 1 presents time-height sections of horizontal winds and air refractive index structure constant (C_n^2) measured on 18 June 1998. This figure shows the good correlation of those two parameters to estimate the depth of the ABL through wind shear and maxima of C_n^2 (indicated with the black curve in Fig. 1).



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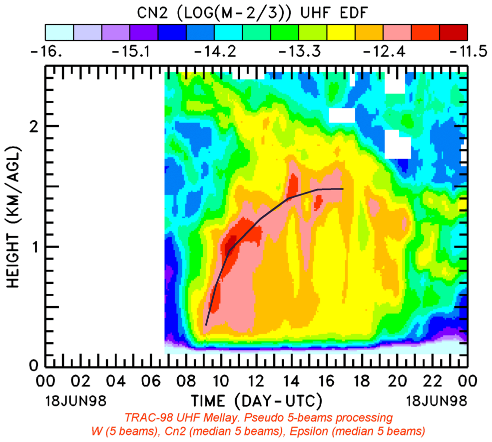

Figure 1: Time-height sections on 18 June 1998 of (at the top) horizontal wind which intensity is indicated with the color scale and the direction with the vectors and (at the bottom) air refractive index structure constant (C_n^2) which intensity is indicated with the color scale (black curve indicate the top of the ABL through C_n^2 maxima)

3. METHODOLOGY

3.1. Turbulent kinetic energy dissipation rate

The turbulent kinetic energy dissipation rate (ε) can be calculated from a Doppler spectral width. The broadening of the Doppler spectrum results in the broadening of several mechanisms independent of each other (Doviak and Zrniæ, 1984). Thus, the measured variance (σ^2_m) of the Doppler spectrum can be expressed as :

$$\sigma^2_m = \sigma^2_t + \sigma^2_s + \sigma^2_x \qquad (1)$$

where σ^2_t is the contribution of small-scale turbulence within the resolution volume, σ^2_s is the variance associated to meso-scale wind shear and σ^2_x includes all broadening or narrowing factors generated by the data acquisition mode and processing.

The variance σ^2_t is then calculated after the determination of the variances σ^2_s and σ^2_x from which is deduced the turbulent kinetic energy dissipation rate (for more details see Jacoby et al., 2002). Since the dissipation rate can be estimated with each beam, the median is retained.

3.2. Momentum fluxes

The momentum fluxes $\overline{u'w'}$ and $\overline{v'w'}$ can be deduced from the Doppler spectral widths of the four off-zenith beams. The radial velocity (v_r) measured by a beam can be expressed in the meteorological coordinates with the wind components (u, v, w):

$$v_r = -\cos\varphi_s \sin\varphi \, u - \cos\varphi_s \cos\varphi \, v - \sin\varphi_s \, w \qquad (2)$$

where φ and φ_s are the azimuth and site angle respectively.

The calculation of the radial velocity variance for each beam (using Eq. 2) and the geometric relations between the four off-zenith beams (in quadrature in azimuth) leads to the expression of $\overline{u'w'}$ and $\overline{v'w'}$ in function of the radial velocity variances of the off-zenith beams (Eqs. 3 and 4).

$$\overline{u'w'} = \frac{\left(\overline{v'^2_1} - \overline{v'^2_2}\right)\sin\varphi_1 + \left(\overline{v'^2_3} - \overline{v'^2_4}\right)\sin\varphi_3}{2\sin 2\varphi_s} \qquad (3)$$

$$\overline{v'w'} = \frac{\left(\overline{v'^2_1} - \overline{v'^2_2}\right)\cos\varphi_1 + \left(\overline{v'^2_3} - \overline{v'^2_4}\right)\cos\varphi_3}{2\sin 2\varphi_s} \qquad (4)$$

where v'^2_i and φ_i are the radial velocity variance and the azimuth angle for the off-zenith beam i=1 to 4 respectively and φ_s the site angle.

The originality of this method is to determine momentum fluxes using only the radial velocity variances which contribute to small-scales turbulence within the resolution volume.

The authors wanted to pointed out that the range of turbulent spatial scales took into account by each instruments is not completely similar. The spatial scales are ranged between several meters to hundreds of meters for the aircraft while turbulence scales measured by the UHF profiler are inferior of about 75m.

