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A model-based approach to adjust microwave observations for operational applications: results of a campaign at Munich Airport in winter 2011/2012

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Abstract

In the frame of the project "LuFo iPort VIS" which focuses on the implementation of a site specific visibility forecast, a field campaign was organised to offer detailed information to a numerical fog model. As part of additional observing activities a 22-channel microwave radiometer profiler (MWRP) was operating at the Munich Airport site in Germany from October 2011 to February 2012 in order to provide vertical temperature and humidity profiles as well as cloud liquid water information. Independently from the model-related aims of the campaign, the MWRP observations were used to study their capabilities to work in operational meteorological networks. Over the past decade a growing quantity of MWRP has been introduced and a user community (MWRnet) was established to encourage activities directed at the set up of an operational network. On that account, the comparability of observations from different network sites plays a fundamental role for any applications in climatology and numerical weather forecast.

In practice, however, systematic temperature and humidity differences (bias) between MWRP retrievals and co-located radiosonde profiles were observed and reported by several authors. This bias can be caused by instrumental offsets as well as by the absorption model used in the retrieval algorithms. At the Lindenberg observatory besides a neural network provided by the manufacturer, a measurement-based regression method was developed to reduce the bias. These regression operators are calculated on the basis of coincident radiosonde observations and MWRP brightness temperature (TB) measurements. However, MWRP applications in a network require comparable results at just any site, even if no radiosondes are available.

The motivation of this work is directed to a verification of the suitability of the operational local forecast model COSMO-EU of the Deutscher Wetterdienst (DWD) for the calculation of model-based regression operators in order to provide unbiased vertical profiles during the campaign at Munich Airport. The results of this algorithm and the retrievals of a neural network, specially developed for the site, are compared with radiosondes from Oberschleißheim located about 10 km apart from the MWRP site.

The bias of the retrievals could be considerably reduced and the accuracy, which has been assessed for the airport site, is quite similar to those of the operational radiometer site at Lindenberg above 1 km height. Additional investigations are made to determine the length of the training period necessary for generating best estimates. Thereby three months have proven to be adequate. The results of the study show that on the basis of numerical weather prediction (NWP) model data, available everywhere at any time, the model-based regression method is capable to provide comparable results at a multitude of sites. Furthermore, the approach offers auspicious conditions for automation and continuous updating.

1 Introduction

The campaign of the project LuFo iPort (innovative airport) was organised from October 2011 to February 2012 and had its focus on forecast techniques of poor visibility, one among various weather related phenomena affecting airport management and traffic. DWD in cooperation with the University of Bonn was implementing a site specific fog forecasting system for Munich International Airport (Rohn et al., 2010). Therefore the fog forecasting model PAFOG (Bott and Trautmann, 2002) was upgraded in order to integrate local observations from instruments installed close to the runways. Among them a 22-channel microwave radiometer profiler MP-3000A from Radiometrics (Ware et al., 2003) was operating at the airport site during the campaign to provide additional observations. Independently from the visibility forecasting studies, the MWRP observations can be used to investigate the capabilities of microwave radiometers for applications in operational networks.

Microwave radiation emitted by the atmosphere contains information on temperature, water vapour, and cloud liquid water. A comprehensive review on ground-based microwave radiometry is given by Westwater et al. (2005). The microwave technology has reached a formidable level over the past decade and state-of-the-art radiometers are capable to provide continuous observations in unattended mode during all weather

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conditions. Thus, the prerequisites exist to start activities towards operational networks. For example, a user community MWRnet (http://cetemps.aquila.ifn.it/mwrnet) was established to support ambitions of people working with ground-based radiometers. Furthermore, within the European COST action EG-CLIMET (European Ground-Based Observations of Essential Variables for Climate and Operational Meteorology) efforts have been initiated, e.g. to establish "best practice" for making MWRP observations/retrievals and to develop common retrieval algorithms with error analysis. However, good calibrations and accurate knowledge about radiative transfer are fundamental for achieving progress towards network applications. Comparable results at just any site of a network are indispensible for operational use.

