Vertical wind radar measurements at high temporal and spatial resolution in clear air conditions

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ABSTRACT

During day time, part of the solar radiation is absorbed by the Earth surface, converted into IR radiation and radiated back into the atmosphere. A fraction of this IR energy is directly used to warm up the air just above the ground. This radiative process is even more efficient during clear air days and can be responsible for the formation of vertical air parcel uplift. Such thermals play an important role in the thermodynamic processes within the boundary layer. Consequently, there is a need for their observations. There are different ways to monitor the vertical motion of the air from remote-sensing instruments. The Doppler lidar (μm-wavelength) observes the vertical wind by measuring the velocity of aerosols (nm-μm) often present within the boundary layer. The Doppler radar, of which the wavelength (cm) is much larger, cannot detect such small particles. Other scattering mechanisms are measured instead.

Vertical air motion induces changes in temperature and humidity, which produces a change in refractivity index. Long wavelength radars (≥ 10 cm) can detect these refractivity index irregularities. The latter produces echoes. Because these irregularities are moving with the vertical wind, the Doppler frequency shift related to the echo signal can be used to calculate the vertical air motion. The 9.1 cm-wavelength Doppler TARA radar (Transportable Atmospheric RAdar) can still measure the vertical air motion with such a technique. For smaller wavelength radars, insects and seeds can be employed as tracers of the dynamic of the boundary layer. This is done as well by TARA.

This paper presents and discusses measurements of the vertical wind carried out by the TARA radar during clear air conditions within EUCAARI IMPACT campaign that took place in May 2008, in the Netherlands. The campaign covered intensive ground-based and airborne measurements in the vicinity of the CESAR observatory in Cabauw. TARA, initially designed for profiling precipitation, performs measurements with high temporal (3-18 s) and spatial resolution (3-30 m).

The principle of the radar measurement, the data processing, and the selection of spatial and time resolutions needed to estimate the vertical wind are introduced. Specific days are selected to discuss the results. Finally, comparisons with other sensors present during the campaign are performed to evaluate the performances of TARA vertical wind measurements in clear air conditions.

1. BACKGROUND

For this work, the atmosphere is assumed not saturated and the considered air parcel adiabatic. This leads to no energy exchange between the air parcel and its surrounding. Nevertheless, short time scale pressure variations happen within a bulk of atmosphere when the air parcel is encountering vertical motion (up or down), the pressure (P) being quasi-simultaneously leveled to the pressure of the new environment. Therefore, an adiabatic updraft leads to an expansion of the volume of air and a decreasing of the air pressure, resulting to a decrease of the air temperature (1 degree Kelvin per 100 m for dry air condition). These thermodynamic variables are not conserved.

Although the refractive index of the air parcel changes while the parcel moves vertically, irregularities Δn are produced when there is change relative to the surrounding environment [1]. For this reason and in order to use the mathematical formalism of the structure parameter C_p^2 of the conserved passive additive p, potential thermodynamic variables are used instead. Consequently to express the backscattered electric field measured by the radar, the potential refractive index ϕ,

$$\phi = \left(\frac{77.6}{\theta}\right)\left(P_0 + 4810\frac{P_{w0}}{\theta}\right), \qquad (1)$$

the potential temperature θ and the potential water vapor pressure P_{w0} at the reference pressure P_0 (1000 mbar), which are conserved properties of the air parcel, are used.

Finally the backscattered electric field depends not only on the potential thermodynamic variables of the atmosphere but also on the intensity of turbulence because it is related to the refractive index structure parameter C_n^2.

$$C_n^2 \approx 10^{-12} C_\phi^2 = a^2 \varepsilon^{-1/3} K_\phi 10^{-12}\left(\frac{d}{dz}\langle\phi\rangle\right)^2, \qquad (2)$$

where $\langle\phi\rangle$ is the ensemble average of the potential refractive index; K_ϕ is its coefficient of turbulent diffusion; ε is the rate at which turbulent energy per unit mass is being dissipated, and a^2 is a constant in the range from 3.2 to 4.0. Hence, radar echoes occur in case of turbulence, or presence of large gradients of potential temperature or potential water vapor pressure.

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2. MEASUREMENT AND PROCESSING

The TARA radar can be used as a wind profiler because of its capability to profile the atmosphere with 3 beams (one polarimetric and the two other ones non-polarimetric). The horizontal wind and the vertical velocity can be retrieved from the Doppler measurements of the 3 beams. An example of measured Doppler spectra is given in Fig. 1.

