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Assessing the potential of passive microwave radiometers for continuous temperature profile retrieval using a three year data set from Payerne

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Abstract

The motivation of this study is to verify theoretical expectations placed on ground-based radiometer techniques and to confirm whether they are suitable for supporting key missions of national weather services, such as timely and accurate weather advisories and warnings. We evaluate reliability and accuracy of atmospheric temperature profiles retrieved continuously by a HATPRO (Humidity And Temperature PROfiler) system operated at the aerological station of Payerne (MeteoSwiss) in the time period August 2006–December 2009. Assessment is performed by comparing temperatures from the radiometer against temperature measurements from a radiosonde accounting for a total of 2088 quality-controlled all-season cases.

In the evaluated time period, HATPRO delivered reliable temperature profiles in 88 % of all-weather conditions with a temporal resolution of 15 min. Random differences between HATPRO and radiosonde are down to 0.5 K in the lower boundary layer and rise up to 1.7 K at 4 km height. The differences observed between HATPRO and radiosonde in the lower boundary layer are similar to the differences observed between the radiosonde and another in-situ sensor located on a close-by 30 m tower. Temperature retrievals from above 4 km contain less than 5 % of the total information content of the measurements, which makes clear that this technique is mainly suited for continuous observations in the boundary layer. Systematic temperature differences are also observed throughout the retrieved profile and can account for up to ± 0.5 K. These errors are due to offsets in the measurements of the microwave radiances that have been corrected for in data post-processing and lead to nearly bias-free overall temperature retrievals. Different reasons for the radiance offsets are discussed, but cannot be unambiguously determined retrospectively. Monitoring and, if necessary, corrections for radiance offsets as well as a real-time rigorous automated data quality control are mandatory for microwave profiler systems that are designated for operational temperature profiling. In the analysis of day/night differences, it is shown that systematic differences between radiosonde and HATPRO decrease throughout the boundary layer if 2 m surface temperature measurements are included in the retrieval.

1 Introduction

A key mission for the national weather services is to provide timely and accurate weather advisories and warnings, with severe events being the major concerns. For this, modern numerical weather prediction (NWP) models are key sources of forecast guidance used by operational meteorologists in their work. A challenge is the forecast at local scale and down to the hour and minute scale, because such information can best minimize damages to property, transport, and population caused by weather-related disasters. To provide high-resolution forecasts, it is imperative to improve the quality, the spatial density and the temporal resolution of crucial *atmospheric measurements*.

Currently, the global radiosonde network, for the most part, makes observations only two times a day. In contrast data assimilation schemes for high-resolution localized nowcast (zero to 2 h) and short-term forecast (2 to 12 h), would very much benefit from observations every few minutes. This can be provided only by automated upper air remote sensing technologies, such as Wind Profilers and MicroWave Radiometers (MWR). An European network of Wind Profilers has already been established within the CWINDE project and its ability to improve numerical weather prediction model performance has been demonstrated (i.e. Calpini et al., 2011). However, NWP models also require upper air temperature and humidity data for improved predictions, especially in the lower troposphere where severe weather is frequently triggered and satellite remote sensing capability is limited.

While the humidity profile from MWR has a relatively low vertical resolution (i.e. less than two independent pieces of information), Löhnert et al. (2009) have also shown that MWR temperature retrievals can provide more than 4 independent pieces of information in the vertical. Former studies have shown temperature accuracies as a function of height, e.g. Güldner and Spänkuch (2001) show STandard DEViations (STDEV) of the MWR-retrieved minus the radiosonde temperature ranging from 0.7 K in the boundary layer to 1.6 K in 7 km. Note, that throughout this paper STDEV will always refer

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to standard deviation of two comparable quantities (i.e. MWR-retrieved temperature minus the radiosonde temperature at a certain height). The temperature retrieval approach of Güldner and Spänkuch (2001) relies on coincident radiosonde and MWR measurements, which are used to periodically update a multi-linear regression algorithm. This type of retrieval is independent of radiative transfer simulations and largely eliminates systematic errors originating from MWR calibration offsets or the gaseous absorption model. Liljegren et al. (2005) also show similar STDEV differences (1 K in the boundary layer and 2 K in the mid-troposphere) with additional systematic differences (BIAS) varying in height between radiosonde and MWR up to absolute values of 1 K throughout the whole troposphere. Their approach relies on a multi-linear regression built upon a radiosonde climatology on the order of 10 000 ascents, where the radiosondes are used to calculate the MWR radiances via radiative transfer simulations and these simulations are then used for calculating the multi-linear regression between temperature profile and MWR radiance. In contrast to the Güldner and Spänkuch approach, this retrieval does not rely on coincident MWR/radiosonde observations, is however subject to systematic error. Liljegren et al. (2005) could show that the observed BIAS was partially due to the applied microwave absorption model, however large discrepancies especially in the lower troposphere still remain. In a paper from Crewell and Löhnert (2007) elevation scanning measurements from microwave profilers are shown to increase the retrieved temperature accuracy in the boundary layer. Especially in the lowest 500 m STDEV are on the order of 0.5 K. All different retrieval approaches mentioned above have been compared and evaluated against each other in a comprehensive overview by Cimini et al. (2006). Here the advantages and disadvantages of each of the methods are outlined in detail on the basis of radiosonde comparisons carried out during the TUC campaign (Ruffieux et al., 2006). Additionally, the performance of a sophisticated 1D-VAR approach, which uses NWP output as a priori data, is compared to the other regression methods.

While different retrieval methods have been proposed and evaluated, this paper now goes a step further and focuses on the long-term (i.e. years) operational performance of

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MWRs for temperature profiling. The goal is to assess the potential of MWR-retrieved temperature profiles for contributing to data assimilation and model evaluation with specific focus on the boundary layer – a range of the atmosphere that is difficult to assess via satellite remote sensing.

In this study, MWR performance is evaluated against radiosondes using a unique 3.5 yr data set of MWR-retrieved temperature profiles with collocated vertical soundings of the atmosphere. Here we build upon the more simple retrieval methods (Liljegren et al., 2005; Crewell and Löhnert, 2007), which provide robust and all-weather temperature-profiles. The questions addressed are:

- What are the long-term random and systematic differences between MWR and radiosonde at one and the same location?

- Where do systematic differences come from and how can they be removed?

- How high is the availability of reliable MWR-retrievals?

- How do MWRs perform during "extreme" conditions?

- What are the data-quality control measures needed in order to maintain the described performance?

Note, that the analysis shown here is valid for measurements carried out between 2006 and 2009. During this time technical updates to the radiometric systems have been carried out, so that some of the described errors may now not be contained in state-of-the-art MWR anymore. MWR system improvements are mentioned in the text when relevant to the analysis performed. Nevertheless, this paper gives an overview on issues that should be carefully assessed when re-processing former MWR data as well as when operating MWRs in future.

