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Reply to 'Comments on "Comparison of radar reflectivity and vertical velocity observed with a scannable c-band doppler radar and two UHF profilers in the lower troposphere"'

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Reply

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1. Introduction

The objective of Lothon et al.'s (2002, hereafter L2002) paper was to investigate the ability of a scanable C-band Doppler meteorological radar for the documentation of the lower clear atmosphere with an emphasis on the atmospheric boundary layer (ABL). Comparison with the observations of two UHF wind profilers provided the opportunity to address the problem of the so-called downward bias of UHF vertical velocity measurements made in a fully developed and turbulent convective ABL previously put in evidence and described by Angevine (1997). Worthington's (2003) reproach of a too-narrow review of the different aspects of this problem is valid, but a thorough survey of this question was beyond the scope of the paper. The ambition of the authors was to bring some elements of discussion to this open debate—elements that tend to confirm Angevine's conclusion on the existence of UHF downward bias of instrumental origin.

In the reply presented in the following section we discuss Worthington's (2003) suggestion of the possible meteorological origin of the UHF vertical velocity bias observed in the ABL. Coming back to certain arguments developed previously in L2002, the importance of which seems underestimated in Worthington's comment, and with new data analysis, we reinforce our position on a most probable instrumental origin of the UHF vertical bias.

2. Discussion

In his comment Worthington does not deny the possibility of measurement errors in the persistent weak downward or upward vertical velocity in wind profilers long averaged time series, but he argues that other po-

tential sources of apparent bias related to atmospheric variability also have to be considered before reaching any firm conclusion. Because nature is more imaginative than any human brain, the given list of possible geophysical biases is certainly far from exhaustive. For our concern we retain Worthington's suggestion of a teleconnection between the surrounding urbanized area and the 1998 Turbulence Radar Aircraft Cells (TRAC-98) experiment domain, which is a relevant and original contribution to this debate. He points out that an urban heat island induces convective currents that are compensated by subsiding motion in the countryside, which might explain the negative vertical bias observed not only over the Beauce plain in France but also over the American flatland area (Angevine 1997).

The major urban area close to the TRAC-98 site is Paris, situated 70 km to the north. In the Lemonsu and Masson (2002) numerical model, cited by Worthington, on the Paris heat island circulation, vertical velocities of tens of centimeters per second are found only in the first 20 to 30 km around Paris. According to V. Masson (2002, personal communication), negligible vertical velocities due to the city breeze are expected above the TRAC-98 site. On the other hand, because the dominant synoptic wind direction associated with the observations presented in L2002 was southwesterly with a mean intensity of 6 m s^{-1} , and so not downwind of Paris, it seems reasonable to discard an eventual impact of this big metropolis. We are left with a patchwork of urban areas surrounding the experiment domain of very small importance compared to Paris (usually less than 10 000 inhabitants). As a result there is also a patchwork of ascents and descents, at the same scale as the cities' dimensions, interacting with each other in a way that is probably not constructive.

Worthington (2003) makes a judicious distinction between UHF observations of the ABL affected by a downward bias and VHF observations of the free atmosphere where, according to several quoted studies,

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downward (troposphere) and upward (stratosphere) bias are both observed. By mistake in L2002 only the tropospheric downward bias was mentioned. This distinction can help in the understanding of the present problem. The origin and intensity of the turbulent mixing, which is a source of radar echoes in clear air, are markedly different in these two regions of the atmosphere. Thermal and dynamic instabilities in the daytime ABL induce strong turbulent mixing, whereas in the free atmosphere usually weak turbulence generated by gravity wave breaking is encountered. The strong stability of the upper layers favors the generation of specular echoes that are only observable at vertical incidence by VHF radars. On the other hand, returns from insects mentioned as a possible source of the UHF bias by Angevine (1997) are likely nonexistent at the high altitudes sensed by VHF radars. Since VHF radar and the free atmosphere were not the concern of the L2002 study we refer to Ralph (2000) for a thorough review on the accuracy and bias of VHF measurements.