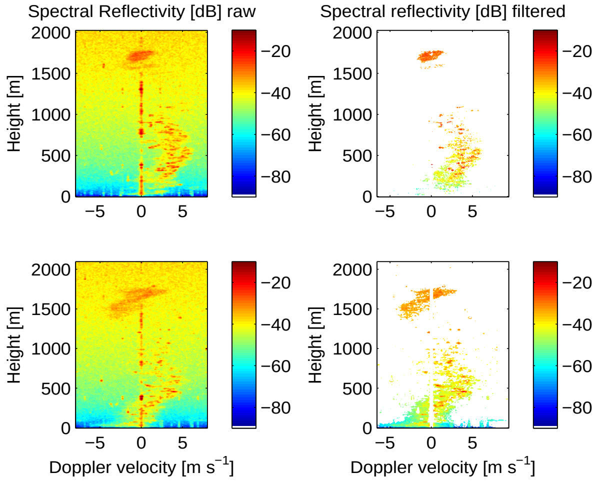

Figure 1.*Measured Doppler spectra for each height. The top panel represents the polarimetric beam at 75 deg elevation and the bottom panel the vertical beam. The right column shows the filtered Doppler spectra.*

The raw data show a clear echo area at heights 1400-1800 m which corresponds to the top of the boundary layer (temperature inversion). Where there is a marked decrease of P_{w0} accompanied by an increase in θ (eqs. 1-2), the echo can be relatively large even if turbulence is weak. Between 200 and 1000 m, there are broken Doppler spectra (spotted area at 2-4 m s^{-1}) related to refractive index irregularities with probably a superposition of debris, insects and seeds echoes transported in the thermal (spots). This interpretation is strengthened by the histograms of the polarimetric parameter Z_{dr} (difference in decibels between the horizontally- and vertically- polarized radar echo) in Fig. 2. This parameter is a shape indicator of hydrometeors and targets. Furthermore, a band of ground clutter (non-atmospheric echoes) is present around 0 m s^{-1} and the data below 200 m are generally not used because of near-field radar effects. The clutter band is removed by discarding Doppler spectra data between -0.2 and +0.2 m s^{-1} for the non-polarimetric vertical beam (notch filter). A polarimetric adaptive filter [2] removes data severely contaminated by non-atmospheric echoes in any Doppler velocity bin in the case of the polarimetric beam. This has the advantage to preserve atmospheric echoes between -0.2 and +0.2 m s^{-1}. Because the radar noise level increases with height, it is then more difficult to measure updrafts/downdrafts in the upper part of the mixed layer (Fig. 1 and Fig. 4).

From the filtered Doppler spectra, the mean Doppler velocity is calculated for every height, leading to one profile (see Fig. 3) with the time resolution 3 s. A time series of these profiles is given in Fig. 4. Fig. 4 (upper plot) exhibits noisy atmospheric data with still some erroneous data, which were not filtered out. The boundary layer is building up from 750 m (7:00) until 2000 m (16:00). Below the top of the boundary layer, there are updrafts and downdrafts. When data are near the radar noise level, the result of the processing can be scarce points, which cannot form a profile (9:00-11:00). Fig. 3 shows individual profiles (blue curves) with significant statistical variations. The first reason is the weakness of the echoes (near the radar noise level). The second reason is the presence of debris, insects and seeds, which biases the mean vertical velocity in the updraft/downdraft zones.

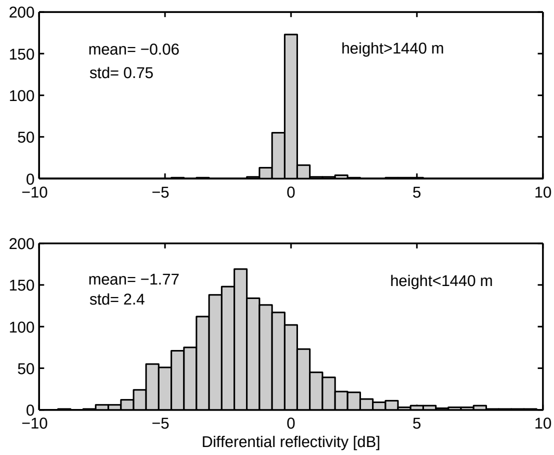

Figure 2. *Histograms of Z_{dr} . The upper histogram is typical for Δn irregularities echoes. No differences are expected whether the polarization horizontal or vertical is used for the electric field. The second histogram clearly differs from the upper one, which indicates the presence of small objects (different shapes) carried away by the vertical air motion.*