3.3. Sensible heat fluxes

The sensible heat fluxes are deduced from the TKE balance equation (Bénech et al., 2003). The TKE balance equation reduced to Eq. 5 assuming horizontal homogeneity and that the production of turbulence is generating and consummating instantaneously locally.

$$-\overline{u'w'}\frac{\partial \overline{u}}{\partial z} - \overline{v'w'}\frac{\partial \overline{v}}{\partial z} + \frac{g}{\theta}\overline{w'\theta'} - \varepsilon = 0 \qquad (5)$$

Eq. 5 indicates that thermal production of turbulence is balanced by the mechanical production and the dissipation of turbulence. Thus, the sensible heat flux can be calculated with Eq. 5 since the dissipation rate, the momentum fluxes and the vertical wind shears are measured by the UHF profiler.

4. RESULTS

The comparison of airborne and UHF wind profiler measurements has been carried out on three days (18, 19 and 23 June 1998) which constitute a dataset of 5 vertical profiles within the ABL. Each UHF radar vertical profiles have been obtained by averaging the data during the duration of the vertical exploration of each flight. Airborne measurements provide turbulent kinetic energy dissipation rates, sensible heat fluxes and momentum fluxes. These latter are measured in coordinates function of aircraft trajectory. To compare these fluxes with UHF radar ones, the horizontal momentum fluxes have been calculated for both instruments using Eq. (6).

$$m = \sqrt{\overline{u'w'}^2 + \overline{v'w'}^2} \qquad (6)$$

where $\overline{u'w'}$ and $\overline{v'w'}$ are the momentum fluxes in a coordinate system.

The statistical comparison consists in averaging vertical profiles of turbulent parameters measured in different meteorological conditions. Thus, turbulent parameters have been normalized using classical scales defined by Stull (1988) :

-length scale (m) : Zi (7)

-vertical velocity scale (m/s) :

$$w^* = (gZi(\overline{w'q'})_s / \overline{T})^{1/3} \qquad (8)$$

-temperature scale (K) : $q^* = (\overline{w'q'})_s / w^*$ (9)

-friction velocity (m/s) :

$$u^* = \sqrt{(\overline{u'w'})_s^{\,2} + (\overline{v'w'})_s^{\,2}} \qquad (10)$$

where Zi is the ABL depth, g is the gravitational acceleration, $\overline{T}$ is reference temperature of the ABL. The 's' subscript corresponds to the covariance value in the surface boundary layer, which is considered in this work as the airborne measurement at 0.1Zi.

4.1. Turbulent kinetic energy dissipation rate

Fig. 2 presents a time-height section of the dissipation rate measured on 18 June 1998 by the UHF radar. This figure illustrates the diurnal cycle of the dissipation rate that is contained within the ABL.

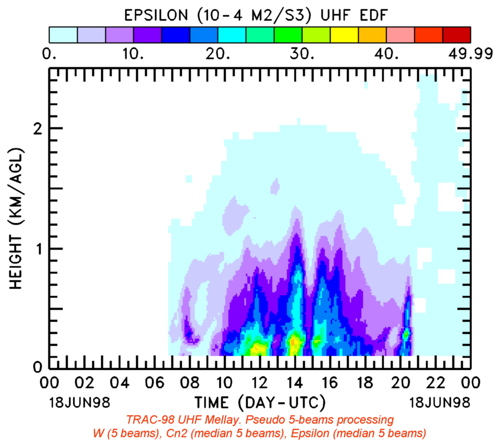

Figure 2: Time-height section on 18 June 1998 of the turbulent kinetic energy of the dissipation rate which intensity is indicated with the color scale

Figs. 3 and 4 present vertical profiles normalized by Zi of the dissipation rate measured during each vertical exploration with the UHF profiler and the aircraft respectively. Both instruments measure relatively similar dissipation rates which decrease with height. Values are ranged from 1.5 and 3.5 10^{-3} m^2/s^3 at 0.1Zi to 0 and 0.5 10^{-3} m^2/s^3 for the UHF profiler, and 1 to 2.5 10^{-3} m^2/s^3 at 0.1Zi to 0.5 10^{-3} m^2/s^3 for the aircraft. However UHF profiler measurements present much more variability than the aircraft ones, notably bellow 0.3Zi. At this level, UHF profiler are strongly affected by ground echoes which perturb the measurements. Ground echoes can combine with Doppler spectra leading to an increase of the spectral width and results in higher values of dissipation rates.

