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Synergy between wind profilers and multifrequency microwave radiometers for tropospheric humidity profiling

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Abstract. An algorithm to compute atmospheric humidity high-resolution profiles by synergetic use of Microwave Radiometer Profiler (MWRP) and Wind Profiler Radar (WPR) is illustrated. The focal point of the proposed technique is based on the processing of WPR data for estimating the potential refractivity gradient profiles and their optimal combination with MWRP estimates of potential temperature profiles in order to fully retrieve humidity gradient profiles. The combined algorithm makes use of recent developments in WPR signal processing, computing the zero-th, first, and second order moments of WPR Doppler spectra via a fuzzy logic method, which provides quality control of radar data in the spectral domain. On the other hand, the application of neural network to brightness temperatures, measured by a multichannel MWRP, can provide continuous estimates of tropospheric temperature and humidity profiles. Performance of the combined algorithm in retrieving humidity profiles is compared with simultaneous in situ radiosonde observations (RAOB). The empirical sets of WPR and MWRP data were collected at the Atmospheric Radiation Measurement (ARM) Program's Southern Great Plains (SGP) site. Combined microwave radiometer and wind profiler measurements show encouraging results and significantly improve the spatial vertical resolution of atmospheric humidity profiles. Finally, some of the limitations found in the use of this technique and possible future improvements are also discussed.

1 Introduction

The role of ground-based remote sensors in boundary layer research is nowadays well established due to the ability of remote sensors to monitor important meteorological parameters continuously in height and time (Strauch et al., 1984). Monitoring of humidity profiles in the lower troposphere has been one of the main goals of recent meteorological research due to its importance for atmospheric dynamics and microphysics. To this aim both passive and active remote sensing techniques have been proposed and successfully applied (Gossard et al., 1982; Stankov et al., 1996; Solheim et al., 1998; MacDonald et al., 2002; Stankov et al., 2003; Ware et al., 2003).

A major focus of current remote sensing research is to evaluate the capability of these instruments to remotely measure derived meteorological quantities when a sensor synergy is possible (Stankov, 1998). An appealing application of this concept to the retrieval of high-resolution atmospheric humidity profiles is the synergetic use of ground-based instruments only, such as either a combination of radar wind profilers and Global Position System (GPS) receivers or either a combination of radar wind profilers and microwave radiometers (Gossard et al., 1999; Bianco et al., 2003). In particular, the latter approach has significant potential due to the profiling capability of both sensors and the possibility to estimate the atmospheric state in terms of wind, humidity, temperature and cloud liquid structures. The synergy between wind profilers and microwave radiometers can exploit recent advances in their respective processing techniques. This aspect is fairly crucial when combining different sensors as the meteorological estimates are affected by the error structure of both sensors.

For what concerns the Wind Profiler Radar (WPR), most atmospheric boundary layer parameters currently obtained by Doppler remote sensing system are derived from the first three moments of the measured Doppler spectra (Gossard et al., 1982, 1998). As a matter of fact, radar signals at most sites often show contamination from other sources, which includes, and is not limited to, ground clutter, intermittent clutter, radio frequency interference, and sea clutter. For the wind, signal-processing techniques have been developed to isolate the true atmospheric signal within the measured spectra (Wilczak et al., 1995; Cornman et al., 1998; Jordan et al., 1997). To obtain accurate moments for the desired atmospheric spectral peak, it is worth using and testing an algorithm that makes use of recent developments in wind profiler

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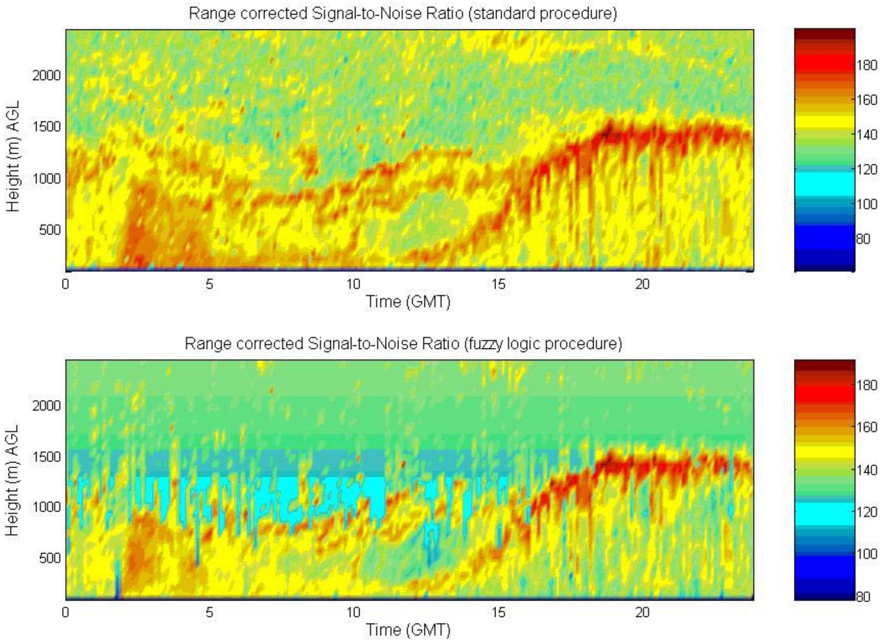
Range corrected Signal-to-Noise Ratio (standard procedure)