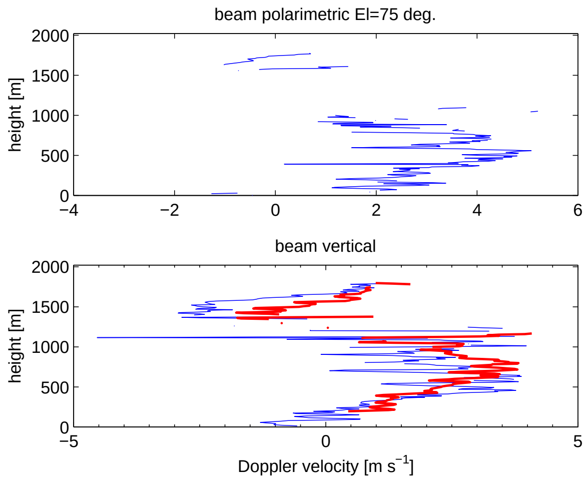

Figure 3.*Profiles of mean Doppler velocity. The blue curves correspond to the time resolution 3 s and the red curve shows the postprocessing result (time resolution 18 s).*

Postprocessing is thus necessary, to discard outliers (velocities larger in magnitude than 5 m s^{-1}) and the first 200 m, to reduce statistical fluctuations and to form pieces of profiles (time averaging and vertical smoothing). The resulting profiles can be seen in Fig. 4 (lower plot) and the time resolution has been reduced to 18 s.

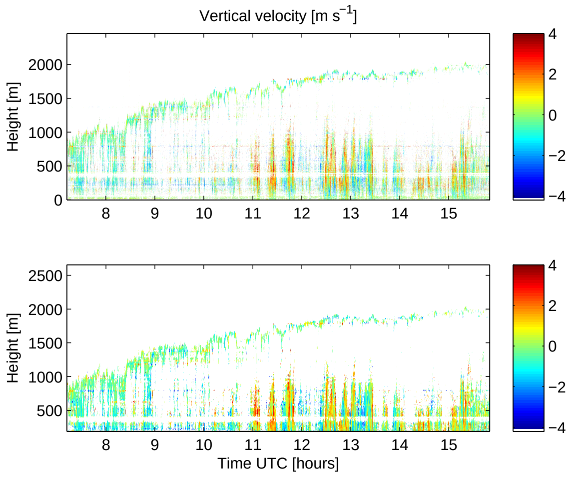

Figure 4. *Profiles of mean vertical Doppler velocity, i.e., vertical wind, (20 May 2008). The height resolution is 7.2 m. The upper plot consists of the initial profiles with the time resolution 3 s. The lower plot represents the postprocessed profiles with the time resolution 18 s.*

3. RESOLUTION AND ACCURACY

A decrease to 18 s resolution keeps all the details of updrafts and downdrafts and reduces the statistical variations. This can be seen in Fig. 5, which shows a zoom into a time series of updrafts and downdrafts. The statistical variations of the vertical wind profiles decrease with the resolution. But this may result in loosing the fine details of the thermals (before 11:00 see the small downdraft between two updrafts which are going to meet up at higher altitude). The height resolution of 7.2 m allows thermals profiling as well as a piece of profile at the top of the boundary layer.

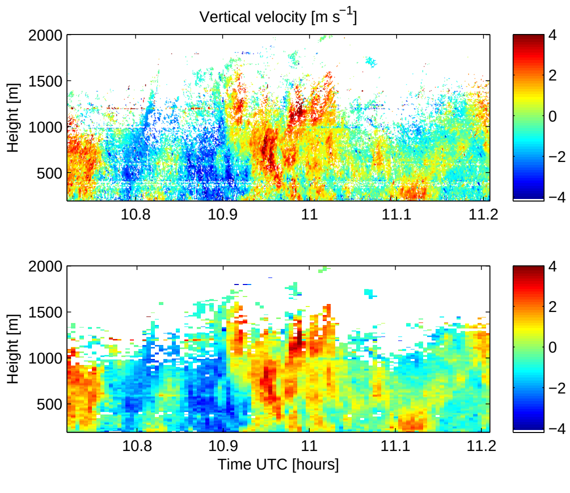

Figure 5. *Comparison of the vertical wind (22 May 2008) obtained with the time resolution 3 s (upper plot) and 18 s (bottom plot). The height resolution is 7.2 m.*

As a first estimate of the vertical wind accuracy, the standard deviation of the histogram of updrafts or downdrafts (the largest one) is calculated. For May the 20th, the estimate of the accuracy is 0.8 m s^{-1} (Fig. 6). This estimate varies between 0.6 and 0.8 m s^{-1} during IMPACT campaign. There is a negative bias on the vertical velocity, generally negligible compared to the given accuracy estimate and which varies from -0.05 to -0.27 m s^{-1}. The values lower than -0.2 m s^{-1} can be explained by the presence of isolated drizzle profiles.