2 Motivation

For the application of retrieval algorithms developed to derive vertical profiles, unbiased measurements are assumed. Experiences obtained during a decade of microwave profiling at the Lindenberg observatory indicate that, in practice, systematic differences in observations and retrievals are not unusual and change over time. Both technical modifications of the instruments and revised retrieval procedures over time can result in relevant variations.

Furthermore, discrepancies do not only occur along the time-axis but can also be caused by uncertainties in the microwave absorption models. A model-dependent bias was found by Liljegren et al. (2005) for the K-band channels between 22 and 30 GHz applying data from the Atmospheric Radiation Measurement (ARM) program site near Lamont, Oklahoma. Hewison et al. (2006) compared various radiative transfer model calculations and radiometer observations from Payerne, Switzerland, in cloudfree conditions during an experiment in 2003/2004 and stated that differences are partially due to the applied absorption model. Data from the same campaign at Payerne were used by Cimini et al. (2006) for an analysis of TB differences between two independent radiometers, as there were: Radiometrics TP/WVP-3000 and ASMUWARA, built by IAP

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of University of Bern. The results showed that discrepancies remain for comparable channels although different channel specifications were taken into account. Löhnert and Maier (2012) evaluate reliability and accuracy of atmospheric temperature profiles derived by the MWRP system HATPRO (Rose et al., 2005) operated at Payerne observatory in the time period from 2006 to 2009. They observed significant TB offsets between radiometer measurements and radiative transfer calculations during clear-sky situations. A comparison of retrievals with simultaneous radiosondes revealed systematic differences ranging from −0.6 to +0.3 K for the lowest 4 km. The deviations had been considerably reduced to smaller than ±0.1 K when a TB offset correction was used. Additionally, liquid nitrogen calibration can result in offset changes as reported in the same work.

In view of these facts, techniques are needed to compensate the well-known deficiencies. At the Lindenberg observatory an observation-based regression method REG_{obs} has been developed and succesfully applied using MWRP and radiosonde measurements from the past to calculate regression operators. The method removes systematic errors and produces weak-biased retrievals with respect to radiosondes (Güldner and Spänkuch, 2001). This technique is quite mature and used operationally. The need of adjustments in order to provide both comparable results over longer time periods and bias-reduced temperature and humidity profiles for practical application is demonstrated in Fig. 1.

Given are bias and standard deviations (STD) of temperature and vapor density from June to August in different years representative for the entire period. Figures of this kind can be generated operationally to evaluate the quality of continuous MWRP observations. Compared are both real-time results of the neural net (NN) which had been used in the considered period (Solheim et al., 1998) and the real-time retrievals derived by the REG_{obs} operator calculated by TB vs. radiosonde combinations from a past period. For temperature the STD of NN and REG_{obs} are quite similar ranging from about 0.5 K near the surface to about 1–1.3 K at 2 km and remainig less than 2 K up to 6 km. In contrast, the systematic deviations of retrievals are different from

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one another. Whereas the bias for REG_{obs} is really small for all examples, the NN differences range from 0 K near the surface to −1 K between 4 and 6 km in summer 2000 (Fig. 1a) and start at 1 K in the lower levels to reach about 0 K above 5 km in 2004 shown in Fig. 1b. In summer 2010 (Fig. 1c) the bias indicate values of even approximately −2 K. The lower panels of Fig. 1 show the accuracy for water vapor density retrievals. The STD of NN and REG_{obs} are rather in accordance. But here too, the retrievals differ considerably in their bias. During the discussed decade from 2000 to 2010, the MWRP participated at field campaigns and was sent back to factory for repair and upgrades. Furthermore, several calibrations were performed. However, each of these actions can cause systematic differences. The examples demonstrate that the REG_{obs} method is capable to harmonise MWRP retrievals over time and that any kind of correction has to be applied to provide suitable temperature and humudity profiles.