The article has been organized in the following way. Section 2 shortly describes the Payerne Observatory where the data used in this study originates. The actual instruments used in this study are then described in detail in Sect. 3. The relevant

specifications of the applied MWR are explained in Sect. 3.1, whereby special focus is given to the calibration procedure and data quality control including BIAS correction. Section 3.2 introduces the radiosonde and its accuracy with a reference to the 30 m tower measurements carried out at Payerne. The retrieval procedure applied is described in Sect. 4 and the data analysis as well as the resulting accuracy assessment is discussed in Sect. 5.

2 Payerne observatory

The aerological station Payerne (Latitude 46.82° N, Longitude 6.95° E, Elevation 491 m m.s.l.) of the Swiss Federal Institute of Meteorology and Climatology (MeteoSwiss) is situated in a rural area halfway between the Jura and the Pre-Alp Mountains. The first upper air balloon soundings (radiosondes) were launched 1942, whereas regular service with two radiosondes per day started in 1954. Next to carrying out the upper air soundings, Payerne is also the major Swiss center for testing and implementing novel remote sensing techniques. The latter include an operational water vapor Raman lidar, wind profilers as well as microwave profilers. At the same location, MeteoSwiss operates a measurement field for the Baseline Surface Radiation Network (BSRN) that includes a 30 m tower with sensors at various heights.

Recently MeteoSwiss achieved the installation of a network with three remote-sensing sites that combine radar wind profiling and microwave temperature profiling. The main goal of this network is to monitor horizontal and vertical wind structures, as well as atmospheric stability in a near-real-time manner around the Swiss nuclear power plants in order to be able to characterize the propagation conditions in case of a nuclear leak (Calpini et al., 2011). As part of this network MeteoSwiss has been continuously operating a Humidity And Temperature PROfiler (HATPRO, Rose et al., 2005) multi-channel multi-angle microwave radiometer since August 2006 at Payerne. This microwave profiler allows temporally highly resolved (currently 15 min) retrievals of the tropospheric temperature profile.

3   Instruments

In the following the instruments and their measurement modes used in the comparisons carried out in this study are described and their errors are characterized.

3.1   HATPRO

The microwave profiler HATPRO was manufactured by Radiometer Physics GmbH, Germany (RPG) as a network-suitable microwave radiometer with very accurate re-trievals of Liquid Water Path (LWP) and Integrated Water Vapor (IWV) at high temporal resolution (1 s). The spectral characteristics of the instrument also make it possible to observe the temperature profile and to a limited extent also the humidity profile. HATPRO is comprised of total-power radiometers utilizing direct detection receivers within two bands. The first band (K-band) contains seven channels from 22.335 to 31.4 GHz and the second band (V-band) contains seven channels from 51 to 58 GHz (Fig. 1). Whereas the seven channels of the first band contain highly accurate information about the atmospheric humidity and cloud liquid water content (Löhnert and Crewell, 2003), the seven channels of the second band (51.26, 52.28, 53.86, 54.94, 56.66, 57.30, 58.00 GHz) contain information on the vertical profile of temperature due to the homogeneous mixing of O_2 throughout the atmosphere (Crewell and Löhnert, 2007). The receivers of each frequency band are designed as filter-banks in order to acquire each frequency channel in parallel. In addition, this approach allows setting each channel bandwidth individually. Just recently the manufacturer has acquired the possibility of measuring the channels bandwidths precisely, which are illustrated in Fig. 1. Unfortunately, the exact center frequencies and band passes for the instrument analysed in this study have not been determined yet. The band passes shown in Fig. 1 are from an identically constructed instrument operated by the University of Madison, WI, USA and are currently the best estimate available.

A steerable parabolic mirror, covered by a microwave transparent radome, guarantees that radiation from ± 90° elevation may be received at the radiometer. The radome

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is protected by a heated blower system to prevent the formation of dew and the accumulation of precipitation. The antenna beam width for the channels along the oxygen line is 2–2.5° full width at half maximum with a side lobe suppression of better than 30 dB so that 99.9 % of the received power stems from an angular range of ± 3°. Additionally, falling precipitation is flagged by an automatic precipitation sensor and furthermore, environmental sensors for temperature, humidity and pressure as well as a GPS clock are part of the system.

The measurement quantity of a MWR is *brightness temperature* (TB). Instead of calibrating in terms of $Wm^{-2}\,sr^{-1}\,Hz^{-1}$, where one would be dealing with very small numbers over a few degrees of magnitude, the DC radiometer output voltage is directly converted into a brightness temperature via the Planck function. This implies that the range of measurements will be between 2.7 K (cosmic background) and ambient temperature.

Absolute calibration for the channels of the V-band is performed using a liquid-nitrogen-cooled load that is attached externally to the radiometer box during maintenance. The cooled load is stored within a 40-mm-thick polystyrene container, which can be considered as a black body at the LN_2 boiling temperature of ~ 77 K. This standard – together with an internal ambient black body load – is used for the absolute calibration procedure. Note that when looking at a black body the physical temperature and the brightness temperature are identical. Assuming a linear characteristic of the detector diode, these two points then lead to an absolute calibration of the MWR. However, it is not convenient to use a LN_2-cooled load for each calibration. For this reason, the radiometer has built-in noise sources that can be added to the receiver inputs. The equivalent noise temperature of the diode is determined by the radiometer itself after the LN_2 calibration. The noise diode is also used to correct for detector diode non-linearity errors. During the time period from 2006 to 2009 five LN_2 calibrations were performed at the dates listed in Table 1.

The accuracy of an absolute calibration carried out with the noise diode as secondary standard (replacing a LN_2-cooled target) and the ambient temperature load is

comparable to the results obtained with a liquid-nitrogen-cooled load and is carried out on the order of hours. The advantage of the secondary standard is obvious: a calibration can be automatically done at any time. All system parameters are recalibrated including slope (gain) and offset (system noise temperature). Additionally, a relative calibration (gain adjustment) is performed every 2–5 min by looking at the built-in ambient load in order to minimize drifts.

3.2 Radiosonde

At Payerne a PTU (Pressure, Temperature, hUmidity) radiosonde is launched twice a day at 00:00 and 12:00 UTC. The radiosonde is launched one hour before the official time to cope with ascent times and data processing issues, however the exact launch time is coded within the sounding data. The radiosonde flies through the atmospheric Boundary Layer (BL) and reaches an elevation of approx. 3000 m within the first 10 min and reaches 10 km within approx. 30 min of flight. It then generally continues up to 30 km. After the first 20 s of flight, the time resolution of the samples varies from 1 s to 10 s, which corresponds to a vertical resolution that ranges from 10 to 80 m.

The Swiss radiosonde SRS 400 used here was introduced in 1990. The sensors of this radiosonde include copper-constantan thermocouples of 0.063–0.050 mm diameter for temperature, a full range water hypsometer for pressure, and a carbon hygristor for relative humidity (Richner and Hünerbein, 1999). The accuracies of the sensors are listed in Table 2.

