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Article

Combining UHF radar wind profiler and microwave radiometer for the estimation of atmospheric humidity profiles

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Abstract

Capabilities of an integrated ground-based system for the operational measurement of humidity profiles, using both an UHF wind profiler and a radiometer, are discussed. The combination takes advantage of the complementary characteristics of each instrument. The radiometer is able to give a fair evaluation of smoothed humidity and temperature profiles, while the wind profiler is more suited for gradient estimations between range gates. Measurements of high-resolution humidity profiles in the combined sensor approach are based on the calculation of the refractive index gradients from the radar return signal power and signal width. Various means are then tested to combine these measurements with the radiometric data in order to deduce the most accurate humidity profile. This study is performed on 51 cases of UHF profiles during which 37 radiometric measurements were available. They have been selected on a data set collected during the international COST 720 Temperature, hUmidity and Cloud (TUC) profiling experiment held in Payerne (CH). During the experiment a LAP-3000 wind profiling radar and a Radiometrics temperature and humidity profiling radiometer operated simultaneously with Swiss radiosonde SRS 400.

Zusammenfassung

Das Leistungsvermögen eines integrierten bodengestützten Systems zur operationellen Messung von Feuchteprofilen, welches aus einem UHF Windprofiler und einem Radiometer besteht, werden diskutiert. Die Kombination nützt die komplementären Eigenschaften jedes Instruments aus. Das Radiometer ermöglicht eine ausreichende Ermittlung von geglätteten Feuchte- und Temperaturprofilen, während der Windprofiler besser geeignet ist für die Abschätzung der Gradienten zwischen den jeweiligen Entfernungsbereichen. Messungen von hochaufgelösten Feuchteprofilen basieren bei kombinierten Sensoren auf der Berechnung von Brechungsindex-Gradienten aus Radar-Rückstreusignalstärke und -signalbreite. Verschiedene Methoden zur genauest-möglichen Berechnung des Feuchteprofils aus einer Kombination dieser Messungen mit Radiometerdaten werden dann getestet. Diese Untersuchung basiert auf 51 UHF Profilen, während welchen 37 Radiometermessungen verfügbar waren. Sie wurden ausgewählt aus einem Datensatz der während des Internationalen COST 720 Temperatur-, Feuchte- und Wolken (TUC) Profiling Experiments in Payerne (CH) erhoben wurde. Während des Experiments liefen ein LAP-3000 Windprofiler und ein Radiometrics Temperatur- und Feuchteprofil-Radiometer gleichzeitig mit Schweizer Radiosonden SRS 400.

1 Introduction

Over the last 20 years many works have been addressed to show that ground-based microwave radiometers can be used to measure temperature and humidity profiles in the lower troposphere (WESTWATER, 1993; STANKOV, 1996; and CIMINI et al., 2006). However, the main weakness of this instrument is found to be in the lack of vertical resolution. Radiometers are not able to reproduce sharp hydrolapses. On the other side, wind profiling radars are very sensitive to changes in the humidity. Taking advantage of the complementary characteristics of each instrument, the idea of combining the two instruments to improve the vertical resolution of the humidity profile seems an attractive prospect, as shown by STANKOV et al. (1996). Several works showed that wind profilers can be used to measure humidity profiles (GOSSARD et al., 1999; TSUDA et al., 2001) or at least to their improvement through the use of GPS integrated water vapor (STANKOV et al., 2003) or radiometer data, in a combined sensor approach (STANKOV, 1998; BIANCO et al., 2005).

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In this paper we try to adapt the method developed by TSUDA et al. (2001) in a combined sensor approach. In Section 2 we describe and discuss the Tsuda technique. Section 3 shows how this method can practically be implemented. In Section 4 the experimental site and instrumentation are introduced. The results are presented in Section 5. The discussion of the results and the conclusions are given in the final Section.

2 The Tsuda technique

This study is based on the remote-sensing technique developed by TSUDA et al. (2001) for measuring the humidity profile directly from the wind profiler data. This technique consists in solving the humidity equation in the following form:

$$q(z) = \theta^2 \left[\int_{z0}^{z} \left(1{,}652 \frac{T^2}{P} M + \frac{T}{7800} \frac{N^2}{g} \right) \theta^{-2} dz + \frac{q_0}{\theta_0^2} \right] \tag{2.1}$$

with:

$$N^2 = g \frac{d \ln \theta}{dz} = \frac{g}{T} \left(\frac{dT}{dz} + \Gamma \right) \tag{2.2}$$

In the previous equations θ (K) is the potential temperature, T (K) the absolute temperature, P (hPa) the atmospheric pressure, M (m^{-1}) the refractive index gradient, N (s^{-1}) the Brunt-Väisälä frequency, g (ms^{-2}) the acceleration of gravity, and z (m) the altitude. q_0 and θ_0 are respectively humidity and potential temperature at the boundary height, while Γ is the dry adiabatic lapse rate (9.8 K km^{-1}).

As suggested by HOOPER et al. (2004), P/T can be approximated as $\rho_0 \exp\left(-z/\overline{H}\right)$ where ρ_0 is the mean density at sea level, and $\overline{H}$ the mean scale height which may be considered as constant. Consequently, Eq. 2.1 can be solved if only M and T profiles, ground data (ρ_0), and boundary conditions (q_0 and θ_0) are known at a given range.

In this study T is deduced from both radiometer and rawinsonde measurements available during the campaign, and M is computed from the wind profiler signals according to two main methods:

$$|M| = \frac{\lambda^{1/6} z}{\alpha L_0^{2/3}} \sqrt{\frac{P_r}{P_t A_e \Delta z \alpha'}} \tag{2.3}$$

(VANZANDT et al., 1978; GAGE and BASLEY, 1980).