Figure 2a shows a further proof that the comparability of microwave observations is not trivial and can not be expected necessarily within a radiometer network. Compared are corresponding channels of the Radiometrics TP/WVP 3000 (MWRP1) and MP-3000A (MWRP2). Channels from 1 to 5 are arranged in the K-band from 22.23 to 30 GHz and the remaining seven channels along the oxygen complex between 51.25 and 58.8 GHz. The observations differ most for channel 1 (ch1) and ch5 at frequency 22.35 and 30 GHz, respectively. In the V-band ch6 and ch7 (51.25 and 52.28 GHz) have maximum differences. Thereby MWRP1 measures higher TB values for ch1 and ch5 whereas the opposite is the case for ch6 and ch7. A specific view is given in Fig. 2b. The radiance was calculated on the basis of the radiosonde (RS) using a radiative transfer model and displayed together with 10 min mean values of both microwave radiometers. Differences of the channel band passes have not been considered. Note, plotted are values at 11:00 UTC when the radiosonde was launched. It can be seen that in some cases MWRP1 and RS agree well, for example ch5 and ch6. For other cases MWRP2 corresponds better with RS, i.e. ch1, ch4 and ch7. However, no statement can be made whether MWRP1 or MWRP2 operates more accurately with

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respect to RS. It can be merely noted that for each frequency the difference between two radiometers includes a specific bias.

We get comparable results if the bias is taken into account as illustrated in Fig. 3. Shown are daily courses of TB differences for the frequencies with minimum and maximum deviations at 30 and 51.2 GHz, respectively. A third curve is plotted for 54.95 GHz which had a mean difference close to zero even from the start. Subsequent to the corrections all deviations matched well.

In conclusion of these facts, it can be stated that corrections of TB observations are necessary if harmonized data are required. This is particularly true for network applications if a multitude of radiometers operate in really unmanned mode. Independent observation-based regression methods have proven their applicability at sophisticated sites equipped with radiosondes. This method compensates radiometer-dependent and radiative transfer model-specific inaccuracies. In the following is studied whether an observation-based method can be potentially generalized for applications at various network sites based only on NWP model data.

3 Data sets

The appropriateness of NWP model data to adjust MWRP observations was shown in a study during the LUAMI campaign in November 2008 applying microwave data from eight stations in Europe (Güldner et al., 2009). In the present work the model-based regression method (REG_{mod}) is analysed in order to get more representative conclusions, made possible through the longer time period of the campaign. In addition, intercomparisons with radiosondes of Oberschleißheim, located approximately 10 km apart, can be performed to assess the accuracy of the REG_{mod} method. Radiosonde observations are generally only used for validation and not for calculation of REG_{mod} operators. For the entire period from October 2011 to February 2012, NWP model data for the gridpoint representing the airport site were extracted from the operational local forecast model (COSMO-EU) of the DWD. The NWP temperature and

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humidity profiles are available with a temporal resolution of one hour for the model runs started at 00:00 and 12:00 UTC, respectively. In addition, MWRP observations and neural network (NN) retrievals, provided with a temporal resolution of about 1 min were summed up to 10 min means.

In principle, any of the hourly model data sets could be used for the calculation of REG_{mod} operators, because for all of these data, TB measurements are available as well. It is recalled that the REG_{mod} method is based on the combination of coincident forecast profiles and MWRP observations. However, as the NWP model data are strongly correlated if located close together in terms of time, just only one of the hourly data sets of each model run was selected for further application. Generally, the NWP model forecasts at the start time 00:00 and 12:00 UTC, respectively, are representing results of a numerical analysis. These data should be used for REG_{mod} applications at numerous sites in an operational network because available meteorological information are optimally integrated in the analysis. Concerning the model gridpoint of the airport site, the numerical analysis is obviously influenced by the RS launched nearby at Oberschleißheim. Therefore, additionally NWP model forecasts of the time step 11 h after the initialisation were selected for the calculation of REG_{mod} operators referred to as REG_{mod+11}. Nevertheless, it is likely that errors of the forecasts 11 h after the corresponding numerical analysis have an impact on the calculated REG_{mod+11} operators. But it should be noted that the presented investigation is directed on the minimisation of systematic deviations at any site of a potential MWRP network. Therefore, it is assumed that the mean profiles of temperature and humidity are homogeneous and weak-biased in respect to the real atmospheric state.