3.3 Tower measurements

The 30 m BSRN-tower (Baseline Surface Radiation Network) is located 200 m to the south of the HATPRO site and radiosonde launch area. It has sensors for environmental measurements at 2, 10 and 30 m, respectively. The temperature sensors have precisions better than 0.2 K throughout the whole dynamic range and deliver instant values every 10 min. The tower measurements were used as a comparison with the

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radiosonde to evaluate the differences between two in-situ methods, which can then be set into relation with the differences between radiosonde and HATPRO. At 30 m above ground, the BIAS between BSRN sensor and radiosonde and over the time period from 1993 to 2004 (7625 samples) is 0.07 K, whereas the standard deviation of the difference between BSRN and radiosonde is 0.53 K. Note that the differences include uncertainties due to the altitude of the radiosonde (± 10 m according to the precision of the hypsometer) and due to linear interpolation in height, because the radiosonde rarely gives a value at exactly 30 m.

4   Data quality control

All radiosondes from 1992–2009 were quality controlled for physical consistency according to Nörenberg et al. (2008). This resulted in approximately ∼10 150 radiosondes that could be used for temperature retrieval development. During the time period of HATPRO measurements of August 2006–December 2009, a total of 2088 quality–controlled all-season, all-weather radiosondes could be matched in time to HATPRO measurements. This is far more than during previous studies, such as during the TUC experiment, which could only account for about 220 radiosondes. A HATPRO temperature retrieval was carried out every 15 min of which the closest in time was used for comparison against the radiosonde ascent.

The study relies on 24 000 h of HATPRO measurements from August 2006 until December 2009. Most of the time the instrument operated continuously (average data availability > 90 %), except for a longer period of maintenance from 11 May to 17 September 2009 following a 2 months period with intermittent failure. A number of quality checks, respectively correction procedures were applied to the HATPRO brightness temperatures to ensure that only trustworthy data flows into the analysis:

- Cases where the HATPRO precipitation sensor detected rain (or snow) were excluded from the analysis.

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– Cases when HATPRO recorded non-physical brightness temperatures (i.e. lower than 2.7 K or higher than a threshold values of 330 K) or retrieved non-physical air temperatures (i.e. lower than 180 K and higher than 330 K) were excluded from the analysis.

– All the data were cross-checked "by eye" to exclude inconsistent spikes in the TB-channels, which may be caused by Radio Frequency Interference (RFI) or non-meteorological "disturbances" (sun, moon, humans, birds, aircraft, . . .).

– Periods after strong precipitation where the dew blower was not powerful enough to evaporate the water on the radome immediately were also excluded "by eye" from the analysis.

These quality controls lead to a reduction of the total available HATPRO data for the radiosonde comparison of about 12 %. The latter two points still remain an open issue for all operational MWR applications. Cross-checking "by eye" is certainly not an option for an operational MWR application, although necessary for the analysis of the current data set. However, latest developments of the RPG-software do include RFI filters, as well as automatic controls concerning the status of the receiver system.

5 Temperature retrieval

The retrieval algorithm (Fig. 2) uses synthetic TBs at required frequencies and elevation angles (see below) derived from the 1992–2009 Payerne radiosonde data via radiative transfer calculations using pressure, temperature and humidity profiles of each sounding. Liquid clouds are assumed to be present at temperatures above –20 ˚C and at relative humidity values higher than 95 %. The liquid water content is calculated with a modified liquid adiabatic model based on an empirical correction accounting for entrainment (Karstens et al., 1994). Temperature and pressure information was generally available up to 30 km height for the simulation, so that no systematic under-estimation

is expected due to the omission of layers in the stratosphere, which contribute to the microwave signal.

For the radiative transfer simulations, gaseous absorption is calculated according to Rosenkranz et al. (1998), whereby the water vapor continuum is modified according to Turner et al. (2009) and the 22 GHz water vapor line width is modified according to Liljegren et al. (2005). The latter could show that the broadening of the line also has an influence on the V-band channels.

For retrieval derivation we have applied monochromatic simulations at the center frequencies of HATPRO (Fig. 1) assuming infinitively small antenna beam widths (pencil beam approximation) – both representing common approximations in the software supplied by radiometer manufacturers up to now. The effects of these approximations are discussed in Sect. 5.3.

5.1 Theory

At the opaque center of the O_2 absorption complex at 60 GHz, most of the temperature information originates from near the surface, whereas further away from the line, the atmosphere becomes less and less opaque so that more and more information also originates from higher atmospheric layers. Using the frequency dependent information alone at zenith results in the order of three independent pieces of vertical temperature information throughout the troposphere (Löhnert et al., 2009).

Because the development of the BL is of special interest due to the large transfer of energy between the surface and the atmosphere, a higher vertical resolution, especially in the lower troposphere is desired. Therefore combined elevation scanning and multiple frequency methods have been developed by Crewell and Löhnert (2007). The retrieval presented here uses the same brightness temperature measurements at six elevation angles 90.0°, 42.0°, 30.0°, 19.2°, 10.2° and 5.4° corresponding to air mass factors of about 1, 1.5, 2, 3, 5, and 10. By assuming horizontal homogeneity of the atmosphere, the observed radiation systematically originates from higher altitudes the higher the elevation angle. In case of an optically thick channel (i.e. when all of the

radiation received at the radiometer originates from the closer environment of the instrument), the lower elevation angles can be attributed to the temperature in the lower layers, whereas higher elevation angles contain temperature information from multiple layers higher above. This fact leads to high accuracy temperature retrievals in the lowest 1 km and can enhance the number of independent pieces of vertical temperature information to four. Since brightness temperatures of optically thick channels typically vary only slightly with elevation angle, elevation scanning temperature retrievals require highly sensitive radiometers, a fact which is realized in the HATPRO instrument by a high thermal stability and by using wide bandwidths up to 2 GHz in the optically thick channels 56.66–58.00 GHz. In contrast, the lower four channels have bandwidths of 230 MHz in order to guarantee a higher degree of spectrally independent information.

5.2 Implementation

As performed by Crewell and Löhnert (2007), a multi-linear regression between the forward modeled TBs and atmospheric temperature as measured by the radiosonde at a defined height level is carried out. Temperature profiles are then retrieved from the TBs measured with the radiometer from 2006 to 2009, using the derived regression coefficients. Algorithms were developed up to a height of 10 km above ground level (a.g.l.) on a 50 m spacing vertical grid close to the ground gradually increasing to 1 km in the upper troposphere. Note that this grid is much finer than the true vertical resolution of the retrievals but similar to the one used by current weather forecast models. Elevation scans were performed every 15 min, so that high-quality temperature profiles are available four times an hour.