Where λ (m) is the radar wavelength, P_r (W) is the radar return signal power, α is a radar efficiency factor, L_0 (m) is the outer length scale of the turbulent spectrum, P_t(W) is the peak transmitter power, A_e (m^2) is the effective area of the antenna, Δz (m) is the altitude interval, and α' is a ratio of eddy diffusion coefficients for potential refractive index and heat which can be estimated as unity. More simply, this equation can be written as:

$$|M| \propto K z \sqrt{P_r} \tag{2.4}$$

$$|M| = \varepsilon^{-1/3} F^{1/2} \eta^{1/2} N \tag{2.5}$$

(TSUDA et al., 2001). Where (HOCKING, 1985):

$$\varepsilon \approx 0{,}5 N \sigma^2 \tag{2.6}$$

ε (m^2 s^{-3}) is the turbulence dissipation rate provided by σ (the width of the turbulence echo on the Doppler spectrum, in ms^{-1}), F is the filling factor of turbulence layers assumed constant (around 0.1 to 0.2), and η (m^{-1}) is the radar volume reflectivity deduced from the turbulence echo power.

In the same way as above, this equation can be simplified as follows:

$$|M| \propto K' \sigma^{-2/3} N^{2/3} z \sqrt{P_r} \tag{2.7}$$

The difference between the above described methods is the explicit use of the signal width $\sigma^{-2/3}$ and the static stability $N^{2/3}$.

3 Practical implementation

Several steps are necessary for an accurate resolution of the humidity equation (Eq. 2.1). Figs. 1 and 2 illustrate the block diagrams of the first and second method respectively. As indicated by the initial boxes in Figs. 1 and 2, both methods require 3 data inputs beside the wind profiler measurements:

First, we need to measure the temperature profile. In the absence of a VHF+RASS capability to reach at least 6 km height on an operational basis (FURUMOTO et al., 2003; KLAUS et al., 2002), we decided to use either the rawisonde or the radiometer data according to the experimental set-up described in Sections 5.2 to 5.4.

Another parameter is the air density at the surface, which allows an estimation of the pressure at various range gates according to the already available temperature profile. We can then easily deduce the potential temperature needed to solve the humidity integration equation.

Finally, an integrated humidity value is necessary to adjust the humidity integral equation. This parameter was extracted either from radiometric (Sections 5.2 and 5.3) or from rawinsonde measurements (Section 5.4).

In both methods, the correct estimation of the signal power return P_r needs a good calibration of the profiler, which is not always available. Consequently, empirical values of K and K' in Eq. (2.4) and (2.7) respectively

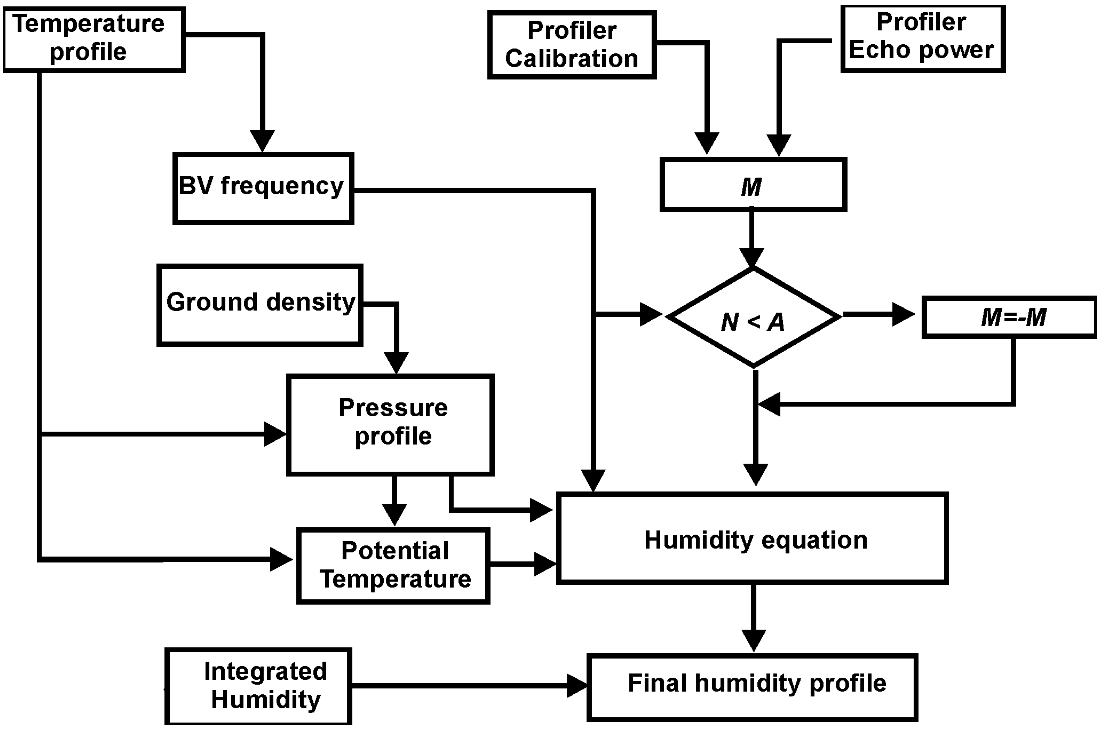

Figure 1: Block diagram of the first method for evaluating the q profile with the wind profiler data.