For this study, the complete dataset was divided into two groups. One part, containing observations on odd-numbered days was used for training of regression operators. The other independent dataset was applied for validation.

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4 Results

The REG_{mod} or REG_{obs} method are specific approaches to the solution of the inverse problem described by the radiative transfer equation (Güldner and Spänkuch, 2001). Estimated profiles $\hat{X}$ are calculated using the equation:

$$\hat{X} = x_0 + \mathbf{C}_{xy}\mathbf{C}_{yy}^{-1}(y - y_0). \quad (1)$$

$\mathbf{C}_{xy}$ represents the covariance matrix of temperature and humidity profiles x, extracted from the NWP model, and the simultaneous MWRP measurements y. $\mathbf{C}_{yy}$ is the auto-covariance matrix of y. Based on this approach various regression operators REG_{mod} were calculated.

For a general characterisation of the campaign period, monthly mean profiles of radiosonde observations are calculated and displayed in Fig. 4. Basically, a decrease of temperature and humidity from October to February is apparent. In November 2011, even the mean temperature profile shows a strong inversion. A large number of fog cases was recorded and with regard to the main aim of the campaign, namely a test of site specific visibility forecasts, it was the most suitable month. Initially, a screening was performed to reject faulty data. Therefore the information of the rain sensor installed on the radiometer was used. Additionally, the brightness temperatures are cross-checked by eye to remove obvious spikes. Appropriate preparations are necessary to avoid that inaccurate observations are included in the training data set, which could cause a smearing of interrelations between TB and NWP model data expressed by REG_{mod} operators. Moreover, outliers in the validation data set result in incorrect assessments of the retrieval accuracy.

After the screening and according to Eq. (1), REG_{mod} operators are calculated from NWP model data on odd-numbered days at 00:00 and 12:00 UTC, respectively. Matrices are prepared for three different period lengths named as follows:

T1mMO: NWP model data of one month (October 2011)
are used for training.

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T3mMO: NWP model data of three months
(October–December 2011) are used.
T5mMO: NWP model data of five months
(October 2011–February 2012) are used.

The even-numbered days of the entire five months period are generally used as validation dataset. Figure 5 show the results of this intercomparison calculated on the basis of 104 cases. Plotted are the mean values (MV) of regression retrievals minus radiosonde profiles and the corresponding STD separated according to the different duration of the training periods. Furthermore, the STD of the radiosondes and the results of the NN algorithm provided by the manufacturer are shown. All calculations were done for temperature and vapor density.

The NN retrievals show large negative temperature deviations increasing steadily with height and a significant moist bias above 300 m up to about 4 km. Regarding the regression methods, the largest differences occur if only one month was used for the calculation of REG_{mod} operators (T1mMO, red lines). The bias of T1mMO is significantly higher ranging for temperature from −1 to +2 K for heights at 1 and 3 km, respectively. The STD has greater values above 2 km height for temperature and up to 2 km for water vapor compared to all other retrieval algorithms. Additionally to the small size of the sample used for T1mMO, differences could be induced by the fact that October was the warmest and most humid month of the campaign, and therefore not adequately representative. Consequentially, water vapor retrievals show the largest bias for the T1mMO operator as well. A negative bias was found for levels between 300 m and 2.5 km a.s.l.