5.3 TB offset correction

Next to the random temperature errors, the retrievals are also almost always subject to systematic error. Such errors can originate from instrumental effects as well as from the radiative transfer simulation. In the following we show how systematic errors may

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be reduced through assessing the systematic TB offsets. We observe that during clear sky situations at Payerne, V-band HATPRO measurements and radiative transfer calculations using collocated radiosonde data show significant differences. For selecting sounding cases at clear sky conditions, the product APCADA (Duerr and Philipona,

5 2004) is used, that derives a global cloud coverage estimation from radiation measurements at Payerne, although it does not necessarily detect thin cirrus clouds, which is irrelevant here, because HATRPO measurements are insensitive to cirrus. Typically, APCADA values of 0/8 or 1/8 of total hemispheric cloud cover are considered as clear sky conditions. For the selected cases, the LWP values derived from HATPRO are

10 then cross checked one hour before and two hours after the radiosonde launch for being close to zero and stable.

Principally we do not expect a perfect agreement because HATPRO performs a point measurement in time and captures the whole atmospheric column within an instant, while the radiosonde is subject to wind drift and has an ascent time of ~ 30 min before

15 reaching the top of the troposphere. However, no significant systematic error is to be expected from this discrepancy. The results of these comparisons are shown in Fig. 3, which makes clear that large systematic offsets of up to 5 K and more are evident in the more transparent V-band channels. Note, that Hewison et al. (2006) and J. Güldner (personal communication, 2011) also observed offsets on the same order of magnitude

20 employing radiometers manufactured by Radiometrics Cooperation Inc.

The fact that some of the observed offsets seem to "jump" after each LN_2 calibration, hints towards a problem with the calibration. Typical error sources in the LN_2 calibration procedure are water condensate forming on the aluminum plate reflector connecting the cold load and the radiometer or on the radiometer radome itself, as well as a non-

25 homogenous covering of the absorber material of the cold load with LN_2. TB offsets after the first, second and fourth calibrations resemble each other, while the TB offsets after the third and fifth calibration are also similar to each other. We here assume that the third and fifth calibrations were faulty in the sense that water condensate formed on the aluminum plate or the radome leading to an additional emission signal and in

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consequence to a underestimation of the TBs as shown in Fig. 3. In order to prevent this, the radome blower and heater are now operated with maximum power in the latest RPG HATPRO software version.

Assuming that the first, second and third LN_2 calculations were performed correctly, the following possible sources remain to describe the TB offsets:

5.3.1 Center-frequency offset

A systematic TB BIAS could results from the fact that the nominal center-frequency of a specific channel does not correspond to the actual center frequency the instrument is measuring at. In order to quantify this possible error, we have calculated the shift in mid-frequency necessary to match the observations to the simulations (Table 3). These calculations are based on the 1992–2009 mean atmospheric profiles of temperature, pressure and humidity of Payerne. Only monochromatic and infinitively narrow (*pencil beam*) radiative calculations have been considered. The highest shifts on the order of −140 to −80 MHz are necessary at the most transparent channel 51.26 GHz. At the other channels the necessary shifts are on the order of −30 to +20 MHz. Measurements of the exact center-frequencies from an identically constructed HATPRO instrument have shown differences to the nominal frequencies on the order of −30 to +80 MHz, so that the incomplete knowledge on the exact mid-frequency may account for a large parts of the offset. However it must again be underlined, that no exact measurements of the mid-frequency are available for the instrument used here so that this is only a potential, while plausible error source. Note, in contrast to the older Generation 1 (G1) HATPRO type used in this study, the current Generation 2 (G2) of HATPRO exhibits exactly determined mid-frequencies with an accuracy of better than 1 MHz considering the complete receiver system response. RPG (Thomas Rose, personal communication) has compared 10 of the 20 G2 instruments to a reference radiometer and found maximum TB differences of 0.5 K at the optically thin V-band channels.

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5.3.2 Band pass effect

Figure 4 shows the effects of the consideration of HATPRO band passes given in Fig. 1. In order to calculate the bandpass-averaged TB, monochromatic radiative transfer calculations were carried at a total of 40–50 (depending on the channel) frequencies rang-
ing from the minimum to the maximum of the bandpass and averaged accordingly. On average, the BIAS between bandpass-averaged and center-frequency monochromatic TB simulations is smaller than 0.4 K in the V-band, except at the 53.86 GHz channel, where the monochromatic approximation can lead to an underestimation on the order of 1 K at 90° elevation. This high deviation can be explained by the width of the
band pass, which "sees" the Zeeman-peak at ~ 53.6 GHz. This effect, however, cannot explain the difference between measurement and model – a consideration of this leads to an even larger difference between measurement and model because of opposite signs. Note, that the variability of the differences are rather small, i.e. below 0.1 K. It is important to note, that RPG has redesigned (narrowed) the band passes
of the first four HATPRO V-band channels significantly for the G2 instruments leading to BIAS values between bandpass-averaged and center-frequency monochromatic TB simulations lower the 0.2 K overall.

5.3.3 Beam width effect

Radiative transfer calculations considering realistic beam widths of 2.25° (defined at Half Power at Full Width – HPFW) are compared to the mono-chromatic, pencil-beam calculations (Fig. 4). At all frequencies and angles larger than 19.2°, the beam width effects are smaller than 0.15 K and thus mostly negligible in contrast to other effects. However, at elevation angles lower than 19.2° and the lower two frequency channels, systematic differences up to 0.7 K occur. These overestimations of the pencil beam approximation may be attributed to a higher degree of saturation in the lower part of the beam. Because lower elevation angles than 90° are used only at frequencies higher

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than 54 GHz in the temperature retrieval, we can neglect the beam width effects from our current discussion.

5.3.4 Gaseous absorption model

Studies comparing different oxygen absorption models for the microwave spectrum (e.g., Hewison et al., 2006; Cadeddu et al., 2007) have shown systematic offsets between model and measurement that are on the same order of magnitude as the differences shown here. Thus, it is not possible in this study to discriminate between the possible sources of discrepancy.

5.3.5 Radiosonde

We do not expect the systematic differences to originate from the radiosonde measurements because these would imply unrealistically large temperature offsets (0.5 K) varying with height in the lower to middle troposphere.

In order to account for the observed systematic differences at each frequency and elevation angle, the observed offsets during clear-sky conditions (Fig. 3) were averaged over the period between two LN_2 calibrations and subsequently subtracted from each corresponding measurement. The offset is generally smaller for increasing frequency and decreasing elevation angle because the atmosphere becomes more and more opaque in both cases and thus the TBs converge towards ambient temperature. The TBs with and without the offset correction are both applied to MWR measurements and the results are discussed in Sect. 6 below.

6 Data analysis

The following retrieval data analysis assesses the accuracies of MWR temperature retrievals under different conditions. We have chosen to divide the analysis into cases only during clear-sky and then for all-sky conditions. Additionally we look into the

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differences of retrieval performance during day and night and try to identify the reliability of MWR temperature retrievals during significant weather, i.e. frontal-passages.

Using the average 2006–2009 Payerne profiles of temperature, humidity and pressure, an information content analysis gives rise to the fact that about 85 % (95 %) of the MWR information originates from the lowest 2 km (4 km) following Rodgers (2000). This result is obtained by analyzing the trace of the averaging kernel matrix which is defined by the sensitivity of the retrieved value at height with index i to the true value at height with index j. As a consequence all error assessments are only shown up to 4 km height.