Range corrected Signal-to-Noise Ratio (fuzzy logic procedure)

Fig. 1. Upper panel: Time-height cross section of range-corrected SNR obtained by the standard procedure for 1 June 2002 at the ARM Southern Great Plains (SGP) site. Lower panel: Time-height cross section of range-corrected SNR obtained by fuzzy logic for the same time period.

radar signal processing, computing the zeroth, first, and second moments of wind profiler radar Doppler spectra via a fuzzy logic method (Bianco and Wilczak, 2002), which provides quality control of radar data in the spectral domain. Toward the aim of retrieving high-resolution humidity profiles in a combined sensor approach, the zeroth, first, and second moments, computed by the fuzzy logic algorithm, can be employed to compute the structure parameter of potential refractivity, the horizontal wind, and the structure parameter of vertical velocity, respectively (Stankov et al., 2003). The quantities , , and can then be properly used together to retrieve the potential refractivity gradient profiles.

Concerning the exploitation of a multi-channel Microwave Radiometer Profiler (MWRP), it is well established that MWRP can provide fairly accurate tropospheric water vapor and temperature profiles when operating in the 20–60 GHz (Westwater, 1993; Solheim and Godwin, 1998; Güldner and Spänkuch, 2001; Liljegren, 2004). Both statistical and neural-network approaches can be used to retrieve atmospheric profiles by coupling radiosonde profile archives and radiative transfer models (Schroeder and Westwater, 1991; Güldner and Spänkuch, 2001; Solheim et al., 1998). Significant improvements in radiometric retrieval accuracy and resolution can be obtained with elevation scanning or with recent developments in forward modeling (Liljegren, 2004). The calibration of MWRP is an issue to be carefully considered as well (Han and Westwater, 2000; Cimini et al., 2003). In a combined sensor perspective, microwave radiometer data can be used to estimate the potential temperature gradient profiles.

As a final step of a combined retrieval technique, profiles of potential refractivity profile, derived from WPR, and potential temperature profile, derived from MWRP, are sufficient to fully estimate humidity gradient profiles, as suggested by Stankov et al. (1996). It is worth mentioning that the advantage of such a synergetic humidity retrieval technique is to increase the vertical resolution of ground-based microwave radiometers, without loosing the high accuracy they can provide for integrated values, and to be completely independent from radiosonde observations. Simultaneous radiosonde observations can be used just as a comparison to check the improvements brought by the combined algorithm in retrieving humidity profiles.

The aim of this work is to set up a combined algorithm exploiting WPR and MWRP measurements, following the approach described above.

2 Sensors and data

The empirical sets of WPR and MWRP data were collected at the Atmospheric Radiation Measurement (ARM) Program's Southern Great Plains (SGP) site, Oklahoma, USA (latitude: 36°37′ N, longitude: 97°30′ W, altitude: 313 m ASL). The time span of simultaneous measurements covers more than one year, but in this work we focused on few case studies. Particularly, we considered days 1, 3, 6, 7, and 17 June 2002. An extensive analysis, concerning the whole data set, is also under consideration and will be a topic of future works.

The Wind Profiler Radar is a 915 MHz five-beam manufactured by Radian Corp. It operates by transmitting