In contrast, the results are quite similar if matrices derived from three months (T3mMO, yellow) or five months (T5mMO, green) training periods are applied. It indicates that data of three months may be sufficient for using site-specific REG_{mod} operators to redraw systematic errors within a microwave profiler network. The systematic deviations are small and have averaged values limited within 0.5 K for temperature and 0.2 g m^{-3} for vapor density. T3mMO and T5mMO provide temperature retrievals with

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STD from 1 K to better than 1.5 K up to approximately 4 km. For humidity maximum STD of 0.7–1.0 g m^{-3} are found between 0.5 and 1.5 km. Note, REG_{mod} humidity retrievals provide about half of the radiosonde STD across all heights.

Even though large systematic differences are observed for the NN, the method provides comparable results concerning the STD. For this calculation unbiased retrievals are assumed. Nevertheless, at height levels above 1 km (temperature) and between 0.5 and 1.5 km (humidity) NN provides slightly better retrievals. For water vapor better NN results are achieved exactly for those altitudes, which show a larger STD. This could be related to the NN ability to handle nonlinear relationships better, especially important for extreme cases. The example demonstrates the potential of NN algorithms if systematic deviations could be avoided.

Finally, a statistic is created, which compares retrievals calculated by the REG_{mod} operator (T5mMO) for the temporary site in Munich with profiles from the reference site at Lindenberg observatory. Additionally, MV and STD are included in the intercomparison if REG_{mod+11} operators are used. They are calculated on the basis of forecast data taken from 11 h after the initialisation, as described in Sect. 3. In Lindenberg temperature and humidity profiles are derived by a retrieval approach basing on radiosonde and in situ MWRP measurements from the past. This REG_{obs} method has been successfully applied for more than ten years. During the campaign the 12-channel MWRP (TP/WVP 3000) was running in Lindenberg, continuing the operational profiling required for the reference site. The airport site is located at 11.48° E longitude, 48.21° N latitude, height 446 m m.s.l. and the Lindenberg site at 14.12° E, 52.21° N, 125 m m.s.l. Figure 6 shows mean values and STD for both sites as performed in Fig. 5. The absolute temperature bias is less then 0.5 K up to 6 km a.s.l. and quite similar in scale for both locations. The mean differences of vapor density are almost all less than 0.1 g m^{-3}. Only between 0.8 and 1.5 km REG_{mod+11} shows slightly higher values. With regard to STD, comparable values are achieved for heights above 700 m. For the levels near to the surface, Lindenberg retrievals are significantly better if compared with the corresponding radiosondes. This result is conceivable if one takes into account that for

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the airport site, the validation is done with RAOBs launched at a distance of about 10 km. Especially in the lowest layers, significant deviation can occur. Furthermore, NWP model data of the 11th hour after the initialization are used for the training of the $\mathrm{REG}_{\mathrm{mod}+11}$ operators. Forecast errors are expected to be larger in lower layers, especially for humidity which is highly variable in terms of time and space. Both issues can result in additional deviations as found and displayed in Fig. 6. Given these facts, the $\mathrm{REG}_{\mathrm{mod}}$ method works reliably and offers good prospects to generate comparable results within a network of microwave profilers.

5 Conclusions

A MWRP had been operating at Munich Airport site from October 2011 to February 2012 to support a campaign aimed to investigations of site-specific visibility forecasts. The radiometer had been worked reliably and observations were used to simulate procedures required for operational application within a microwave profiler network. In particular, NWP model data were used to produce weak-biased temperature and humidity profiles. In order to provide comparable retrievals, regression operators were calculated on the basis of various training data sets using forecasted profiles and MWRP measurements. The results of the model-based regression $\mathrm{REG}_{\mathrm{mod}}$ used for data from the temporary site Munich and the observation-based regression $\mathrm{REG}_{\mathrm{mod}}$ applied at the permanent site Lindenberg were compared. The accuracies of retrievals for both methods show a good correlation above 700 m a.s.l. The differences below 700 m are mainly caused by the use of forecast data instead of in situ observations.

The usefulness of a model-based regression method to redraw systematic errors and to provide comparable results within a network has been demonstrated. Additionally, the preconditions have been established to make NWP model applications possible. Harmonized brightness temperature values can be provided by forward model calculations of the radiative transfer using the model-consistent algorithm, if required. Furthermore, it is interesting to note, that permanent interferences at selected frequencies are

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recognized by observation-based regression methods. The observations of disturbed channels are automatically devaluated by the site-specific REG_{mod} operator.