6.1 Clear sky comparisons

In order to test the consistency of the TB offset correction procedure, a first clear-sky comparison is carried out. Here, the temperature retrieval coefficients are derived using exactly the same 487 clear-sky cases as for deriving the TB-offset corrections (Sect. 5.3). This retrieval was then again applied to the corresponding clear-sky HAT-PRO measurements: once applying the TB offset correction and once using the original TBs (Fig. 5). If the TB offset correction is not applied, systematic differences between -0.7 and $+0.2$ K arise in the lowest 4 km. The systematic difference is even similar in size to the random difference in the boundary layer. As expected, a clear positive influence of the TB-offset correction can be seen both with respect to BIAS as well as STDEV between MWR and radiosonde temperature. The BIAS has practically vanished throughout the profile and the STDEV values range within 0.4 and 1.3 K within the lowest 2 km increasing to 1.5 K at 4 km. The overall lowest STDEV can be observed at 250 m m.s.l. with a value of ~ 0.4 K. The STDEV value decreases from 0.75 K at the surface to this value due to the high temperature variability directly close to the surface coupled with the fact that MWR is sensitive to a volume of air, whereas the radiosonde measures at relatively fixed points in time and space. Additionally the radiosonde needs typically 50 m to reach an equilibrium temperature concerning its natural ventilation due to ascent speed.

6.2 All sky comparisons

The retrieval algorithm coefficients, which are applied to the whole HATPRO data set are derived from all 1992–2009 radiosondes as seen in Fig. 2 and described in Sect. 5. Using $\sim$ 10 150 radiosondes from this time spam allows to develop a much more robust algorithm that should be applicable for all cases between August 2006 and December 2009. Similar to the clear-sky comparison, systematic differences range between −0.6 and +0.3 K in the lowest 4 km if the TB offset correction is not applied (Fig. 6). After applying the correction the overall BIAS difference is smaller than ± 0.1 K, except for the surface point (+0.2 K) and above 3.5 km where the BIAS gradually increases up to +0.15 K at 4 km. This makes clear that the TB offset correction derived from the clear-sky cases can also significantly help reducing the BIAS difference for all sky cases. Note that the STDEV values are very similar to the clear-sky values shown in (Sect. 6a, Fig. 5) underlining the all-sky potential of MWR for temperature profiling. For the TB-offset corrected values, the RMS values are within 0.4 to 1.4 K in the lowest 2 km and increase to 1.7 K in 4 km. Note that these long-term comparisons are consistent with the predicted accuracies based on simulations by Crewell and Löhnert (2007) using an identical retrieval algorithm setup. The high accuracies below 1 km are due to the information contained in the elevation scans.

In order to correctly interpret Fig. 6, it is important to consider the availability of quality controlled HATPRO temperature data during the all-sky cases analysed. Within the period August 2006 to December 2009, 2088 cases of simultaneous HATPRO and radiosonde measurements have been identified. 249 ($\sim$ 12 %) of these cases are not included in the analysis of Fig. 6 because these did not pass the HATPRO measurement quality control due to reasons described in Sect. 4. In summary we can say that HATPRO can deliver reliable and accurate temperature profiles in 88 % of all-sky cases, with an uncertainty ranging from 0.5 K in the lower boundary layer and rising up to 1.7 K at 4 km height.

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6.3 Day vs. night effects

When analyzing TB offset corrected temperature retrievals for 00:00 and 12:00 UTC radiosondes separately (Fig. 7), the STDEV values are both comparable to the case when both are analyzed together. However, the BIAS shows a non-zero behavior as a function of height with opposite sign. The opposite sign non-zero behavior varies between -0.2 and $+0.3$ K at the surface and shows minima around ± 0 K at 250, respectively 1300 m a.g.l. This effect is due to the fact that the derived retrieval coefficients have been derived without discriminating between day and night. It is important to note that, when also differentiating between day and night, a BIAS behaviour of similar vertical structure as shown in Fig. 7 is obtained when applying the retrieval to the calculated TBs from which the retrieval was derived. Because only radiosonde ascents at 00:00 and 12:00 UTC are available, BIAS errors will always be an issue, even if one would derive separate retrieval coefficients for day and night. A way to reduce these effects is to include 2 m-temperature observations as shown in the right panel of Fig. 7. Instead of using only calculated TBs as predictors for the temperature profile in the multi-linear regression (Fig. 2), the 2 m-temperature is additionally included and the BIAS and STDEV values are much lower at the surface. However, BIAS values are also slightly reduced to -0.15 to 0.2 K throughout the lowest 4 km. The additional temperature information at 2 m allows the retrieval to better discriminate between day and night time conditions. This BIAS reduction is also visible again when applying the retrieval to the synthetic TBs, differentiated by day and night.

The latest HATPRO developments include temperature, humidity and pressure measurements on a 100 cm long mast located about 80 cm above the instrument. With these measurements, the quality of surface sensor readings will be close to those of professional meteorological stations so all sensor readings can be used as retrieval input without disturbances from the instrument itself.

6.4 Significant weather

In order to evaluate the temperature retrieval performance during significant weather, *frontal* conditions are extracted from the radiosondes. A situation was classified as *frontal* when available records report a front or occlusion crossing Zürich (170 km NE of Payerne) up to 12 h before or after the launch of a Payerne radiosonde.

As can be seen in Fig. 8, throughout the lowest 4 km the STDEV during the frontal passages between radiosondes and HATPRO are even up to 0.5 K smaller than in the case of all evaluated cases. This could be due to missing lifted inversions during frontal passages, in contrast to fair weather situations, i.e. during winter anti-cyclonic situations or when residual layers occur at night after a sunny day. This also makes clear that the performance of the MWR temperature retrieval can be considered as non-crucial towards a severe weather condition. However, quality-controlled data availability decreases down to 60 % in these cases – which is mainly due to precipitation accumulation on the MWR radome making a physically consistent retrieval impossible. It is also important to note, that the BIAS difference between MWR and radiosonde varies between −0.2 and +0.2 K as a function of height. This, as in case of the day-night comparison, is again due to the fact, that we are regarding a certain subset of cases, for which multi-linear regression coefficients were not explicitly derived.

7 Summary and conclusions

This study has tried to show the current strengths and weaknesses of microwave radiometry for atmospheric temperature profiling using a unique set of collocated MWR and radiosonde measurements. While the advantages of high temporal resolution and un-manned routine observations must be stressed, a limited vertical resolution (with respect to radiosondes) and corresponding random error inherent within the measurement principle must be kept in mind. Random errors range on the order of 0.5 K in the lower boundary layer and rising up to 1.7 K at 4 km height. Above this height only 5 % independent information originates from the radiometer measurement itself.