The following discussion focuses on the UHF measurements in the ABL. In the first section we return to some important arguments pointed out in L2002 showing strongly convincing evidences of an instrumental bias. In addition, we present a new analysis of TRAC-98 observations. In the second section we follow Worthington's (2003) suggestion to analyze UHF observations made over a large city.

a. TRAC-98 experiment

The remarkable similarity between the daily mean ABL vertical velocity magnitude and temporal evolution obtained by L2002 and Angevine (1997) from vertical incidence beam observations ensures, first, that the UHF persistent downward bias is general and not a particular feature related to Angevine's flatland location. Second, as these observations were made with different types of UHF profilers, data resolution, processing, and sampling, this tends to indicate that the bias is not due to a failure in the radar technique itself. Moreover, L2002 obtained nearly the same vertical velocity time series when using pairs of opposite oblique beams. Consequently, they conclude that if the observed bias is real, it is not limited to the vertical velocity measurement but to any radial Doppler velocity observation.

We reinforce the most important contribution of L2002, to this debate which is related to the vertical velocity magnitude derived by the vertical integration of the horizontal divergence retrieved from the Doppler C-band radar measurements using the volume velocity processing (VVP) technique. This indirect methodology gave mean vertical velocity estimates that were usually smaller than 3 cm s^{-1} and positive. This is an order of magnitude less than the direct vertical velocity observation. One may object that because the divergence is derived from biased Doppler measurements it is also biased, and therefore so is the retrieved vertical velocity.

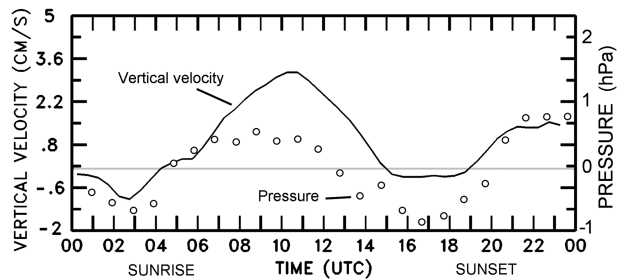


FIG. 1. (solid line) Mean time series, averaged over 11 days of TRAC-98 experiments, and over the height interval 0.1–1.2 km, of the vertical velocity derived from the observations of the network of three wind profilers. A running average over 3600 s was also applied. (open circles) Averaged time series of surface pressure (3-week TRAC-98 accumulation) after removing the daily mean.

Fortunately, divergence involves a spatial velocity difference, and it is reasonable to think that on average the biases attached to each radial velocity measurement cancel each other out.

Angevine (1997) also deduced vertical velocity from the integration of the horizontal divergence retrieved from a network of three wind profilers disposed on a triangular basis of about 7-km dimension. This method produced vertical velocity magnitude of the order of 1 cm s^{-1} , which is comparable with our estimates based on the C-band radar. This result allowed Angevine to conclude that UHF instrumental bias does exist.

During the TRAC-98 campaign, along with the two UHF profilers described in L2002, a powerful sodar provided, up to about 1500-m height, wind vertical profiles averaged over 1 h with a vertical sampling of 100 m. These three instruments, about 37 km away from each other, were disposed at the vertices of a quasi-equilateral triangle (Campistron et al. 1999). Figure 1 presents the daily variation of the vertical velocity averaged between 100- and 1200-m height, and over the same 11 days used for the UHF radars. It was computed from the upward vertical integration of the divergence of the horizontal wind deduced from the network data analysis with an assumption of a zero vertical velocity at the surface. The methodology used is described in Campistron (1997). It is based on the assumption of a local and temporal linearity of the wind in a restricted time period (3 h) and vertical depth (250 m). The magnitude smaller than 3 cm s^{-1} of the retrieved vertical velocity confirms C-band radar analysis and Angevine's network results. These three independent analyses converge to the same conclusion, but we agree with Worthington (2003) that, because of the underlying assumptions, it is quite impossible to assess the accuracy of these vertical velocity estimations.