Finally, model data as well as radiometer measurements are always available in operational weather services. That offers good prospects for a continuous and partially autonomous updating of REG_{mod} operators at a multitude of radiometer sites.

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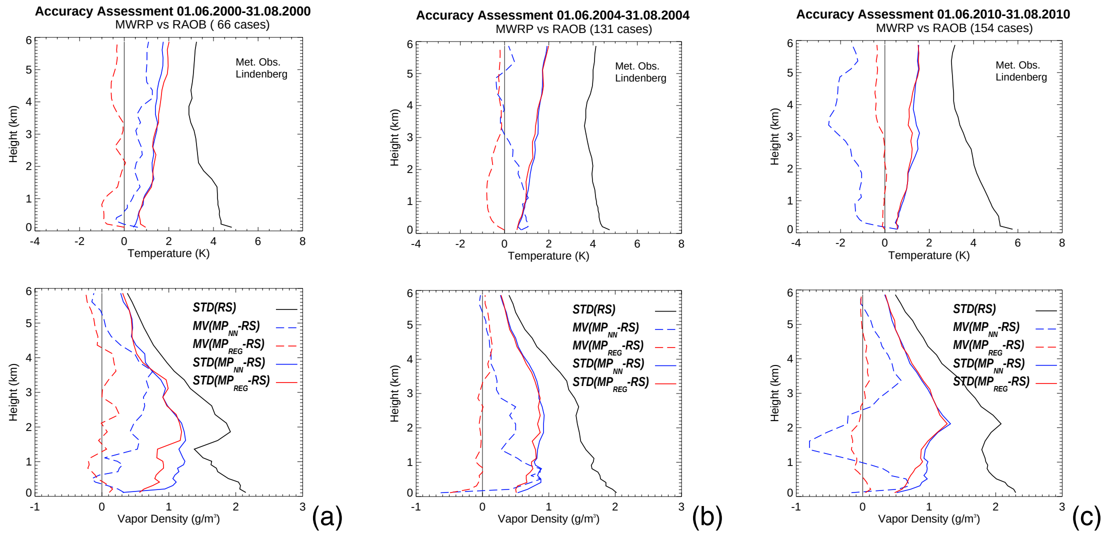

Fig. 1. Temperature (top panels) and humidity (bottom panels) retrieval bias (MV; dashed lines) and standard deviation (STD; solid lines) for different techniques – NN (blue) and REGobs (red) – calculated for the summer periods 2000 **(a)**, 2004 **(b)**, and 2010 **(c)**. Black lines show STD of radiosondes used in the intercomparison.

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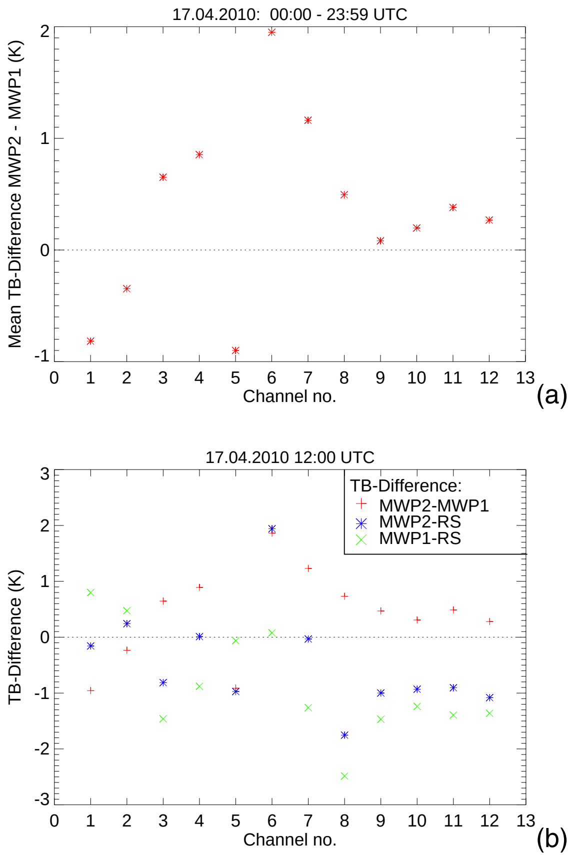