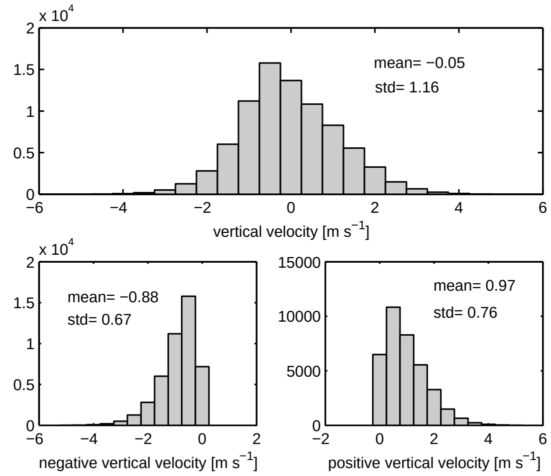

Figure 6. *Histograms of vertical wind (top panel), downdrafts (bottom left panel) and updrafts (bottom right panel). This is done from the 9 hours time series of May 20th.*

4. COMPARISON WITH OTHER SENSORS

It is the first time that TARA measurements of vertical wind in clear air conditions are examined. Already present on the Cabauw atmospheric site, are the KNMI tower-mounted sonic anenometers (3, 60, 100 and 180 m height), which provide data in the surface layer and the KNMI radar wind profiler (LAP3000), which can provide vertical wind profiles every 6 min based on 20 s measurement with a height resolution of 100 m or 400 m, but gives hourly-averaged profiles in routine mode. TARA can complement these sensors because of its high resolution capability, both in time and height. At the end of IMPACT campaign, the Leosphere WindCube lidar carried out measurements (first deployment). The time and height resolution of the Doppler lidar were 20 s and 200 m respectively. All instruments were located less than 350 m apart from each other.

Fig. 7 gives a first comparison of the mean vertical wind measured by all these sensors. The mean vertical wind is estimated on 24 min with 300 m step in height from 22 until 24 May. During this period, TARA and WindCube did not measure continuously. There is a reasonable agreement between all the instruments. When a sensor measures an updraft, generally the other sensors do as well. But there are discrepancies in the values of the mean vertical wind.

Based on these estimates of the mean vertical wind velocity, further comparisons are made between the different sensors in Figs. 8-9 and Table 1. The distributions of mean vertical wind velocities show a wide distribution for TARA and possibly drizzle outliers for the LAP-3000 (Fig. 8). Only the data between -1.0 and 1.0 m s^{-1} are used for the scatter plots (Fig. 9) and the estimation of the root mean squared differences in mean vertical wind velocity (Table I) for all the sensors. These RMS estimates are typically 0.3 m s^{-1} when TARA is compared with another sensor and 0.2 m s^{-1} between the sensors (LAP-3000, WindCube and sonic anemometer).

5. CONCLUSIONS

This first comparison of mean vertical wind estimates obtained from different sensors, which is based on three days, shows a mean deviation of 0.2 m s^{-1} excluding the TARA radar. This is a good result. Comparing with TARA leads to a mean deviation of 0.3 m s^{-1}. This is still a good result. However the following question arises: is it possible to improve the TARA measurement of vertical wind in clear air conditions? For this specific measurement, the polarimetric beam should be used. The main advantage is then the applicability of a spectral polarimetric technique for clutter suppression. In that case, atmospheric data in the Doppler spectrum between -0.2 and 0.2 m s^{-1} remain. Estimates of small velocities become possible and non-atmospheric echoes are better reduced. Nevertheless the statistical variation of the profiles, which is beam independent, is large. There are two reasons for this: the Doppler spectra can be near the noise level and a superposition of two echoes: refractive index gradients and objects transported in the up- and downdrafts, which are then not fully suppressed by the spectral polarimetric filter. It would be interesting to carry out another evaluation of TARA vertical wind measured with the polarimetric beam.