In search of a meteorological origin of the observed residual vertical velocity, the mean diurnal surface pressure evolution is intentionally superimposed in Fig. 1. The time series represents the average of the accumulation of 3 weeks of TRAC-98 pressure data after removing the daily mean. The result displays the well-

known sum of the diurnal and semidiurnal thermal atmospheric tide perturbations (Chapman and Lindzen 1970). There is an evident correlation in the diurnal evolution of pressure and vertical velocity. Unfortunately, we cannot attribute the observed vertical velocity to the atmospheric tides because its magnitude is at least 10 times greater than that expected from this phenomenon (Chapman and Lindzen 1970).

b. ESCOMPTE-01 campaign

In his comment, Worthington (2003) writes, “Nevertheless, if \bar{W} [mean vertical velocity] by UHF profiler is found to be upward above a large heat island, then spatial variability of convection is real and significant. If profiler \bar{W} remains downward above a heat island, then measured \bar{W} could be false. . . .” The opportunity to test this scenario was offered by UHF and sodar profiler observations collected recently during the June–July 2001 Field Experiment to Constrain Models of Atmospheric Pollution and Emissions Transport (ESCOMPTE-01) campaign.

The domain of this experiment, centered on Marseille, France (43.31°N, 5.39°E) (population about 1 000 000), extended along the Mediterranean coast within a strong industrial region with many sources of pollutants. Investigation of pollution transport, diffusion, and production was the scientific objective of the campaign. A UHF profiler was operated in the center of the town at about 1 km from the coast. Westward and 30 km away from Marseille, another UHF profiler was installed in Saint-Chamas, near the Mediterranean Sea in a rural area (43.53°N, 5.07°E). These profilers are identical to the ones described in L2002. In particular, every 5 min they provide a vertical profile with a 75-m height resolution based on a 30-min-duration consensus. At Saint-Chamas a Doppler sodar, collocated with the UHF profiler, provided 20-min-averaged vertical profiles of the wind with a 50-m range resolution, from 50 m up to about 600 m above ground level. These three instruments provide the support for the following analysis.

During fair-weather days, usually related to a high pressure system on the synoptic scale, a land–sea-breeze circulation prevails. Profiler observations collected during 7 days in June 2001 with a well-established breeze were selected. Vertical profiles and time series averaged over this period are presented in Figs. 2–4. On a 100-km scale, the coast has roughly a west–east orientation, which gives during the daytime a southwesterly sea-breeze wind and during the nighttime a northeasterly land-breeze flow. This daily circulation is clearly apparent at a 150-m altitude on the Saint-Chamas sodar wind direction and wind speed averaged times series presented in Figs. 2a and 2b, respectively. According to these figures sea-breeze circulation begins at about 0900 UTC and peaks at about 1500 UTC. After 1700 UTC, wind intensity decreases and the flow begins to rotate southward progressively. At 2300 UTC a weak

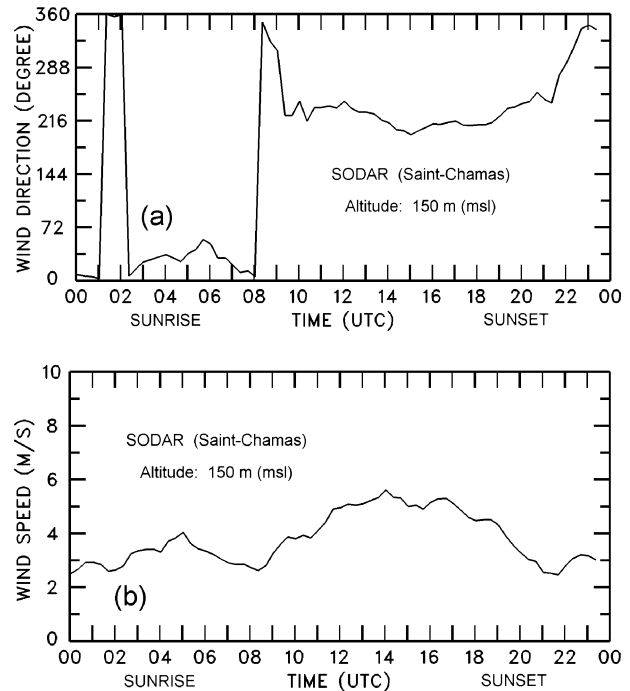


FIG. 2. Mean time series averaged over 7 days of sea–land-breeze circulation of (a) wind direction and (b) wind speed at 150-m altitude. These observations were obtained in Jun 2001, during the ESCOMPTE-01 campaign, by the sodar located on the rural coastal site of Saint-Chamas, France. A running average over 3600 s was also applied.

northerly land breeze is established. A similar (not shown) wind evolution is observed by the Marseille UHF profiler.