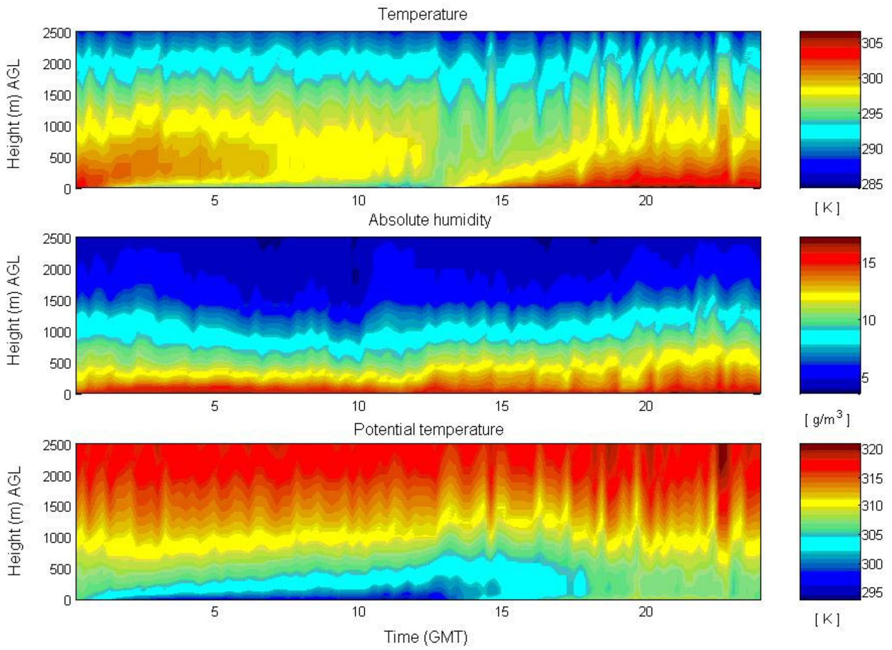

Fig. 2. Upper panel: Time-height cross section of temperature T. Central panel: Time-height cross section of absolute humidity Q. Lower panel: Time-height cross section of potential temperature θ. Profile of θ is estimated from profiles of T and P which are retrieved from MWRP measurements for 1 June 2002 at the ARM Southern Great Plains (SGP) site.

electromagnetic energy into the atmosphere and measuring the strength and frequency of backscattered energy. It consists of a single-phased microstrip antenna array consisting of nine "panels". The antenna is approx 4 m square and is oriented in a horizontal plane so the "in-phase" beam travels vertically. The used mode sampled the boundary layer from 90 m to 2500 m height in the vertical, using only a 60 m resolution. A fuzzy logic is used to compute the first three moments of the radar Doppler spectrum (details can be found in Bianco and Wilczak, 2002).

As an example in Fig. 1 we show the time-height cross section of range corrected SNR obtained by the 915 MHz radar for one of the days under observation (1 June 2002). The upper panel shows the results for the time-height cross section of range corrected SNR obtained by the standard procedure which performs the atmospheric peak detection using the method of Strauch et al. (1984), in which no fuzzy logic is involved, while the lower panel shows the results obtained by the second procedure that uses the post processing fuzzy logic algorithm.

The multichannel microwave profiler is a frequency synthesized radiometer (Solheim and Godwin, 1998), manufactured by Radiometrics (TP/WVP-3000). It observes atmospheric brightness temperature (Tb) at twelve frequencies in a region of the microwave spectrum that is dominated by emission of atmospheric water vapour, cloud liquid water, and molecular oxygen. By observing radiated power at selected frequencies in this region, the temperature, water vapour and cloud liquid profile can be estimated (Ware et al., 2003). Observation frequencies (22.035, 22.235, 23.835, 26.235, 30.00, 51.25, 52.28, 53.85, 54.94, 56.66, 57.29, 58.80 GHz) were chosen through eigenvalue analysis to optimize profile retrieval accuracy (Solheim et al., 1998).

For one of the days under observation (1 June 2002), the time-height cross section of temperature T (K) (top panel), absolute humidity Q (g Kg^{-1}) (central panel), retrieved by the MWRP, are presented in Fig. 2. We also show the time-height cross section of potential temperature θ (K) (lower panel) as derived from the MWRP observations. We show only the first 2500 m in order to match the WPR vertical range and thus compare with Fig. 1.

3 Synergy between radar wind profiler and radiometer

The theory used for the retrieval of humidity profiles is well explained in Stankov et al. (2003) and will be briefly recalled here. Following Gossard et al. (1995), we define potential refractivity ϕ as:

$$\phi = \frac{77.6 p_r}{\theta}\left(1 + \frac{7.73 Q}{\theta}\right) \tag{1a}$$

where Q is the specific humidity in g/Kg, and

$$\theta = T\left(p_r/p\right)^{0.286} \tag{1b}$$

is the potential temperature, and p_r is the reference pressure. The linearized equation for small perturbations of ϕ is (Gossard et al., 1995):

$$d\phi = \frac{\partial\phi}{\partial\theta}d\theta + \frac{\partial\phi}{\partial Q}dQ \tag{2}$$