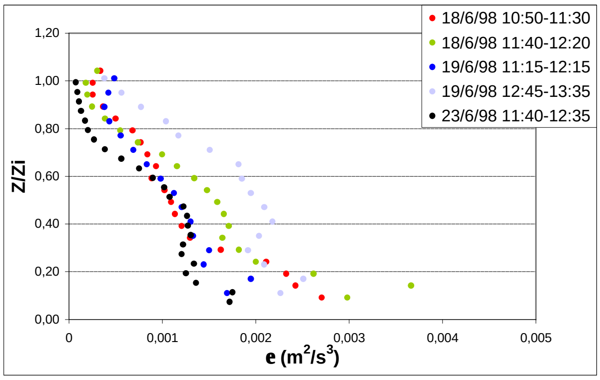

Figure 3: Normalized vertical profiles of the turbulent kinetic energy dissipation rate measured by the UHF profiler on each vertical exploration

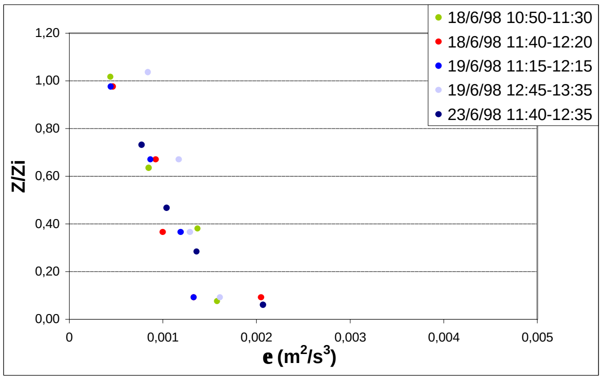

Figure 4: Normalized vertical profiles of the turbulent kinetic energy dissipation rate measured by the aircraft on each vertical exploration

Fig. 5 shows the average of all normalized vertical profiles of the normalized dissipation rate with the standard deviations for the UHF profiler and the aircraft. Both profiles are quite similar and show the decreasing of the dissipation rate with height. The differences between each profile are low with less than 10% above 0.2Zi and slightly more important with 20-25% below this level corresponding to perturbations of ground echoes. However, the UHF profiler overestimated slightly the dissipation rate below 0.7Zi and underestimated slightly above this level. The standard deviations indicated the dispersion of the data. The airborne data are quite constant with height around 10-15% while the radar one decrease with height from 45 to 10%.

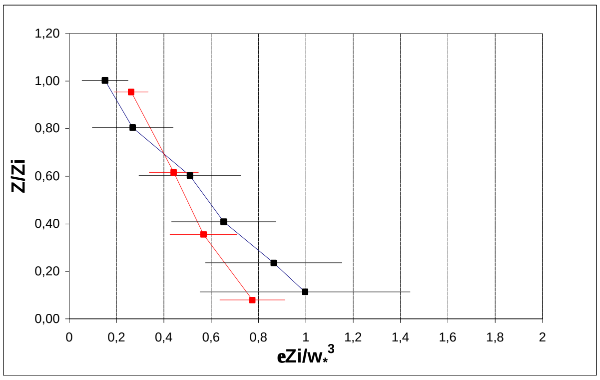

Figure 5: Average of the normalized vertical profiles of the normalized turbulent kinetic energy dissipation rate and standard deviations measured by the aircraft (in red) and the UHF profiler (in black)

4.2. *Momentum fluxes*

Figs. 6 and 7 present the normalized vertical profiles of the horizontal momentum fluxes measured during each vertical exploration with the UHF profiler and the aircraft respectively. These figures show that the order of magnitude of this parameter is relatively similar for both instruments. The values are ranged between 0 and 0.4 m^2/s^2 for the UHF profiler and 0 and 0.35 m^2/s^2 for the aircraft. However the variability of these fluxes is important for each instrument.

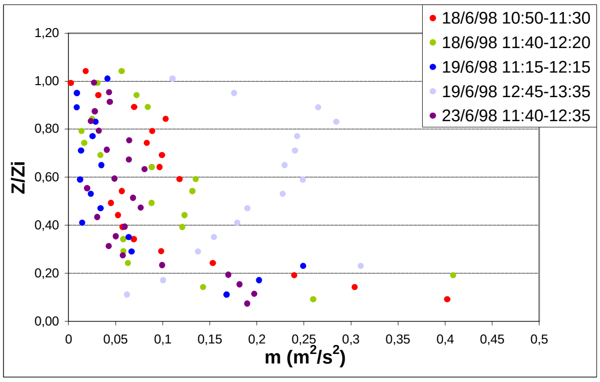

Figure 6: Normalized vertical profiles of the horizontal momentum flux measured by the UHF profiler on each vertical exploration