Owing to this mesoscale circulation and to the presence at a few tens of kilometers to the north of the experiment domain of a hilly terrain related to the Alps foothills, a null vertical velocity on average is not expected. For this reason sodar observations are used as reference for UHF data. For the data interpretation, we have also presented in Figs. 3b and 4c the dissipation rate of turbulent kinetic energy ε derived from the UHF Doppler spectral width measurement. The details of this technique and its assessment versus in situ aircraft data are described in Jacoby-Koaly et al. (2002).

Figures 3a and 3b present mean vertical velocity and mean ε vertical profiles, respectively, averaged over the selected breeze days restricted to the 0800–1600 UTC period of the sea-breeze flow. Figure 3b shows clearly that in the lower layer above the urban site the turbulence is stronger than above the rural area. Both ε vertical profiles tend to converge above 800-m height, which corresponds to the maximum depth of the atmospheric boundary layer during breeze days.

Vertical profiles of averaged vertical velocity displayed in Fig. 3a are rather simple to explain. Above the rural site there is, as usual, a persistent UHF downdraft, whereas a mainly persistent UHF updraft is ob-

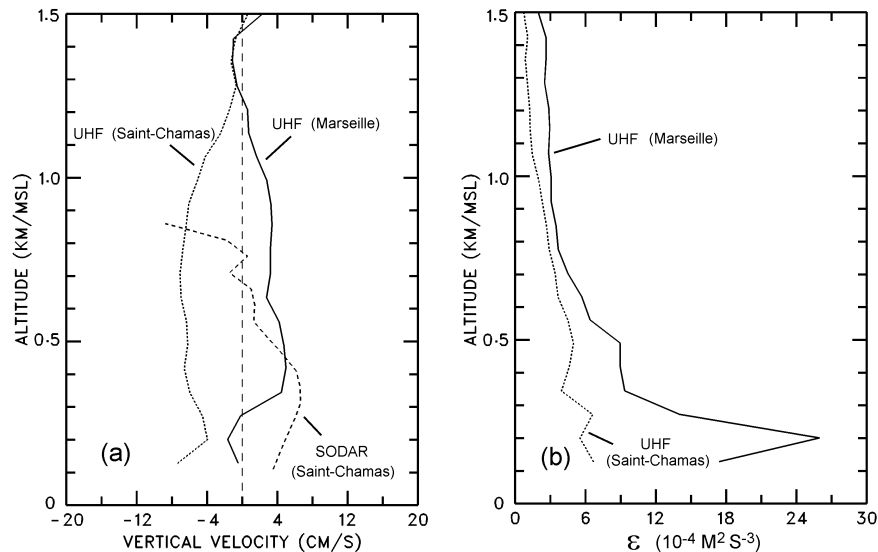


FIG. 3. Mean vertical profiles averaged over 7 days of sea-land-breeze circulation restricted to 0800–1600 UTC. These observations were obtained in Jun 2001 during the ESCOMPTE-01 campaign, by the sodar and the UHF wind profiler located on the rural coastal site of Saint-Chamas, and by the UHF sited in the coastal city of Marseille. (a) Mean vertical velocity profiles provided by these three profilers. (b) Dissipation rate of turbulent kinetic energy ϵ deduced from the observations of the two UHF wind profilers.

served above the city. The negative vertical velocity below 300 m of the Marseille profile has to be considered with caution because of a possible effect of clutter echoes. However, this layer is associated with strong turbulence (Fig. 3b), and we will see below the importance of turbulence intensity in the understanding of the vertical velocity bias. This description tends to prove Worthington's (2003) conjecture right. Unfortunately, things are not so simple, and we cannot conclude because a negative bias may be present, the consequence of which is an underestimate of the true updraft magnitude above Marseille. On the other hand, one can see that sodar data (Fig. 3a) indicate ascents over the rural site, in contradiction to UHF observation.