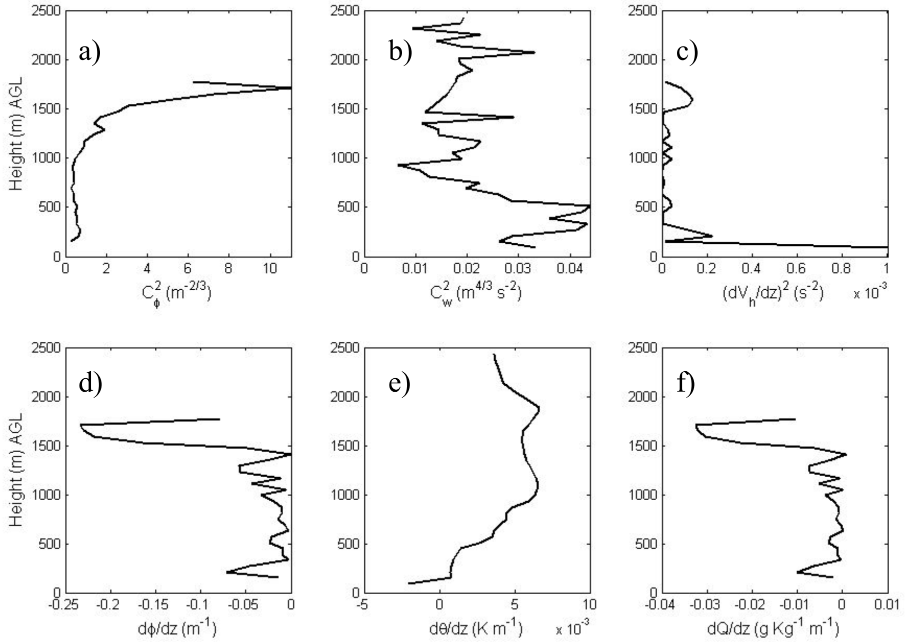

Fig. 3. Day 7 June 2002, 23:30. Upper panel: hourly radar-obtained vertical profiles for: (a) C^2_ϕ, (b) C^2_w, and (c) $(dV_h/\mathrm{dz})^2$. Lower panel: (d) hourly radar-obtained vertical profiles for *dϕ/dz*, (e) *dθ/dz* obtained from microwave radiometer measurements, (f) retrieved humidity gradient profiles *dQ/dz* obtained from the combination of *dϕ/dz* and *dθ/dz* with the use of Eq. (4).

where:

$$\begin{aligned} \frac{\partial\phi}{\partial\theta} &= -\frac{77.6p_r}{\theta^2}\left(1+15.46\frac{Q}{\theta}\right) \equiv -a_0, \\ \frac{\partial\phi}{\partial Q} &= 77.6p_r\left(\frac{7.73}{\theta^2}\right) \equiv b_0. \end{aligned} \tag{3}$$

In this work a_0 and b_0 are estimated from vertical profiles of Q and θ as respectively measured and retrieved by the MWRP. Their values are found to be constant, as already predicted by Gossard et al. (1982) within the vertical range of interest, and particularly a_0=1 and b_0=6, for this data set. From Eq. (2):

$$\frac{dQ}{dz} = (b_0)^{-1}\left[\frac{d\phi}{dz} + a_0\frac{d\theta}{dz}\right] \tag{4}$$

which gives the vertical profile of humidity gradient as a function of vertical profiles of potential refractivity and potential temperature gradients. By integrating the vertical profile of *dQ/dz* we can therefore compute the vertical profile of Q. In our approach we constrain the value of Q at the first level of the profile to be equal to the MWRP retrieval at the same level. Moreover, the profile of Q is scaled in order to match the MWRP water vapor content, integrated up to the maximum height reached by the WPR measurement.

Considering the given definition of the potential temperature θ, we can estimate this quantity and its vertical gradient by using the temperature profile as retrieved by the MWRP together with the measurements of surface pressure and a prediction of the atmospheric scale height. Gossard et al. (1982, 1998) found that for homogeneous isotropic turbulence in a horizontally homogeneous medium with vertical gradients of mean properties, the vertical gradient of potential refractivity is:

$$\left(\frac{d\phi}{dz}\right)^2 \approx \left(\frac{L_w}{L_\phi}\right)^{4/3}\left(\frac{dV_h}{dz}\right)^2\left(\frac{C_\phi}{C_w}\right)^2 \tag{5}$$

where V_h is the horizontal wind, C^2_ϕ is the structure parameter of potential refractivity, and C^2_w is the structure parameter of vertical velocity. Calling ε the turbulent dissipation rate, then $C^2_w = B_w\varepsilon^{2/3}$, where B_w=4/3$B$and B=2.1 is the Kolmogorov constant. L_ϕ and L_w are the outer length scales for potential refractive index and shear defined in Gossard et al. (1982).

Note that in Eq. (5) we have the squared vertical gradient of potential refractivity, which therefore cannot be resolved unambiguously. Stankov et al. (2002) determined the sign of the radar-obtained *dϕ/dz* by using radiosonde observations. In our approach we are able to compute the same quantity from Eq. (1), using microwave radiometer estimated profiles of Q and T, leaving our retrieval of vertical humidity profiles being completely independent from radiosonde measurements. Radar obtained values of *dϕ/dz* are derived combining V_w, C^2_ϕ and C^2_w, which are respectively related to the first, zero-th, and second moments calculation of the radar-derived spectra acquisitions.

The quantity V_w is obviously related to the estimation of the first moment (Doppler shift) in the spectral data. Vertical profiles of its gradient are computed using values of horizontal components collected in the consensus files by the wind profiler.