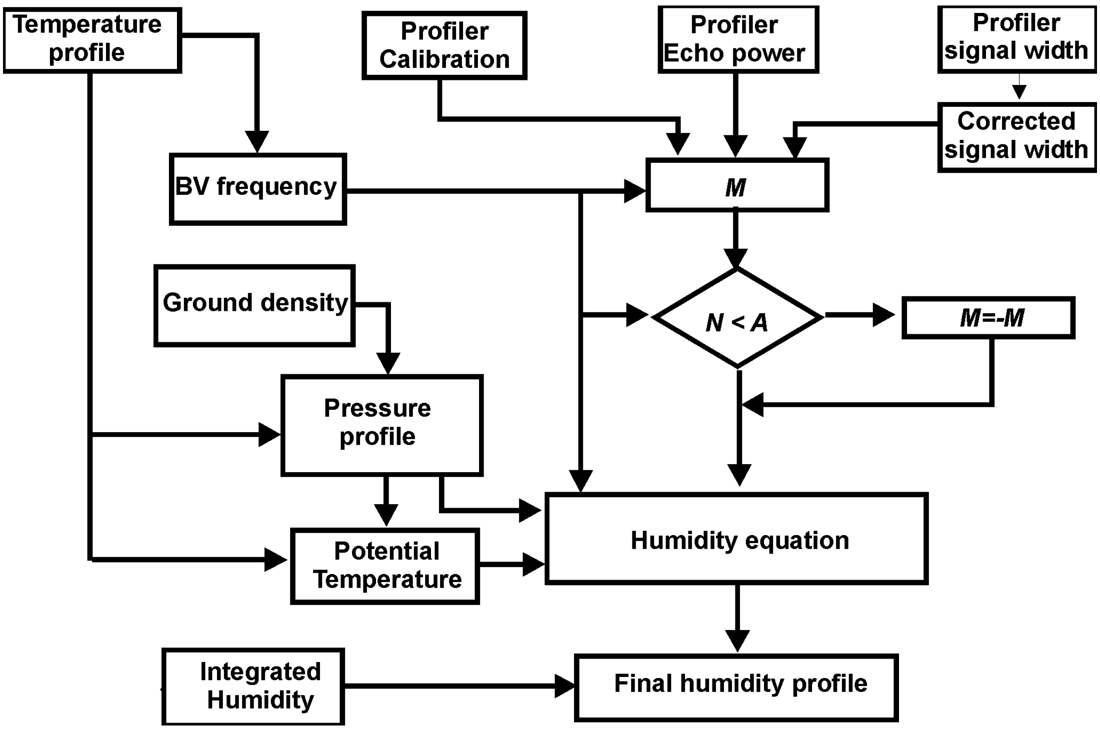

Figure 2: Block diagram of the second method for evaluating the q profile with the wind profiler data.

were calculated. In Sections 5.2 and 5.3 they were estimated for each profile to fit the radiometric values using the mean square method. In Section 5.4, unique constants K and K' were used for the whole experiment. They were deduced from a match with M profile calculated from a rawisonde, specially selected to display important variations with altitude to facilitate a more accurate calibration.

For the second method, as described for example by JACOBY-KOALY et al. (2002), the σ values provided

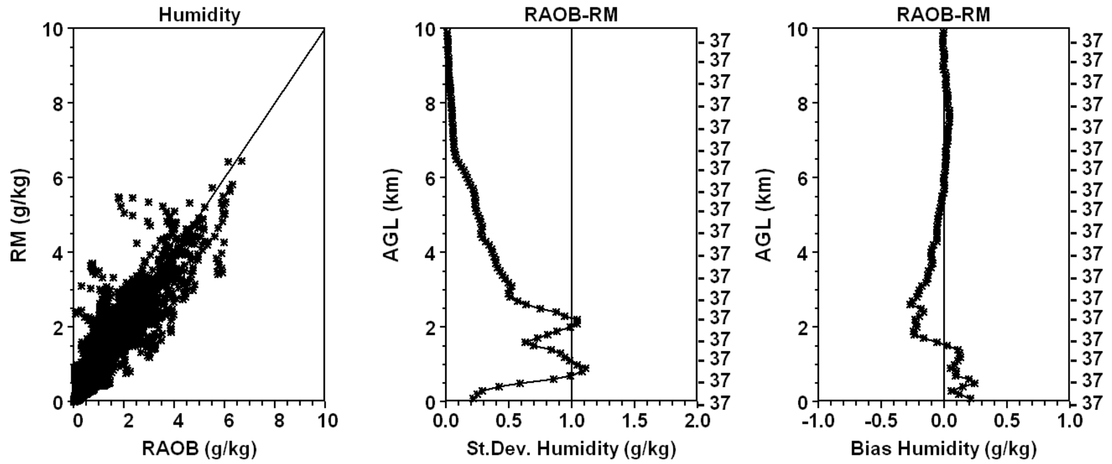

Figure 3: Statistical comparison of the humidity data obtained from the Radiometrics profiler (RM) versus those measured by radiosonde (RAOB). Left: Scatterplot of humidity values (x-axis RAOB measurements, y-axis RM). Middle: Standard deviation with height. Right: Bias with height. The numbers on the right of the middle and right-hand panels represent the number of cases taken for the statistics at each range.

by the profiler need to be corrected because of possible wind shear. When horizontal wind, vertical wind shear, or wind time variation is significant, the correction may become quite important and consequently, lower accuracy is observed for σ.

Once these initial boxes have been implemented, automatic calculation of humidity is possible. In this process, attention should be paid to the sign ambiguity of M in Eq. (2.1), because statistically M can become positive in 10 to 20 % of cases. However, as already observed by TSUDA et al. (2001), a good correlation generally exists between N^2 and M when horizontal advection is not very important (MAPES and ZUIDEMA, 1996). Practically, M becomes positive when N^2 is low, with a threshold of about $3x10^{-5}$ s^{-2}. Theoretically, an automatic adjustment of this threshold could be possible at each profile, provided a reliable reference value of M is available from another automated sounding system. Unfortunately, as we shall see, radiometric M profiles are not accurate enough to exploit this possibility.

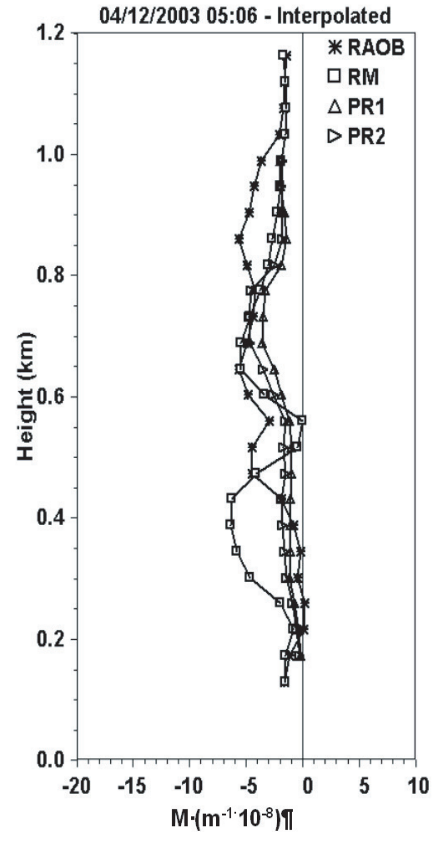

Figure 4: Example of refractive index gradient M calculated from rawisonde (RAOB), radiometer data (RM) and profiler in low mode using first (PR1) and second method (PR2) after adjusting the coefficient to fit by mean square method the RM curve.