Fig. 2. Brightness temperature differences observed by two radiometers operating at the same site. Shown are the mean differences during a cloudless day (17 April 2010) at Lindenberg **(a)** and the deviations from radiative transfer model calculations based on a simultaneous radiosonde **(b)**.

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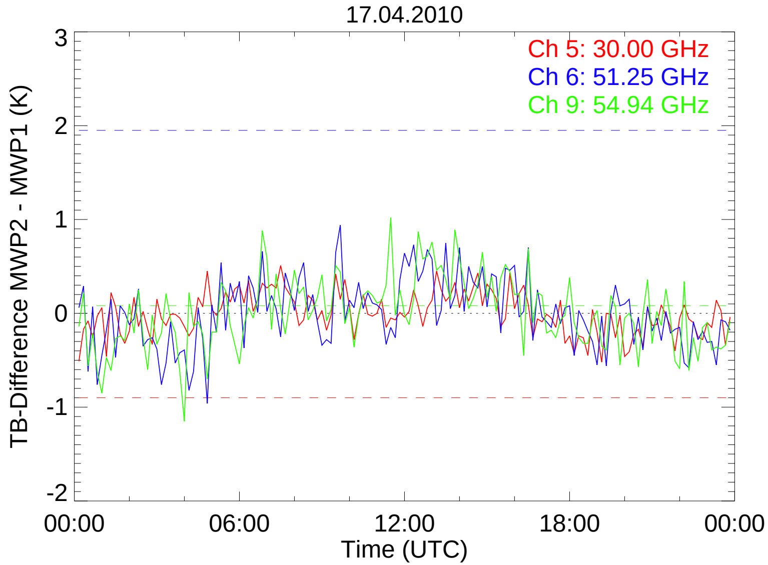

Fig. 3. Bias (dashed lines) and diurnal cycle of unbiased TB deviations from selected channels observed by two microwave radiometers operating at Lindenberg. Shown are data from 17 April 2010 as in Fig. 2.

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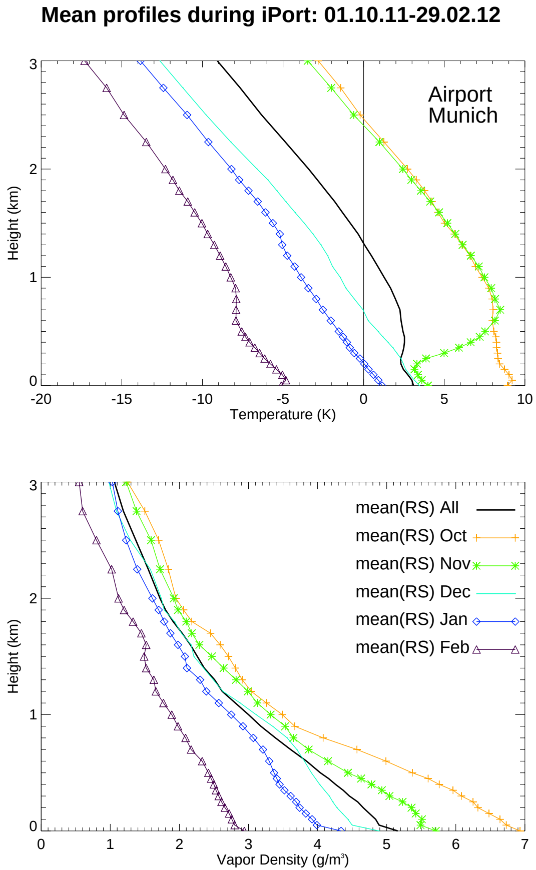

Fig. 4. Monthly mean temperature (top panel) and vapor density profiles (bottom panel) during the campaign 2011/2012.