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While MWR measurements may prove very valuable for NWP model applications considering the random error, this study has also quantified and corrected for systematic error. The different possible sources of the observed systematic differences are difficult to allocate in retrospective, but these are currently subject of intense study in the microwave remote sensing community (University of Cologne, NOAA-Severe Storm Laboratory, RPG). This study makes clear that future operational MWR measurements need to be monitored permanently during clear sky conditions, i.e. using simple non-scattering radiative transfer modeling. Such monitoring is necessary to identify possible TB-offsets. TB offset corrections are essential for providing an optimized temperature profile product. The observed "stability" (w.r.t. the radiosondes) between two LN_2 calibrations makes clear that HATPRO type MWRs may only need LN_2 calibrations on the time scale of one year or even less often.

The quality control procedures and offset correction method described in this paper are currently subject of intense discussion within the newly-found "International network of ground-based microwave radiometers" (MWRnet; http://cetemps.aquila.infn.it/mwrnet/). It is currently a central platform for uniting European-wide MWR measurements under the aspect of harmonization of measurement modes, data formats, retrievals etc. and is embedded with the COST action ES0702 EG-CLIMET (European Ground-Based Observations of Essential Variables for Climate and Operational Meteorology; http://www.eg-climet.org). Basics on MWR operations and advice for MWR users are given through this portal via an open WIKI site.

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Table 1. Absolute calibration times of the HATPRO instrument at Payerne between 2006 and 2009.

Date	Time (UTC)
28 Sep 2006	12:00–13:00
24 Apr 2007	13:00–14:00
24 Oct 2007	7:00–8:00
28 Mar 2008	13:00–15:00
17 Sep 2009	12:00–14:00

Table 2. Accuracies of the Swiss SRS400 radiosonde sensors.

Parameter	Sensor type	Accuracy in the troposphere
Temperature	copper-constantan thermocouples	± 0.2 K
Pressure	water hypsometer	± 2 hpa (accuracy increases with height)
Humidity	carbon hygristor until Apr 2009	± 10 to 20 %
	capacitive polymer starting May 2009	± 5 to 10 %

Table 3. Necessary center frequency shifts (in Mhz) to account for the systematic differences shown in Fig. 3 as well as standard deviation (stddev) of the TB differences in K: (shift [MHz]/stddev [K]).

	Before 1st calibration	After 1st calibration	After 2nd calibration	After 3rd calibration	After 4th calibration	After 5th calibration
51.26 GHz	−170/1.0	−140/1.0	−80/1.2	+190/0.6	−140/1.0	+100/0.5
52.28 GHz	−10/0.8	± 0/0.7	+20/0.8	+160/0.5	−10/0.8	+80/0.4
53.86 GHz	+10/0.3	−20/0.9	−20/0.4	+30/0.4	−30/0.4	± 0/0.3
54.94 GHz	+90/0.3	+40/0.4	+40/0.3	+180/0.4	+20/0.2	+180/0.3
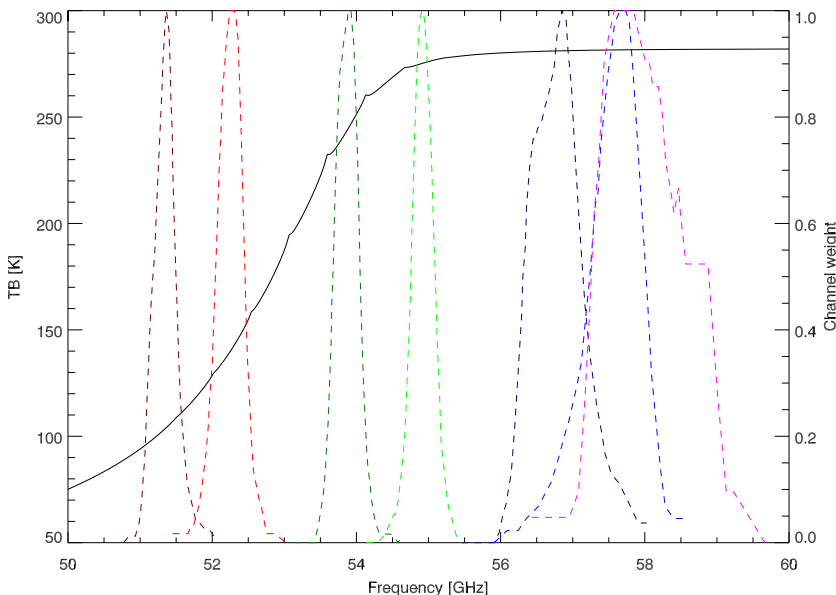
Fig. 1. Brightness temperature as a function of frequency in the microwave spectrum (V-Band: 50–60 GHz). The spectrum (black line) is calculated for the long-term average Payerne atmospheric state. The colored, dashed vertical lines show the center frequencies of the MWR HATPRO channels together with their band passes (normalized to 1).
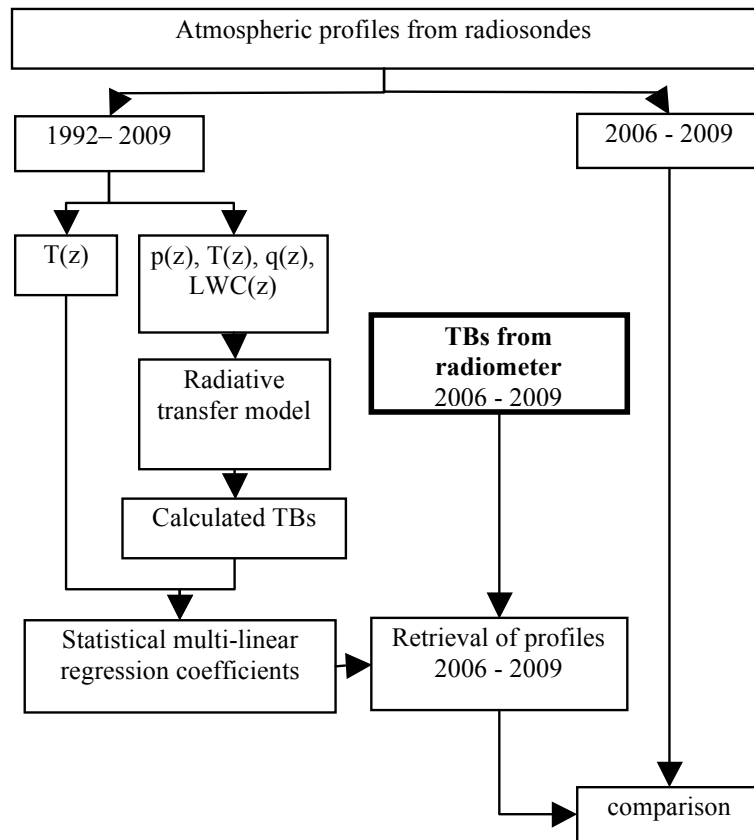
Fig. 2. Flow chart of retrieval derivation and comparisons performed in this study. Note that the following input is needed in order to perform radiative transfer calculations: temperature profile $T(z)$, pressure profile $p(z)$, humidity profile $q(z)$, liquid water content profile LWC(z).