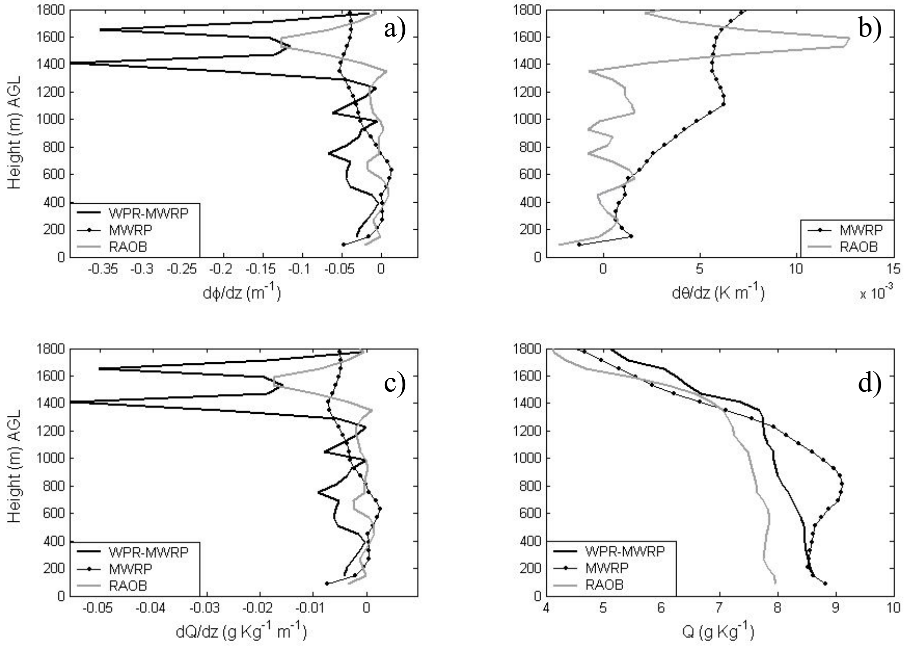

Fig. 4. Day 6 June 2002, 23:30. (a) Hourly vertical profiles for *dϕ/dz* as measured by radiosonde (solid grey line), estimated by MWRP (dotted line), and computed with the use of Eq. (5) (solid black line); (b) *dθ/dz* as measured by radiosonde (solid grey line) and estimated by MWRP (dotted line); (c) hourly vertical profiles for dQ/dz as measured by radiosonde (solid grey line), estimated by MWRP (dotted line), and computed with the combined technique (solid black line); (d) retrieved humidity vertical profiles (Q) obtained from the integration of dQ/dz in (c).

The quantity C_ϕ^2 is related to the structure parameter of refractive index C_n^2 (Gossard et al. 1982) through the relation:

$$C_\phi^2 = e^{1.428z/H} C_N^2 \tag{6}$$

where H is the scale height, $C_N^2 = C_n^2\ 10^{12}$ from definition, and $N = (n-1)10^6$ (known as radio refractivity). Therefore, C_ϕ^2 is related to the estimation of the zero-th moments of the spectral data in accordance with (Stankov et al., 2003):

$$C_n^2 = \frac{1.54 \times 10^{-13} T_0}{\alpha^2 P_t n_c A_p} \lambda^{1/3} \left(\frac{R}{\Delta R}\right)^2 \Sigma \tag{7}$$

In this equation T_0 (system noise temperature), α^2 (which accounts for the losses in the transmission line), P_t (transmitted power), n_c (the number of coherent integrations), A_p (physical antenna area), λ (radar wavelength), R (range to the target), ΔR (range resolution) are all known, and Σ is the Signal-to-Noise Ratio estimated from the spectral data.

The quantity C_w^2 is related to the second moment of the radar-obtained spectra when only the vertical beam is working. $C_w^2$is in fact related to the turbulent dissipation rate ε, which is in turn determined through the correct estimation of the broadening of the spectrum as pointed out by Gossard (1990) and White et al. (1999).

Figure 3 shows a summary of the variables used in the retrieval of humidity gradient profiles and the result of their combination using Eq. (4) for the case of 7 June 2002, 23:30.

4 Case studies

In this section we analyze some measurements collected during June 2002 at the ARM SGP site in order to validate the technique shown in Sect. 3. The data we were able to access were collected by a MWRP and a WPR, which have been introduced, together with the respective retrieval techniques. Also, radiosonde balloons were launched at the same site every 6 h.

In Fig. 4 we present results relative to the case study of 6 June 2002, 23:30 (GMT). Upper panels show profiles of vertical gradients of potential refractivity *dϕ/dz* and vertical gradients of potential temperature *dθ/dz* as measured by radiosonde (solid grey line) and estimated by MWRP (dotted line). In the upper left panel we show in addition the profile of *dϕ/dz* as computed with the use of Eq. (5) (solid black line) with the sign ambiguity solved looking at the microwave radiometer estimates of *dϕ/dz* profile. As anticipated, this approach leaves the technique being completely independent from radiosonde measurements. As expected, the vertical resolution achieved by MWRP is much lower than the one of the radiosonde for what concerns both *dϕ/dz* and *dθ/dz* profiles. Although, coupling WPR and MWRP measurements, we significantly increase the vertical resolution of *dϕ/dz*. Moreover, looking at upper panels we point out that values of *dθ/dz* are about one order of magnitude smaller than values of *dϕ/dz*, and thus of second order with respect to *dϕ/dz* in Eq. (4). In the lower left panel are shown profiles of the vertical gradient of absolute humidity (*dQ/dz*)