To go further into the discussion, Fig. 4 presents mean daily time series of vertical velocity and ϵ averaged over the 7 breeze days and over the 300–600-m altitude interval. The lower bound ensures that UHF measurements are not contaminated with clutter echoes, and the upper bound corresponds to the sodar mean maximum altitude coverage. During the nighttime, between 2000 and 0400 UTC, Marseille UHF data are not plotted because there were perturbed by strong interference.

Figure 4a shows that the convection plume above Marseille, as seen by the UHF profiler, lasted about 4 h, between 1200 and 1600 UTC, with a maximum of 22 cm s^{-1} at 1400 UTC. Averaged UHF ϵ time series plotted in Fig. 4c confirm the weaker turbulence intensity above the rural site compared to the urban area with about a factor of 3 for the ratio of the maximum values. They show also an offset in the turbulence development between these two sites. At Saint-Chamas the turbulence

peaked at 0900 UTC and above Marseille at about 1300 UTC. This offset might be explained by the different thermal inertia between a bare soil and urbanized terrain.

The most instructive information for the UHF bias issue is gained in Fig. 4b, in which sodar and UHF averaged time series acquired above the rural site are presented. During the sea-breeze circulation between 0900 and 1600 UTC, sodar vertical velocity presents a series of mainly positive oscillations, whereas mainly negative oscillations affect UHF vertical velocity. The largest discrepancy between both series occurs during the 0900–1000 UTC period, corresponding to UHF ϵ maximum values (Fig. 4c). From 1200 until 1700 UTC both curves oscillate in phase and converge progressively with time. According to Fig. 4c, this period corresponds to a rapid decrease of turbulent intensity. Between 1700 and 0000 UTC, ϵ has acquired negligible values, and UHF and sodar vertical velocity are nearly superposed. Finally, negligible to weak ϵ intensity between 0000 and 0800 UTC corresponds also to very close vertical velocity values for both instruments.

This last result indicates a strong link between turbulence intensity, quantified here with the dissipation rate of turbulent kinetic energy, and the difference between UHF and sodar vertical velocity measurements. This is not a surprise since turbulent mixing is the main source of UHF and sodar echoes from which Doppler velocity is derived.

3. Conclusions and perspective

All the preceding independent analyses give significant weight to an instrumental bias source hypothesis