4 Experimental site and instrumentation

The dataset used for this study was collected during the international COST 720 Temperature, hUmidity and Cloud (TUC) profiling experiment (RUFFIEUX et al., 2006). This experiment was organised during 3 months (November to February) in winter 2003–2004 at Payerne, Switzerland. Various *in situ* and active/passive ground-based remote sensing systems, including three microwave radiometers, a cloud radar, a wind profiler and radiosonde were operating at the same location.

The wind profiler used in this work is a LAP-3000 manufactured by Vaisala (ex Radian). The operating frequency is 1290 MHz. This radar operates in pulse mode, using 3 beams (1 vertical and 2 oblique). It is configured to operate in two modes (thereafter called "low mode" and "high mode") which differ by the vertical resolution (respectively 45 and 210 m) and the vertical ranges (respectively from 135 to 1035 m, and from 675 to 4975

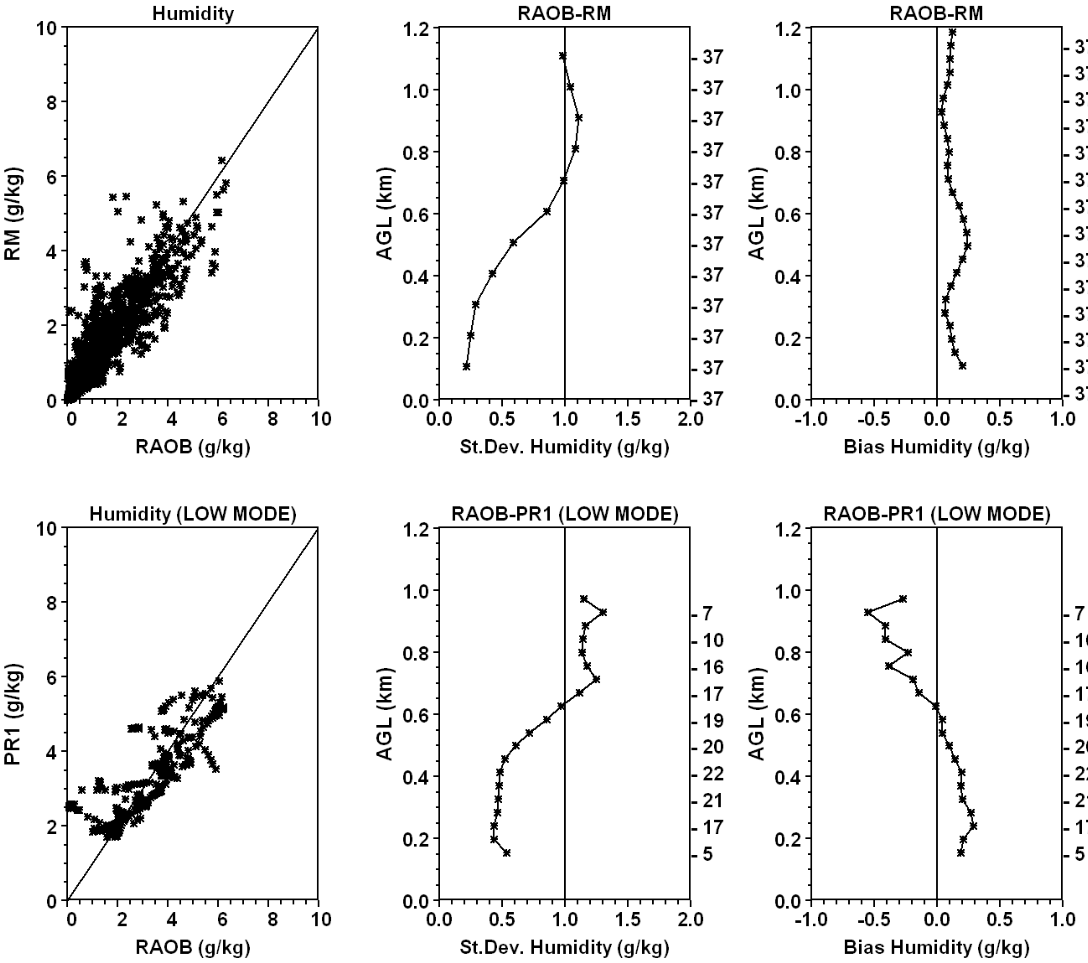

Figure 5: Statistical results with humidity calculation obtained in low mode with radiometer (RM) (above) and profiler data (below) (Same captions as Fig. 3). *M* was adjusted by least mean square method to the *M*(RM) values and *Q*(RM) data integrated over a height covering the 5 first profiler range gates was used for the integral constant.

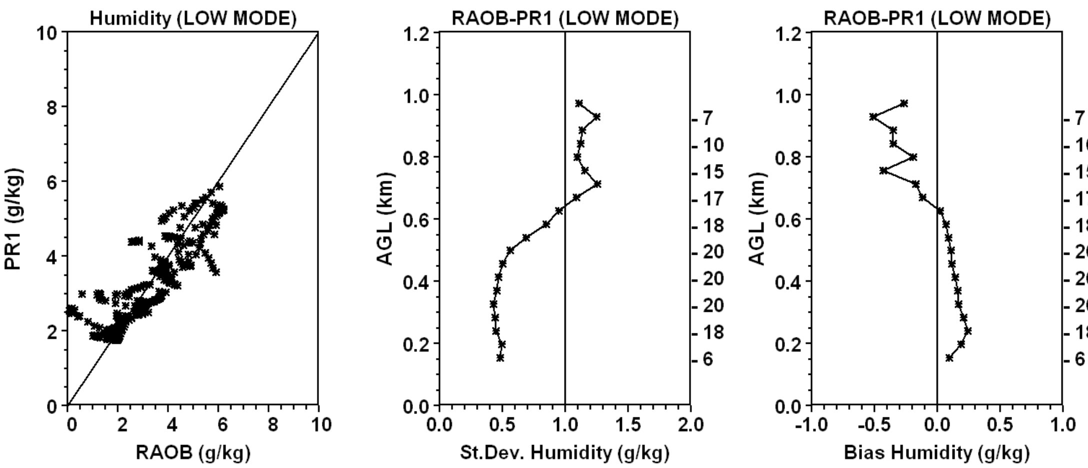

Figure 6: As in Fig. 5 below, but using temperature from rawisonde measurements.

m). The wind profiler dataset used for this experiment is formed by 51 30-minute measurement cases (25 for the low mode and 26 for the high mode) which have been subjected to a validation study already described in this issue (GAFFARD et al., 2006).