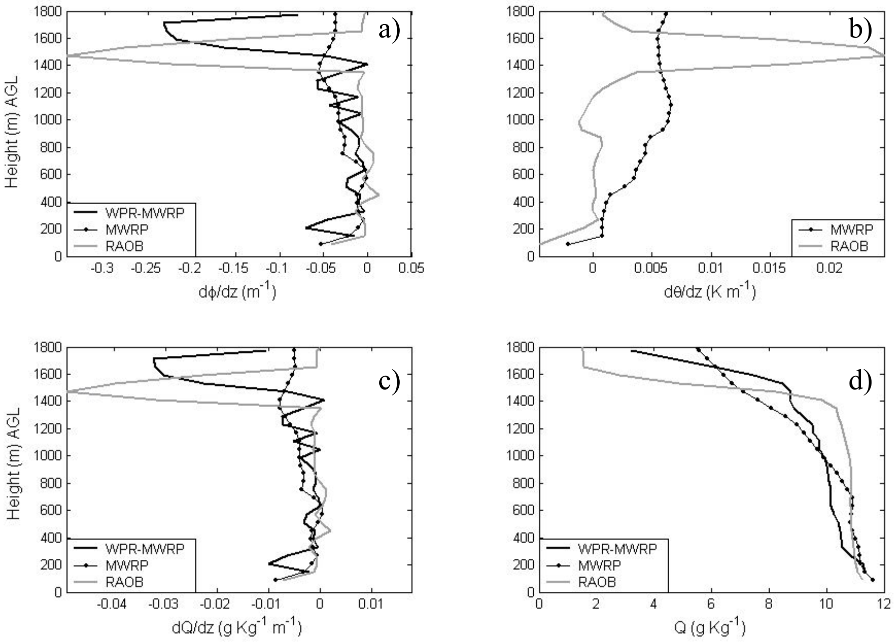

Fig. 5. As in Fig. 4, but for 7 June 2002, 23:30.

as measured by radiosonde (solid grey line), estimated by MWRP (dotted line), and obtained by the combination of *dϕ/dz* and *dθ/dz* as described in Eq. (4) (solid black line). Finally, in the lower right panel are shown profiles of absolute humidity (Q), as measured by radiosonde (solid grey line), retrieved by MWRP (dotted line) and obtained by integrating *dQ/dz* profile retrieved by the combined technique (solid black line).

Note that, as already introduced, the value of Q at the first level of the profile and its integrated value up to the maximum height reached by WPR measurements are constrained considering equivalent quantities estimated by MWRP, in order to make the most of the well established accuracy for integrated contents retrieval by microwave radiometry. The vertical profile of Q derived with the combined technique seems to correct for the artifact shown by the MWRP estimate between 600 and 1200 m (height) and to follow better the trend shown by the radiosounding. Although, difference in the radiosonde and MWRP humidity sensor measurements in the first level, leads to a bias which remains present along the entire vertical range. This bias might be related to error in the radiosonde humidity sensor. Indeed, Turner et al. (2003) analysed an ensemble of six-year ARM SGP radiosondes (1994-2000), and found differences of greater than 25% in PWV, when considering data from dual-sonde soundings. Since September 2000, the operational radiosondes deployed at ARM SGP belongs to a new generation packaging, which is supposed to increase the quality of humidity measurements (Cimini et al., 2002), although a systematic analysis is still under study.

Figure 5 presents the same plots of Fig. 4, but for the case study of 7 June 2002, 23:30. The lower right panel shows that the combined technique better catches the sharp humidity drop measured by radiosonde, although there is a vertical shift of about 100 m, as also revealed by the vertical profiles of dQ/dz in the lower left panel. However, as shown by Bianco et al. (2003), the height of the peak in the WPR-MWRP dQ/dz profile is consistent with the fact that the refractive index structure parameter C_n^2 presents a local maximum at the entrainment zone at some 1650 m (height) for the same hour. Thus, the vertical shift between the two measurements might be related to horizontal drift of the balloon rather than to a displacement of the combined technique estimate.

5 Summary and conclusions

In this paper we presented a technique for improving resolution and accuracy of atmospheric humidity profiling based on the combination of passive and active remotely sensed measurements. The method relies on the relationship between the gradients of the absolute humidity, potential refractivity, and potential temperature as described by Eq. (4) (Stankov et al., 2002). The described approach has the advantage that it is independent from in situ measurements, although we compare with radiosoundings for validation purposes. Indeed, we derive the potential refractivity gradient from Wind Profiler Radar (WPR) data, while potential temperature gradient is estimated from multichannel Microwave Radiometer Profiler (MWRP) observations.

The empirical set of data was collected during June 2002 at the Atmospheric Radiation Measurement (ARM) Program's Southern Great Plains (SGP) site in Oklahoma, USA. The WPR is a 915 MHz five-beam manufactured by Radian

Corp., while the MWRP is a 12-channel manufactured by Radiometrics. We post processed the raw measurements from the two instruments using recent developments in data analysis including fuzzy logic (Bianco and Wilczak, 2002; Cornman et al., 1998) and neural networks (Solheim et al., 1998).