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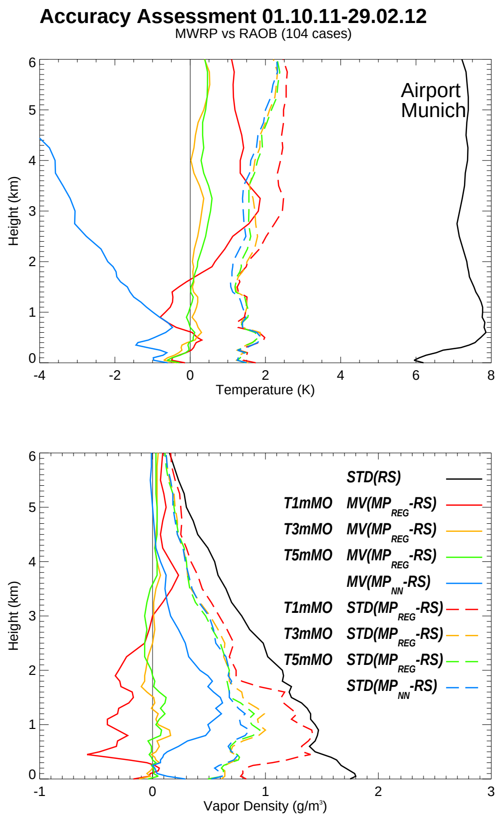

Fig. 5. Retrieval errors of temperature (top panel) and vapor density (bottom panel) during the campaign at Munich Airport from October 2011 to February 2012. Plotted are mean values (MV; solid line), defined as retrieval minus radiosonde, and standard deviations (STD; dashed line) for various methods representing different time periods of training. Solid black line shows the STD of radiosondes used in the intercomparison.

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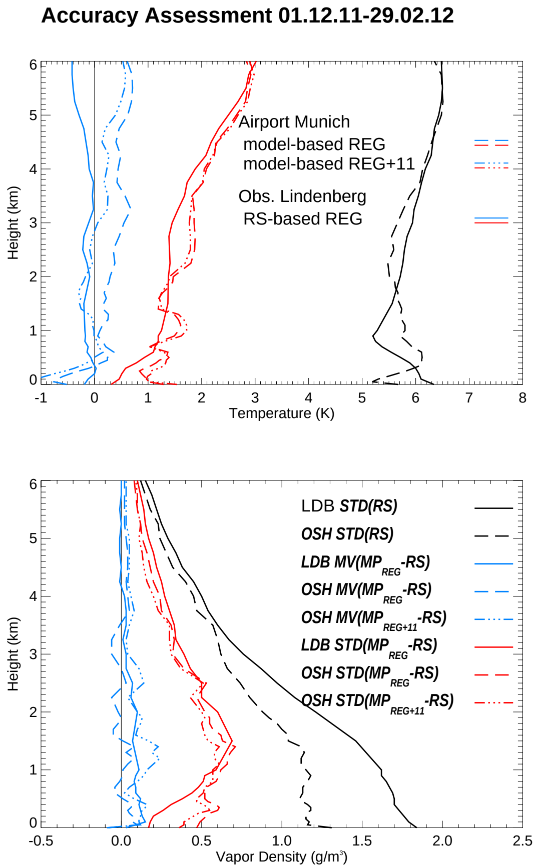

Fig. 6. Retrieval errors of temperature (top panel) and humidity (bottom panel) calculated for Lindenberg (REG_{obs} was applied, solid lines) and Munich (REG_{mod} – dashed lines – and REG_{mod+11} – dash-dotted lines – were used). Bias (MV, blue) and STD (red) are plotted together with the STD of radiosondes (black) at the corresponding sites in Lindenberg and Munich/Oberschleißheim.

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