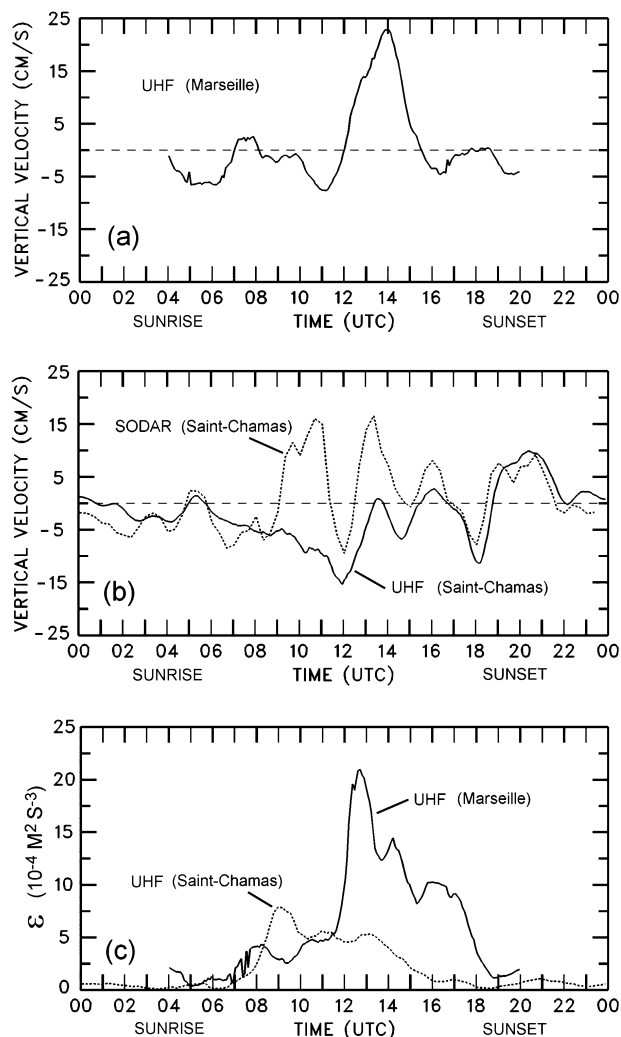


FIG. 4. Mean time series averaged over 7 days of sea-land-breeze circulation and over the height interval 0.3–0.6 km obtained in Jun 2001 during the ESCOMPTE-01 campaign. Vertical velocity time series of (a) the UHF profiler of Marseille and (b) the sodar and UHF profiler of Saint-Chamas. (c) Dissipation rate of turbulent kinetic energy ϵ deduced from the observations of the two UHF wind profilers. A running average over 3600 s was also applied.

to explain UHF vertical velocity errors, and cannot be ignored even if they do not provide complete certitude. Moreover, we showed that the Doppler velocity bias seems related to the turbulence intensity.

Two important recent works were made in the past 3 years for a theoretical understanding of the possible instrumental bias of the Doppler velocity measurement in a turbulent medium. Muschinski et al. (1999) were able to simulate at the Bragg wavelength scale the back-scattered radar signal in a large-eddy simulation of a turbulent atmospheric boundary layer. They found a vertical velocity bias amounting to several tens of centimeters per second for 1-s simulated signal radar time series. This bias, called third-order bias by Tartarskii and Muschinski (2001), is explained by these latter au-

thors by the presence of refractive index irregularities at length scales smaller than the size of the radar resolution volume and larger than the Bragg wavelength. However, only a persistence in time of these irregularities can be conducted after temporal averaging to a measured bias. Owing to the atmosphere homogeneity assumption on average, Muschinski et al. (1999) conclude that the simulation does not provide evidence of an instrumental origin of the downward bias.

As a consequence, Tartarskii and Muschinski (2001) revisited the standard theoretical knowledge on wave scattering in a turbulent environment (Tartarskii 1961). They found a second-order correcting term for the Doppler radial velocity called “correlation velocity” that might explain the bias in Doppler radial velocity measurement. This term, a function of the instrument wavelength, is related to the correlation between velocity fluctuations and air refractive index fluctuations. In a stable atmosphere it is proportional to the vertical velocity standard deviation, and therefore to the turbulence intensity, which can explain the observations presented in the preceding section. Because a monostatic sodar is only sensitive to temperature fluctuations and UHF radar mainly to humidity fluctuations in the lower atmosphere, they can get differing velocity biases. In particular, this can explain the vertical velocity discrepancy between both instruments observed in Fig. 4b during daytime.

We now have a theoretical framework that has to be tested with experimental observations in different atmospheric conditions. With turbulence measurements collected in the marine boundary layer, Tartarskii and Muschinski (2001) found, for the correlation-velocity term at UHF band, a value on the order of centimeters per second. We are far from the tens of centimeters per second of the reported UHF bias, but this is only one example of comparison with the theory made in a particular boundary layer. Consequently, the third-order bias term has to be more thoroughly investigated theoretically. Since it is related to atmospheric inhomogeneity and anisotropy (it can be related to the presence of coherent structures), the problem of radar temporal and spatial sampling pointed out by Worthington (2003), but also discussed by L2002, Angevine (1997), and others, needs to be further clarified, like the other instrumental bias sources given by Worthington (a list that is certainly not exhaustive).

In his comment, Worthington (2003) suggests that meteorological phenomena might be at the origin of the UHF vertical velocity bias. In particular, a descending branch of the convection associated with heat islands generated by cities surrounding the UHF profiler site. We were not able to refute or confirm this relevant conjecture, which is an original contribution to this issue. It is also a relevant issue for the urban pollutant transport investigation. However, the search for a geophysical source for the vertical bias has to accommodate observed mean UHF downward motion of -10 to -30

cm s^{-1} lasting for several hours, with our present knowledge of the convective homogeneous ABL, based on several decades of experimental and theoretical works, in which vertical transports are made by turbulent fluxes.

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