We focused our attention on some case studies although an extensive analysis, concerning the whole data set, is under consideration. For cases during June 6, 7, and 17 (Figs. 4, 5, and 6) we showed that the combined technique is able to capture sharp gradients in the absolute humidity profiles, enhancing the vertical resolution of the MWRP estimates, as demonstrated by the comparison with simultaneous radiosoundings. Moreover, the absolute humidity profiles retrieved with the combined technique keep the well known accuracy of microwave radiometry for integrated water vapor content, as we used this information as a constraint. The use of WPR by itself, or in combination with a Radio Acoustic Sounding System (RASS) for potential temperature estimates, would not guarantee this advantage. Even adding a GPS receiver, it would provide the total, not the partial, integrated water content. However, an array of GPS receivers could provide humidity vertical structure by tomography, as discussed by MacDonald et al. (2002).

The proposed technique has the limit to work better during well developed convection periods, when the turbulence is well developed. This explains why case studies analyzed in this work happened all around 22:00 GMT. However, even limiting our sample to these hours, we experienced several unsatisfactory cases in which the combined technique did not outperform MWRP estimates. In a deeper analysis, not shown here, we found out that the use of vertical gradients of the horizontal wind as computed by standard consensus algorithms strongly influences the quality of the humidity profile retrieval. We think that generating consensus files from the raw moments data, as computed on the post-processed spectra, could limit this undesired aspect.

Possible improvements of the proposed technique concern both data processing and experimental setup. On the first side, we could use a statistical, rather than analytical, approach to derive the absolute humidity profile from the remote observations (Stankov, 1998). Although other investigators (Gossard et al., 1999) found a good agreement comparing the two methods, the statistical approach provides tools for making the estimate possibly more robust. On the other hand, we have to consider that the present experimental setup was not designed for this purpose, and much shrewdness could be adopt for the purpose. As pointed out by Stankov et al. (2002), the more powerful 449 MHz radar system performs better than the 915 MHz one, due to its narrower beam. Also, by increasing the number of points in the spectral domain of the WPR acquisition, we would obtain a better resolution on the vertical radial velocity computation which could improve the retrieval of the structure parameter of vertical velocity. Further improvements might come from the optimization of other settings, such as the dwell time.

In order to quantify the improvements brought by the combined technique, an extensive validation on a larger data set must be performed and is under consideration. Finally, ground-based MWRP estimates of temperature and humidity profiles could be further improved by coupling these measurements with those available from other sensors, such as satellite radiometers and ground-based Raman lidars.

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References

Bianco, L. and Wilczak, J. M.: Convective boundary layer mixing depth: Improved measurement by Doppler radar wind profiler using fuzzy logic, J. Atmos. Oceanic Technol., 19, 1745–1758, 2002.

Bianco, L., Cimini, D., Ware, R., and Marzano, F. S.: Combining microwave radiometer and wind profiler radar measurements to improve accuracy and resolution of atmospheric humidity profiling, Proc. of Int. Geosci. Remote Sens. Symp. (IGARSS03), Toulouse, France, 2003.

Cimini, D., Westwater, E. R., Han, Y., and Kehim, S. J.: Accuracy of ground-based microwave radiometer and balloon-borne measurements during the WVIOP2000 field experiment, IEEE Trans. Geosci. Rem. Sensing, 41(11), 2605–2615, 2003.

Cimini, D., Westwater, E. R., and Lesht, B.: Evaluation of the improvements in humidity sounding by balloon-borne sensors, in Proc. of the COST720 Meeting, L'Aquila, June 19–21, 2002. [Online]. Available: http://www.cost720.rl.ac.uk/, 2002.

Cohn, S. A.: Radar measurements of turbulent eddy dissipation rate in the troposphere: A comparison of techniques, J. Atmos. Oceanic Technol., 12, 85–95, 1995.

Cornman, L. B., Goodrich, R. K., Morse, C. S., and Ecklund, W. L.: A fuzzy logic method for improved moment estimation from Doppler spectra, J. Atmos. Oceanic Technol., 15, 1287–1305, 1998.

Gossard, E. E., Chadwick, R. R., Neff, W. D., and Moran, K. P.: The use of ground based Doppler radars to measure gradients, fluxes and structure parameters in elevated layers, J. Appl. Meteorol., 21, 211–226, 1982.

Gossard, E. E., Welsh, D. C., and Strauch, R. G.: Radar-measured height profiles of and turbulence dissipation rate compared with radiosonde data during October 1989 at Denver. NOAA Tech. Report ERL 442-WPL 63, Enviromental Research Laboratories, 115 pp. [Available from NOAA/ERL/ETL Broadway, Boulder, Co, 80305], 1990.

Gossard, E. E., Strauch, R. G., Stankov, B. B., and Wolfe, D. E.: Measurements of property gradients and turbulence aloft with ground-based Doppler radars. NOAA TM ERL 453-ETL 67, Enviromental Technology Laboratory, Boulder, CO, 31 pp. [Available from the National Technical Information Service, 5285 Port Royal Rd., Springfield, VA, 22161], 1995.