In this work we decided to show results relative to the use of two different advanced post-processing methods for the estimation of the spectral moments of the wind profiler radar measurements: Vaisala Multi Peak Programme (MPP) (Figs. 5–8) and NCAR Improved

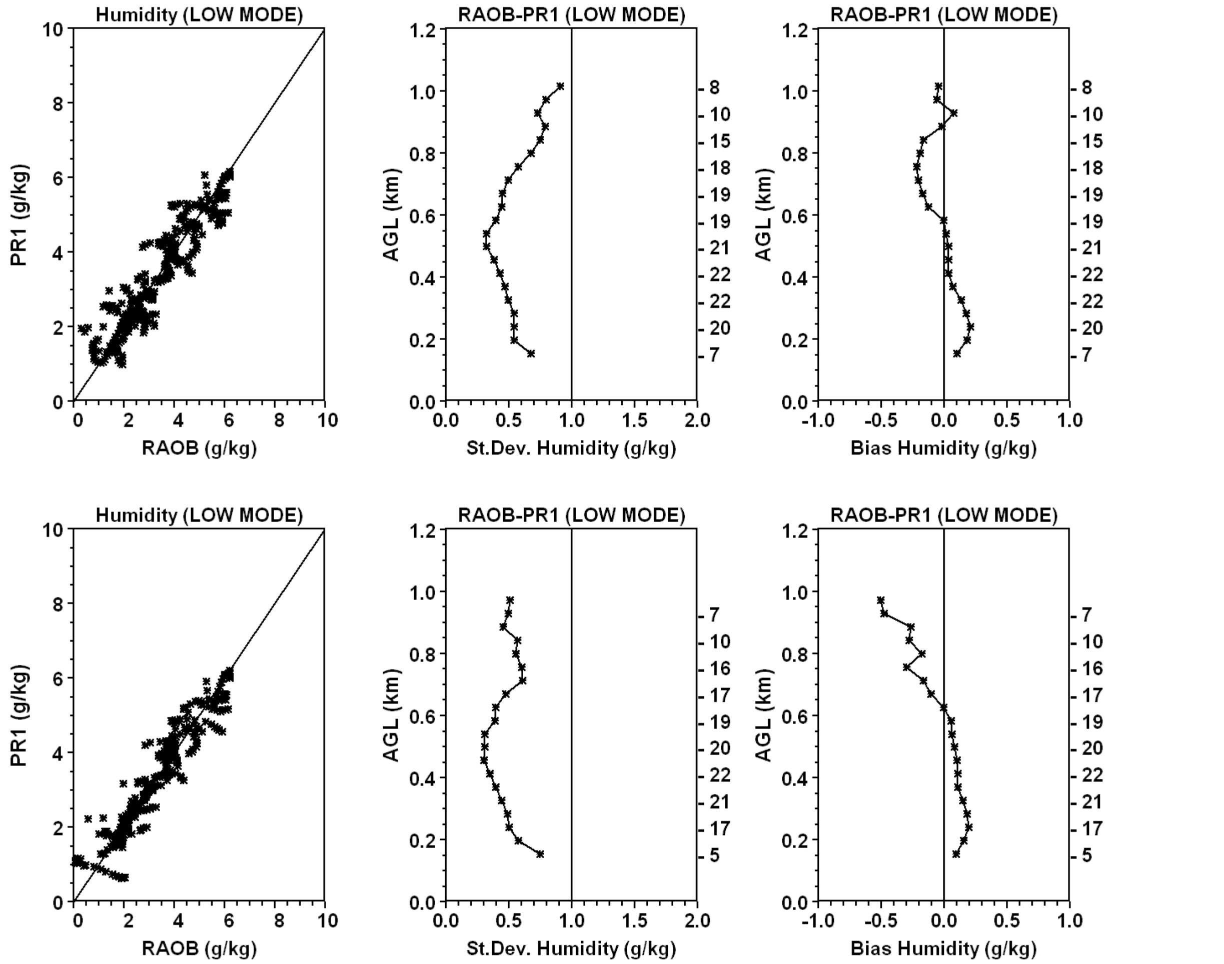

Figure 7: As in Fig. 5, but using a fixed coefficient for M and estimating the integrated humidity over the profiler range from rawisonde. Above: Here we use the MPP post-processing procedure as quality control of radar data in the spectral domain. Below: Here we use the NIMA_04 post-processing procedure as quality control of radar data in the spectral domain.

Moments Algorithm (NIMA_04) in the last comparison (Figs. 7–8).

MPP is fully described by Griesser and Richner (1998). Briefly, the noise level is computed above which up to 3 peaks can be selected. Each peak is then weighted according to the continuity in space and in time and special rate is given to the ground clutter and possible symmetric signals. Chains are built across the range gates, by connecting those peak locations that satisfy a continuity constraint.

An extensive description of the NIMA method is given in Morse et al. (2002). Briefly, NIMA uses a combination of fuzzy logic and image processing techniques under the assumption that the atmosphere is continuous to determinate the location of the atmospheric signal in a series of spectra collected at different heights, at the same time. In NIMA_04, the quality control flag rejects moments with confidence values lower than 0.4.

We also tested the other *advanced* post-processing methods (introduced in Gaffard et al., 2006) and noticed that very slight variations can be observed so that any of them could actually be used for humidity calculation.

Besides, no significant difference was observed in the methodology used to calculate M (Eq. 2.4 and 2.7), so figures related to the first method (Eq. 2.4) equally apply to the second one. The radiosonde used in this comparison are the corrected operational Swiss rawisonde SRS 400 (Ruffieux et al., 2006). They report temperature, humidity and wind vector measurements. The height sampling is variable, 10–30 m for temperature and humidity, 40 m to a couple of hundred meters for the wind.