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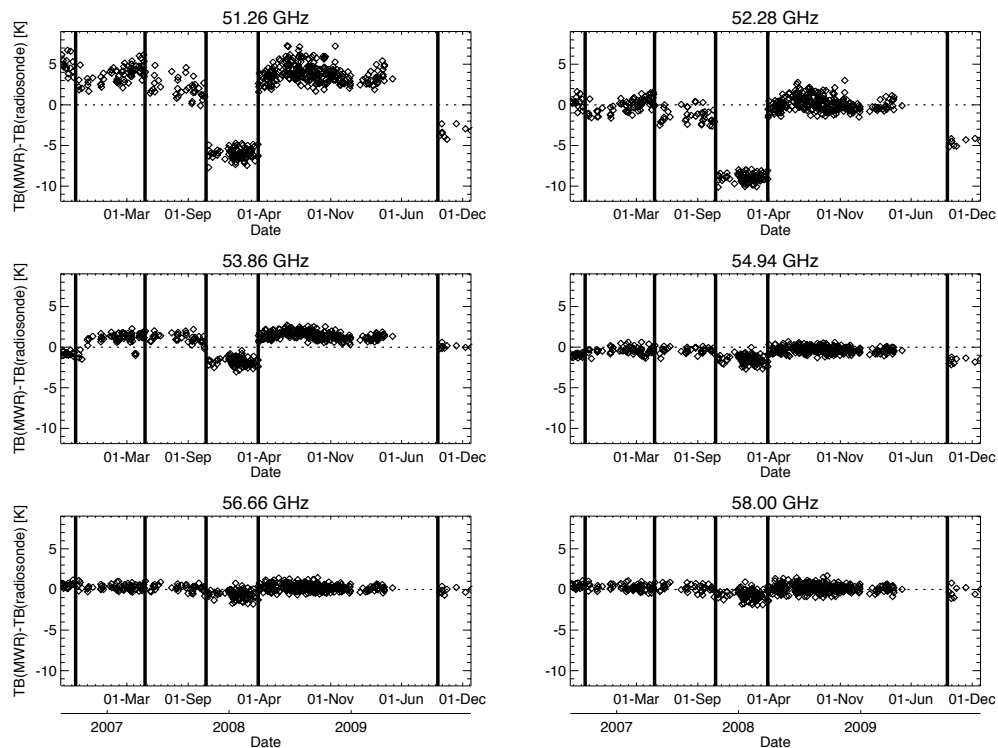
Fig. 3. TB offset time series at 90° elevation for 6 HATPRO V-band channels: TB(measured by MWR)-TB(simulated from sonde). The thick vertical lines indicate the absolute calibration times with liquid nitrogen.
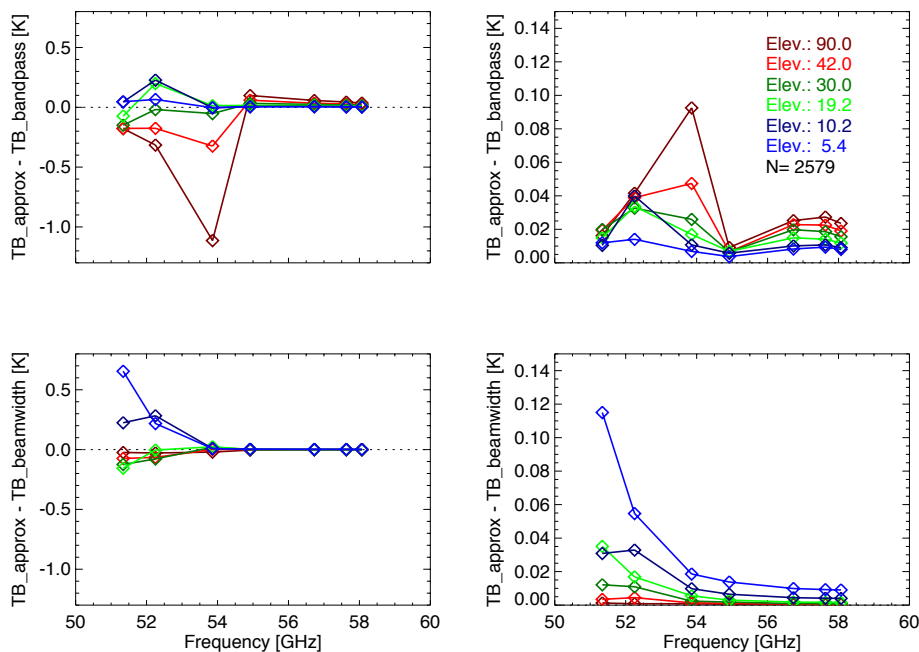
Fig. 4. Differences of simulated TBs: approximated minus realistically modelled TBs. The approximated TBs (TB_approx) assume a monochromatic receiver and an antenna with an infinitively narrow beam, while the realistically modelled TBs take into account either the HAT-PRO specifications concerning the band pass (TB_bandpass, upper two panels) or beam width (TB_beamwidth, lower two panels). Left: systematic differences, right: random differences. The calculations rely on 2579 all-sky radiosonde ascents and are shown for different elevation angles (colored).
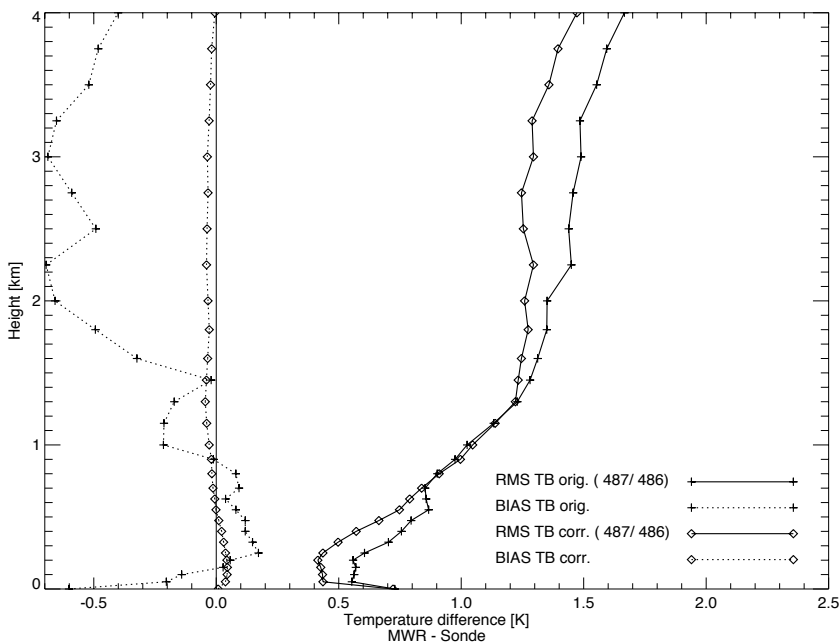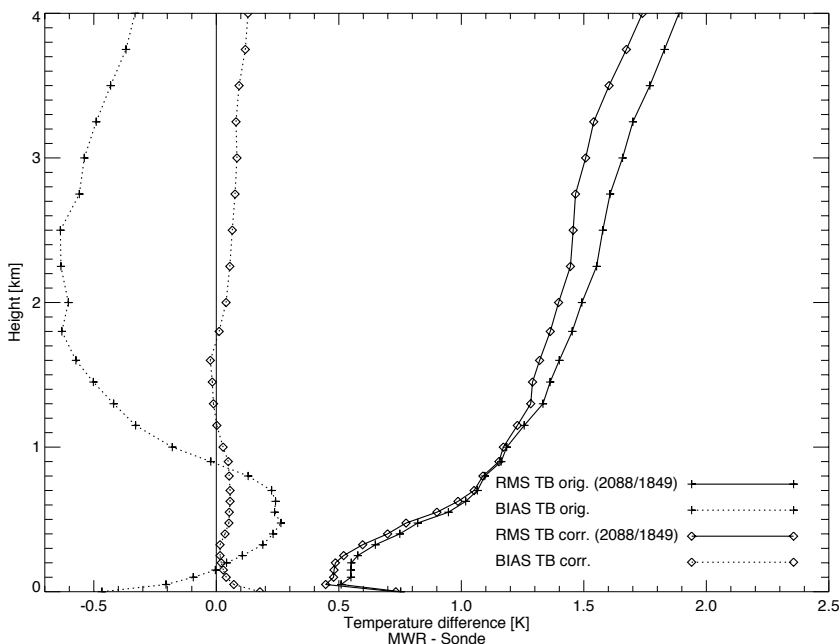
Fig. 5. Temperature profile differences during clear-sky conditions only from August 2008–December 2009 between HATPRO and radiosonde measurements. The HATPRO retrieval coefficients and the TB-offset correction were derived using exactly the same clear-sky measurements as considered in the evaluation. TB org. shows the retrieval results without using the systematic TB offset correction while TB corr. shows the results applying the systematic TB offset correction. A total number of 487 matching HATPRO/radiosonde cases were considered, in 486 cases the MWR measurements passed the quality control and were evaluated in the plot.
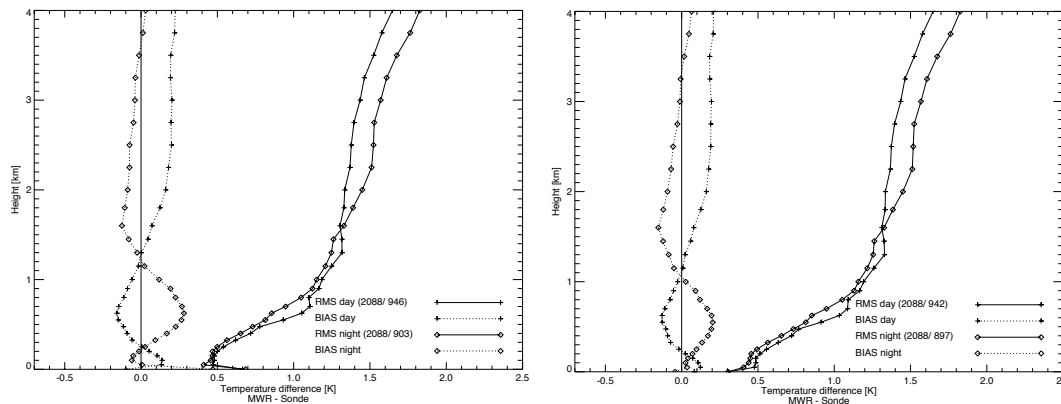
Fig. 6. Temperature profile differences during all-sky conditions from August 2006–December 2009 between HATPRO and radiosonde measurements. The HATPRO retrieval coefficients were derived from the whole 1992–2009 radiosonde data set, whereas and the TB correction was derived only from clear-sky measurements as in Fig. 5. TB org. shows the retrieval results without using the systematic TB offset correction while TB corr. shows the results applying the systematic TB offset correction. A total number of 2088 matching HATPRO/radiosonde cases were considered; in 1849 cases the MWR measurements passed the quality control and are evaluated in the plot.