Gossard, E. E., Wolfe, D. E., Moran, K. E., Paulus, R. A., Anderson, D. K., and Rogers, L. T.: Measurements of clear-air gradients and turbulence properties with radar wind profilers, J. Atmos. Oceanic Technol., 15, 321–342, 1998.

Gossard, E. E., Gutman, S., Stankov, B. B., and Wolf, D. E.: Profiles of radiorefractive index and humidity derive from radar wind profilers and the Global Position System, Radio Science, 34, 371–383, 1999.

Güldner, J. and Spänkuch, D.: Remote Sensing of the Thermodynalic State of the Atmospheric Boundary Layer by Ground-Based Microwave Radiometry, J. Atmos. Oceanic Technol., 18, 925–933, 2001.

Han, Y. and Westwater, E. R.: Analysis and improvement of tipping calibration for ground-based microwave radiometers, IEEE Trans. Geosci. Remote Sensing, 38(4), 1260–1276, 2000.

Jordan, J. R., Lataitis, R. J., and Carter, D. A.: Removing ground clutter and intermittent clutter contamination from wind profiler signal using wavelet transforms, J. Atmos. Oceanic Technol., 14, 1280–1297, 1997.

Liljegren, J.: Improved retrievals of temperature and water vapor profiles with a twelve-channel radiometer, Proceedings of Eighth Symposium on Integrated Observing and Assimilation Systems fo Atmosphere, Oceans and Land Surface, American Meteorological Society, 11–15 January 2004, Seattle, Washington, 2004.

MacDonald, A., Xie, Y., and Ware, R.: Diagnosis of Three Dimensional Water Vapor Using Slant Observations from a GPS Network, Mon. Wea. Rev., 130, 386–397, 2002.

Schroeder, J. and Westwater, E. R.: User's guide to microwave radiative transfer software, NOAA Tech. Memo, ERL WPL-213, 84 pp., 1991.

Solheim, F. and Godwin, J. R.: Passive ground-based remote sensing of atmospheric temperature, water vapor, and cloud liquid water profiles by a frequency synthesized microwave radiometer, Meteorol. Zeitschrift, 7, 370–376, 1998.

Solheim, F., Godwin, J., Westwater, E., Han, Y., Keihm, S., Marsh, K., and Ware, R.: Radiometric profiling of temperature, water vapor, and liquid water using various inversion methods, Rad. Sci., 33, 393–404, 1998.

Stankov, B. B., Westwater, E. R., and Gossard, E. E.: Use of wind profiler estimates of significant moisture gradients to improve humidity profile retrivial, J. Atmos. Oceanic Technol., 13, 1285–1290, 1996.

Stankov, B. B.: Multisensor retrieval of atmospheric properties, Bull. Amer. Meteor. Soc., 79(9), 1835–1854, 1998.

Stankov, B. B., Gossard, E. E., Weber, B. L., Lataitis, R. J., White, A. B., Wolfe, D. E., and Welsh, D. C.: Humidity gradient profiles from wind profiling radars using the NOAA/ETL advanced Signal Processing System (SPS), J. Atmos. Oceanic Technol., 20, 3–22, 2003.

Strauch, R. G., Merritt, D. A., Moran, K. P., Earnshaw, K. B., and van de Kamp, D.: The Colorado wind profiling network, J. Atmos. Oceanic Technol., 1, 37–49, 1984.

Turner, D., Lesht, B., Clough, A., Liljegren, J., Revercomb, H., and Tobin, D.: Dry Bias and Variability in Vaisala RS80-H Radiosondes: The ARM Experience, J. Atmos. Oceanic Technol., 20, 117–132, 2003.

Ware, R., Solheim, F., Carpenter, R., Gueldner, J., Liljegren, J., Nehrkorn, T., and Vandenberghe, F.: A multi-channel radiometric profiler of temperature, humidity and cloud liquid, Radio Science, 38(5), 8079, 1–13, 2003.

Westwater E. R.: Ground-based microwave remote sensing of meteorological variables, in: Atmospheric remote sensing by microwave radiometry, M. A. Janssen Ed., Wiley, New York (NY, USA), 1993.

White, A. B., Lataitis, R. J., and Lawrence, R. S.: Space and time filtering of remotely sensed velocity turbulence, J. Atmos. Oceanic Technol., 16, 1967–1971, 1999.

Wilczak, J. M., Strach, R. G., Ralph, F. M., Weber, B. L., Merritt, D. A., Jordan, J. R., Wolfe, D. E., Lewis, L. K., Wuertz, D. B., Gaynor, J. E., McLaughlin, S. A., Rogers, R. R., Riddle, A. C., and Dye, T. S.: Contamination of wind profiler data by migrating birds: Characteristics of corrupted data and potential solutions, J. Atmos. Oceanic Technol., 12, 449–467, 1995.