The radiometric data were obtained from a Radiometrics TP/WVP-3000 (Ware et al., 2003). This ground-based microwave radiometer is designed to allow retrieval of temperature and humidity in the lower troposphere. It is configured to sample sequentially 5 channels in the water vapour band between 22.235–30 GHz and 7 channels along the edge of the oxygen complex between 51.25–58.8 GHz. It can use also elevation angle in addition to vertical pointing to increase the information content. The manufacturer's software uses a

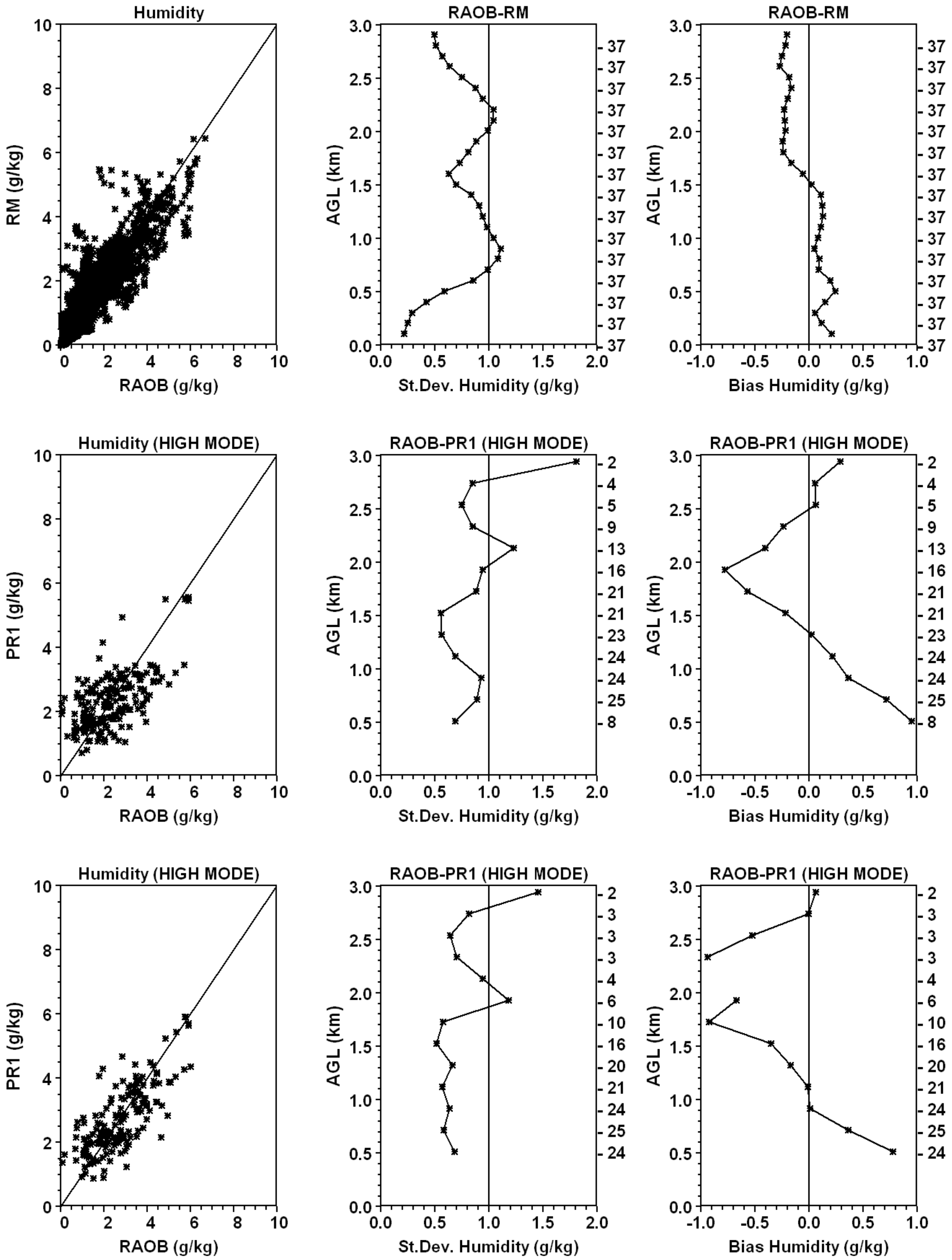

Figure 8: As in Fig. 7, but for high mode. Middle: Here we use the MPP post-processing procedure as quality control of radar data in the spectral domain. Below: Here we use the NIMA_04 post-processing procedure as quality control of radar data in the spectral domain.

neural network method to retrieve temperature and humidity profiles. For the neural network retrieval, no significant improvement was found in using elevation angle acquisition (CIMINI et al., 2006), therefore we used in this study profiles obtained from vertical pointing only. For this study, 37 radiometric profiles were available over the period covered by the wind profiler data set.

5 Results

5.1 Radiometer vs. rawisonde

The first question to solve is the level of accuracy we expect to reach in this study. Our starting point is consequentially the performance of the radiometer alone, because it is already an operational sounding instrument. From this result, considered as the state of art of auto-