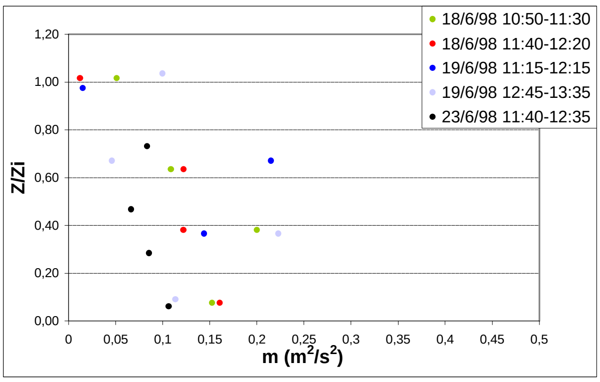

Figure 7: Normalized vertical profiles of the horizontal momentum flux measured by the aircraft on each vertical exploration

Fig. 8 shows the average of all the normalized vertical profiles of the normalized horizontal momentum flux with the standard deviations for the UHF profiler and the aircraft. The shape of these profiles are different. UHF profiler measurements are overestimated below 0.3Zi and underestimated above this level. The difference between each profile is important with more than 50% below 0.7Zi and around 20% above this level. The standard deviations indicated also a large variability, previously observed, with values reaching 140% at 0.6Zi for the aircraft and 100% at 0.2Zi for the UHF radar.

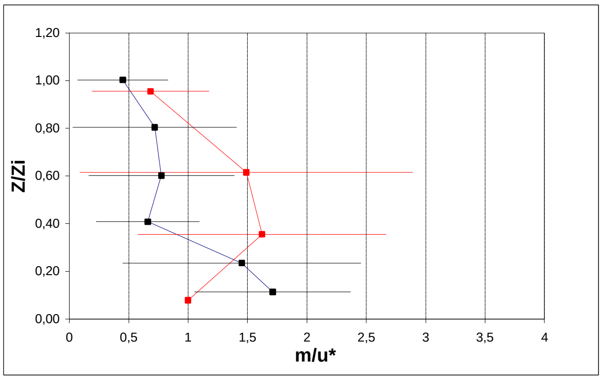

Figure 8: Average of the normalized vertical profiles of the normalized horizontal momentum fluxes and standard deviations measured by the aircraft (in red) and the UHF profiler (in black)

The underestimation of the UHF profiler above 0.3Zi can result of the larger spatial scales not took into account by this instrument for the calculation of momentum fluxes. Below this level, perturbations from ground echoes can be responsible of the overestimation observed.

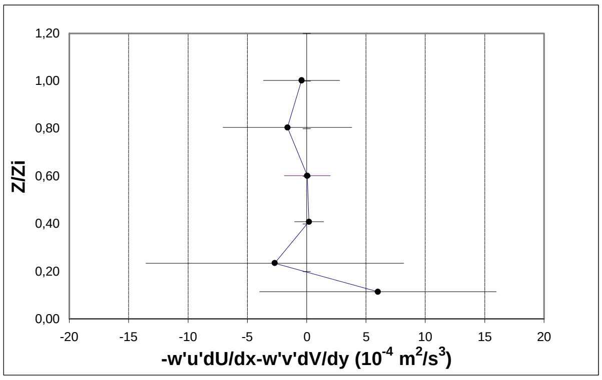

Figure 9: Average of the normalized vertical profiles of the mechanical production and standard deviations measured by the UHF profiler

However, the ABL that forms during the cases studied here is essentially convective. In such conditions the method used to calculate momentum fluxes with UHF profiler shows coherent results. Fig. 9 presents an average of the normalized vertical profiles of the mechanical production (using normalized vertical profiles of the horizontal momentum fluxes presented in Fig. 6) with the standard deviations measured by the UHF radar. This term is low with values inferior to 2.10^{-4} m^2/s^3 in absolute with small standard deviations inferior to

5.10^{-4} m^2/s^3 (keeping out the levels below 0.3Zi where ground echoes perturb UHF radar measurements).

4.3. *Sensible heat fluxes*

Figs. 10 and 11 present the normalized vertical profiles of sensible heat fluxes measured during each vertical exploration with the UHF profiler and the aircraft respectively. Both instruments measure relatively similar sensible heat fluxes which decrease with height. The majority of the values are ranged from 50 and 100 W/m^2 at low levels to 0 to 30 W/m^2 at upper levels for the UHF profiler, and from 50 and 75 W/m^2 at low levels to –20 and 0 W/m^2 at upper levels for the aircraft. However, the dispersion of the UHF profiler data is more important than airborne ones notably below 0.3Zi.