Fig. 7. Temperature profile differences during all-sky conditions from August 2006–December 2009 between HATPRO and radiosonde measurements differentiated by day and night (left). The HATPRO retrieval coefficients were derived as in Fig. 6; *day* shows the retrieval results only at 12:00 UTC, whereas *night* only at 00:00 UTC. A total number of 2088 matching HAT-PRO/radiosondes were available, 946 12:00 UTC, respectively 903 00:00 UTC MWR measurements passed the quality control and are evaluated in the plot. The plot on the right hand side shows the same retrieval evaluation setup, with the exception that also the 2 m-surface temperature is used as a predictor for the multi-linear regression.
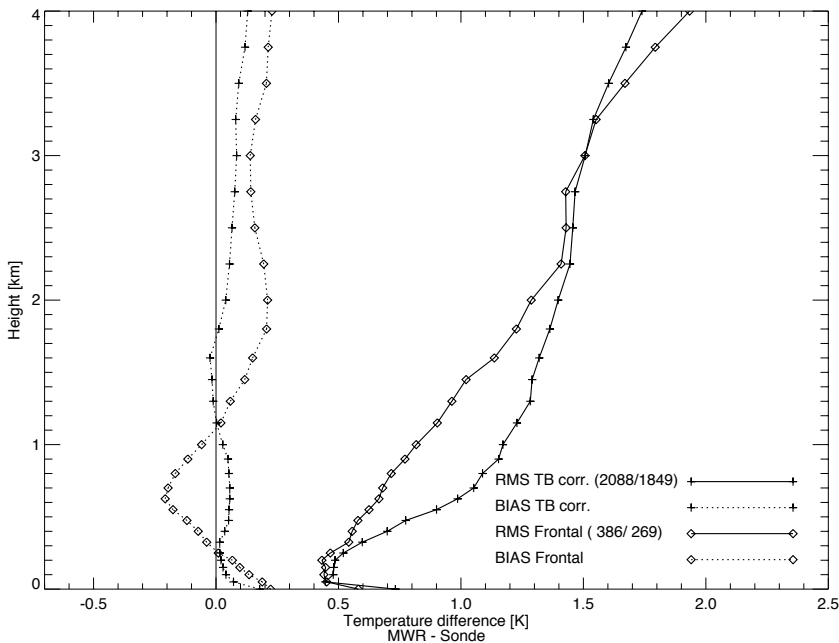
Fig. 8. Temperature profile differences during all-sky and frontal (see text for details) conditions from August 2006–December 2009 between radiosonde and HATPRO measurements. A total number of 2088 all-sky HATPRO/radiosondes measurements were available – 1757 measurements passed the quality control and are evaluated in the plot. Of the simultaneous 385 frontal HATPRO/radiosonde measurements, 236 passed the quality control and are evaluated in the plot.