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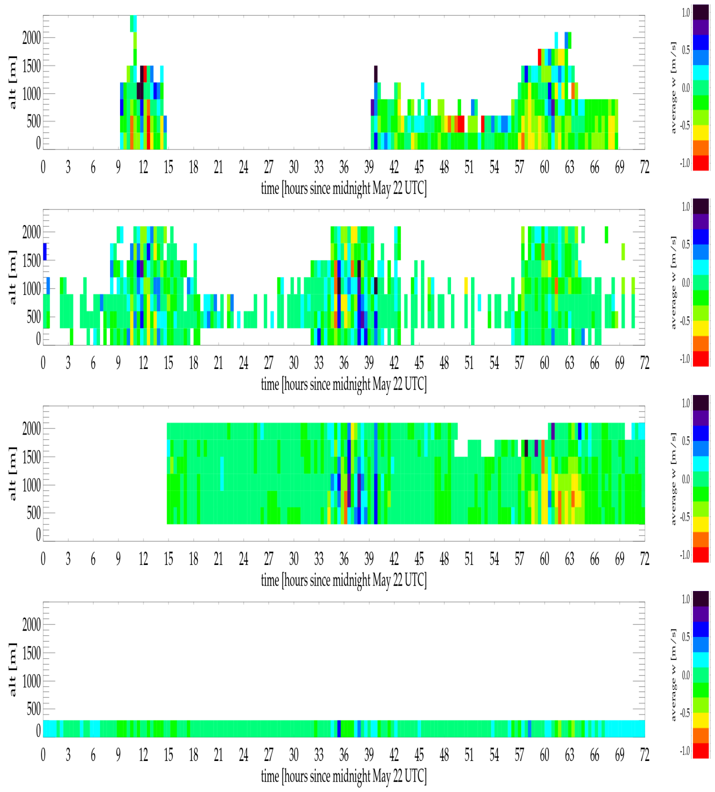

Figure 7 *Mean vertical wind measured by TARA and LAP-3000 radars, WindCube lidar and the sonic anemometer (180 m), from top to bottom. Data are plotted as function of height and time. Color scales represent values of the parameter between -1.0 and 1.0 m s^{-1}, calculated from 24 minutes by 300 m data subsets.*

Table I. Mean vertical wind velocity RMS.

RMS (M S^{-1})	LAP-3000	WIND CUBE	TOWER SONIC ANEMOMETER
TARA	0.33	0.35	0.36
LAP-3000		0.24	0.25
WindCube			0.22

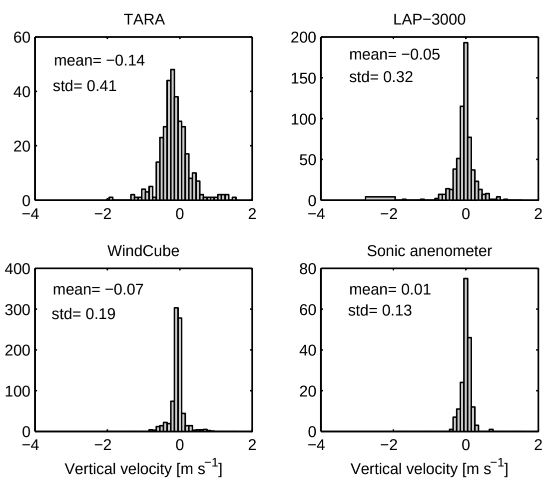

Figure 8 *Mean vertical wind velocity distributions.*

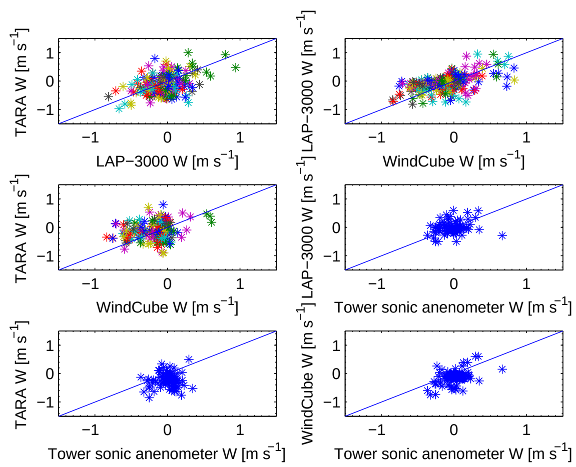

Figure 9 *Scatter plots of the mean vertical wind.*