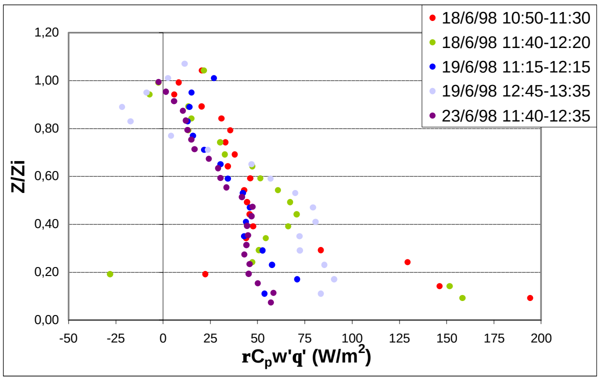

Figure 10: Normalized vertical profiles of the sensible heat fluxes measured by the UHF profiler on each vertical exploration

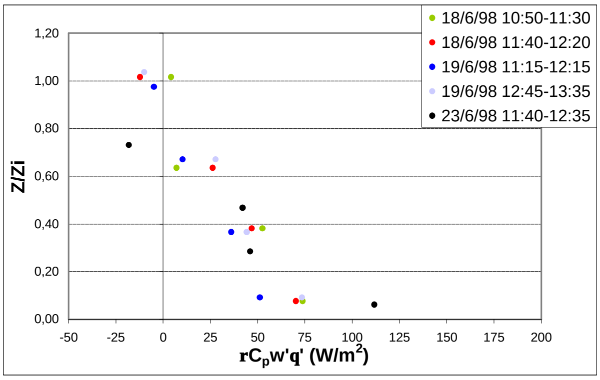

Figure 11: Normalized vertical profiles of the sensible heat fluxes measured by the aircraft on each vertical exploration

Fig. 12 shows the average of all the normalized vertical profiles of the normalized sensible heat flux with the standard deviations for the UHF profiler and the aircraft. The UHF radar profile has a similar slope to the one measured by the aircraft. Nevertheless, the UHF profiler overestimate the values of the sensible heat fluxes from 15 to 30%. Below 0.7Zi, the overestimation of the sensible heat fluxes can be explained by the overestimation of the dissipation rate observed previously since the mechanical production is negligible in these levels in regard to the dissipation rate. Above 0.7Zi, the overestimation of the sensible heat fluxes is due to mechanical loss since the dissipation rate is much more inferior to the mechanical production term.

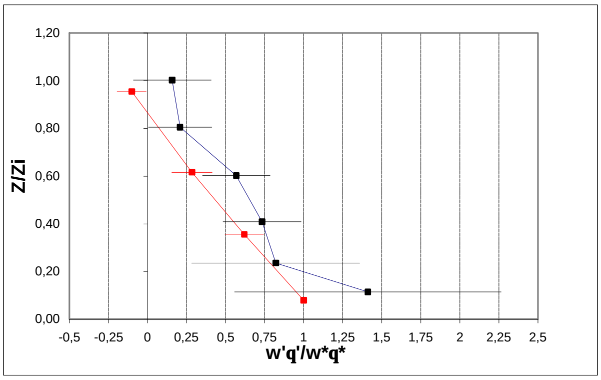

Figure 12: Average of the normalized vertical profiles of the normalized sensible heat fluxes and standard deviations measured by the aircraft (in red) and the UHF profiler (in black)

5. CONCLUSION

This study presents methods to determine turbulent parameters in the ABL with UHF wind profilers. These methods are compared with aircraft data measured during TRAC-98 campaign. The results of this comparison show that : (i) the turbulent kinetic energy dissipation rate measured by both instruments are well correlated with a slightly overestimation and underestimation of the UHF radar below and above 0.7Zi respectively ; (ii) the momentum fluxes measured by the UHF profiler is the same order of magnitude than the aircraft ones but is globally underestimated in the ABL, which can be the consequence of the larger turbulent scales not took into account by this instrument (keeping out the levels inferior to 0.3Zi where ground echoes perturb UHF profiler measurements) ; (iii) the sensible heat fluxes measured by both instruments are well correlated with a slightly overestimation of the UHF radar mainly caused by the overestimation of the dissipation rate and losses of mechanical production below and above 0.7Zi respectively.

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