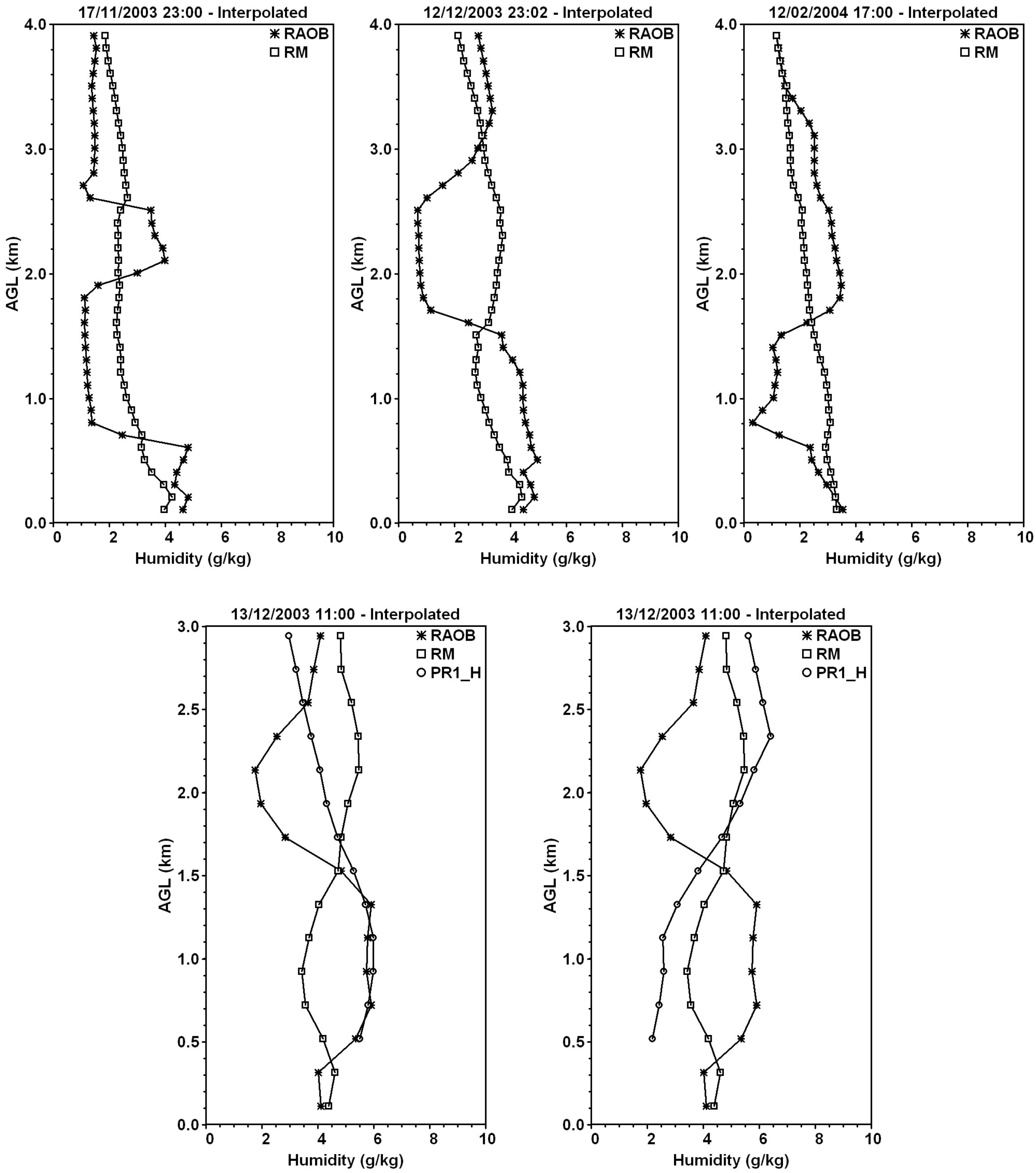

Figure 9: Examples of humidity profile difference between the rawisonde (RAOB) and the radiometer (RM) (abowe). Humidity profiles from UHF radar (PR1_H) calculated respectively by method 1 (lower left) and 2 (lower right) for 13/12/2003 at 11:00.

matic sounding of upper level humidity, we try to quantify the contribution of the wind profiler in term of data quality improvement. Fig. 3 shows the distribution (3 left), standard deviation (3 middle), and bias (3 right) of the humidity profiles given by the radiometer compared to the rawisonde observations. We notice a general good agreement with few larger discrepancies which may be due not the instrument itself, but to the local variations of humidity because of the distance between the volumes measured respectively by the rawisonde and the radiometer. The standard deviation does not extend much above 1 g kg^{-1} with a bias less than ± 0.4 g kg^{-1} showing slight variations with height.

5.2 Profiler calibrated by radiometer, temperature and integrated humidity from radiometer

In the first step, the profiler data need to be calibrated in order to extract the M values in Eqs. (2.4) and (2.7). To this purpose, M profiles from radiometer (M(RM)) were calculated to serve as a reference for determining at each time the coefficients K and K' in Eqs. (2.4) and (2.7) respectively. More precisely, M(PR) profile from profiler was estimated using a mean square method to globally fit the M(RM) profile. Fig. 4 gives an example when both methods were used for M estimation. Then, humidity

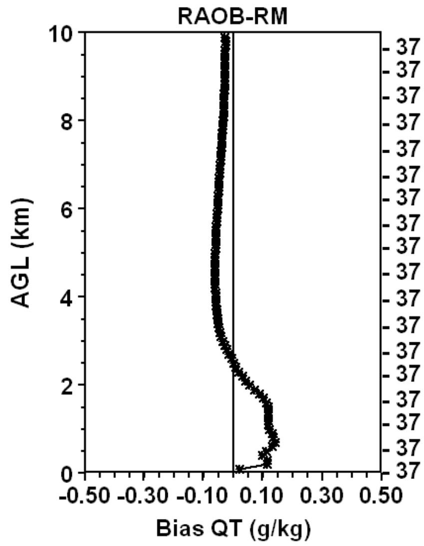

Figure 10: Bias in specific humidity integrated from the surface to different heights from rawisonde (RAOB) relative to radiometer (RM).

equation (Eq. 2.1) is solved using the temperature data from radiometer and the boundary conditions extracted from integrated values of humidity from radiometer over a range containing identified atmospheric signals from the profiler. The results in Fig. 5 (lower row) for the low mode, compared to the radiometer alone (5 upper row), show that in the lowest layers, no improvement is detected.

5.3 Profiler calibrated by radiometer, temperature from rawisonde and integrated humidity from radiometer

The previous approach may be flawed because it relies only on radiometer data. We may expect to use in the future more accurate temperature measurements provided by an advanced integrated system. These capabilities were not available during the TUC experiment; therefore we decided to simulate accurate T profiles from rawisonde data. Little improvement in the data accuracy was reached by this method (Fig. 6), confirming the fact that higher quality T measurements are not required, as already demonstrated by TSUDA et al. (2001) who simply use the virtual temperature profiles provided by the RASS (Radio Acoustic Sounding System) instead of an original T profile.

5.4 Profiler calibrated separately, temperature from radiometer, integrated humidity from rawisonde observations

So far, we tried to dynamically adjust the coefficients for the M value according to the M(RM) curve. This approach showed some limitations due to the fact that any error related to radiometer is transferred to the profiler calculations. In order to avoid this interference, we decided to use a fixed coefficient for the calculation of M(PR). The integral for ρ (Eq. 2.1) is then solved by using the T(RM) profiles and the integrated values of humidity provided by radiometer over a range containing identified atmospheric signals from the profiler. This method did not bring much better results. Finally, the integrated value of humidity was calculated in the same way from rawisonde observations. The results presented in Figs. 7 and 8 respectively for low and high mode show significant improvements.

In the low mode, the lowest height gives a little higher Standard Deviation (StD) of about 0.5 g kg^{-1}, except in the first gate that we know was not well estimated by MPP (GAFFARD et al., 2006). It stays at this level up to 700 meters AGL (Above Ground Level) with even a slight decrease between 400 and 600 m. The bias is quite stable, not exceeding 0.3 g kg^{-1} on the whole profile except for the lowest range. In the high mode, StD is kept under 0.7 g kg^{-1} up to 2 km height, but the bias can exceed 0.5 g kg^{-1} in the lower range and above 1.7 km height. In Figs. 7 and 8 we present the results obtained using with two different post-processing methods on the wind profiler spectral data (MPP in Figs. 7b and 8b, and NIMA_04). Differences among the results obtained with the two advanced post-processing methods are very small. The two methods perform in a very similar way and therefore, as suggested in a previous work (GAFFARD et al., 2006), the MPP algorithm seems to be very suitable for operational use. These results obtained on this data set show that an independent method, using a general calibration and a good estimation of integrated humidity, is the best way to give accurate humidity profiles.

6 Discussion and conclusions

Several methods were tested to combine the humidity information from independent observations by a wind profiler and a radiometer.

The first important result shows that the integrated humidity data measured by the radiometer over the range covered by the profiler is not a reliable parameter for solving the integral in the humidity equation (Eq. 2.1). Besides, the M values calculated from radiometer are not the best way to calibrate the profiler, and no major improvement in the quality of humidity profile was obtained by this method. In fact, large discrepancies in the humidity measurements were sometimes observed between the radiometer and the rawisonde measurements, mainly due to the radiometer smoothing effect, and more rarely to the sensing volume distances in a rapidly changing weather pattern (examples are given

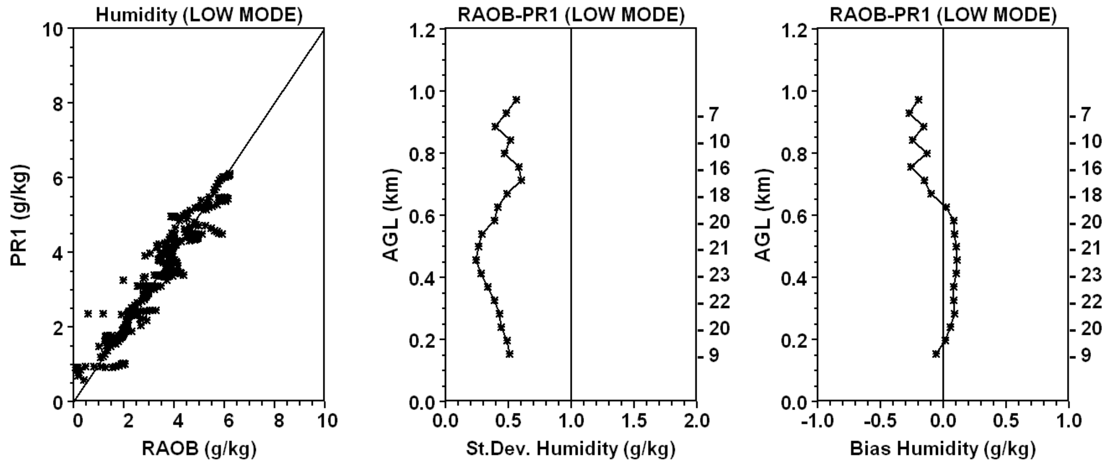

Figure 11: As in Fig. 7 (lower row), but using as input the climatological temperature profiles from a mean value calculation over the whole data set.

in Fig. 9). A once-for-all calibrated profiler appears as a much better solution for this integration task.

Several prospects can thus be drawn. First, humidity measurement techniques of radiometer can still be perfected with more constraints, provided for example by a profiler. Second, radiometer integrated humidity values seems to be more reliable over a larger altitude range, due to their poor vertical resolution. This is illustrated in Fig. 10, which shows the radiometer's specific humidity integrated from the surface becomes closer to that from the rawinsondes after 3 km height. Such range coverage is within the reach of conventional VHF and UHF radars operating at few kW peak power, especially in summer. In these conditions, new tests could improve the contribution from the radiometric humidity.

Third, a VHF reaching the tropopause combined with a low layer UHF could cover practically the whole humidity range which makes it possible to cross-check with the GPS derived integrated humidity as already implemented on the MU radar in Japan (FURUMOTO et al., 2003). Such a method could also benefit from using surface humidity measurements to account for the humidity below the lowest useage UHF range gate. Moreover, neglecting humidity at the higher boundary will provide by itself the integration constant (Eq. 2.1) without the need of external input (KLAUS et al., 2003).

The temperature data from the radiometer were quite useful to solve the profiler equations without any significant distortion. This confirms previous studies (TSUDA et al., 2001) where virtual temperature profiles provided by RASS were used to solve the profiler equations. The fact that this parameter does not need to be very accurate is further corroborated by a test we made using a climatologic temperature profile. It was obtained by calculating at each level the mean temperature from all the rawisonde launchings relative to the selected cases between November 2003 and February 2004 (Fig. 11). Only quite small differences were observed compared with the results obtained using individual temperature profiles from rawisonde or radiometer. This demonstrates that even climatological temperature data can provide good humidity profiles with the method presented here. However, no guarantee is given over a longer period of time or for particular situations.

In conclusion, sounding techniques using wind profiler radars can significantly improve the automatic estimation of humidity in the lowest kilometer. The only conditions are a temperature profile, which need not be accurate, and a good estimate of humidity either at a single point or on a given integrated layer not exceeding the profiler range coverage. For the analyzed data set, except for temperature profile, we cannot conclude that a radiometer can provide a definite contribution to this retrieval technique. However, many prospects still exist not only in the evolution of the radiometric measurements, but also in a more complete instrumental set-up with instruments such as VHF, RASS and GPS which will further help to provide significantly improved high-resolution humidity measurement in the upper atmosphere by only remote sensing technique.

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