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Study of cloud effect on the tropospheric temperature retrievals

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Abstract

In this paper, we address the characterization of clouds and its inclusion in microwave retrievals in order to study its effect on tropospheric temperature profiles measured by TEMPERA radiometer. TEMPERA is the first ground-based microwave radiometer that allows to obtain temperature profiles in the troposphere and stratosphere at the same time. In order to characterize the clouds a multi-instrumental approach has been performed. Cloud base altitudes were detected using ceilometer measurements while the integrated liquid water was measured by TROWARA radiometer. Both instruments are co-located with TEMPERA in Bern (Switzerland). Using this information and a constant Liquid Water Content value inside the cloud a liquid profile is provided to characterize the clouds in the inversion algorithm. Microwave temperature profiles have been obtained incorporating this water liquid profile in the inversion algorithm and also without considering the clouds, in order to asses its effect on the retrievals. The results have been compared with the temperature profiles from radiosondes which are launched twice a day at the aerological station of MeteoSwiss in Payerne (40 km W of Bern). Almost one year of data has been analyzed and 60 non-precipitating cloud cases were studied. The statistical analysis carried out over all the cases evidenced that temperature retrievals improved in most of the cases when clouds were incorporated in the inversion algorithm.

1 Introduction

The importance of the knowledge of the temperature structure in the atmosphere has been widely recognized. Temperature is a key parameter for dynamical, chemical and radiative processes in the atmosphere. In the troposphere the atmospheric temperature profiles are important for weather fore- and now-casting. Different techniques allow to measure atmospheric temperature profiles as radiosonde, FTIR, LIDAR or satellite and ground-based microwave radiometers. The main advantage of microwave radiometers against other instruments is a high temporal resolution with a reasonable good spatial resolution. Moreover, the measurement at a fixed location allows to observe local atmospheric dynamics over a long time period.

Ground-based microwave radiometers for tropospheric temperature profiles are well established and exist in different configurations (Stähli et al., 2013). Some examples are MICCY (microwave radiometer for cloud cartography) (Crewell et al., 2001), RPG-HATPRO (Radiometer Physics GmbH-Humidity and Temperature Profiler) (Rose et al., 2005), Radiometrics MP-3000A (Ware et al., 2003) and ASMUWARA (All-Sky MUlti-WAvelength RAdiometer) (Martin et al., 2006).

Many studies have addressed the characterization of the temperature in the troposphere using microwave radiometer measurements (Stähli et al., 2013; Löhnert and Maier, 2012). However, despite the presence of clouds in many atmospheric observations, the study of cloud effect on the temperature retrievals has not yet been dealt properly. This work addresses the characterization of clouds and its incorporation in the temperature retrievals in order to study its effect on the temperature profiles.

The paper is organized as follows: in Sect. 2, the instrumentation and the measurements are described. The methodology used to characterize the clouds and its inclusion in the retrievals are presented in Sect. 3. Section 4 presents the results obtained for almost one year of measurements. Finally the conclusions are found in Sect. 5.

2 Instrumentation and measurements

Temperature profiles are provided using the radiometer called TEMPERA. This instrument is a heterodyne receiver at a frequency range of 51–57 GHz. Figure 1 shows a picture of TEMPERA which is operated in a temperature-stabilized laboratory at the ExWi Building of the University of Bern (Bern, Switzerland; 575 m above see level; 46.95° N, 7.44° E, view direction in azimuth: southeast (131.5°)). In this lab a styrofoam window allows views of the atmosphere over the zenith angle (za) range from 30° to 70°. The instrument mainly consists of three parts: the frontend to collect and detect the microwave radiation with two backends, a filterbank and a digital FFT spectrometer for the spectral analysis. Technical details about the antenna, the signal treatment in the frontend and calibration can be found in Stähli et al. (2013).

For tropospheric measurements we use a filterbank with 4 channels. By adjusting a local oscillator (LO) frequency with a synthesizer it is possible to measure at 12 frequencies which are listed in Table 1. In this way we cover uniformly the range from 51–57 GHz at positions between the emission lines (see Fig. 2). The lower 9 channels have a band-width of 250 MHz and the channels 10–12 have a bandwidth of 1 GHz to enhance the sensitivity in the flat spectral region.

The second backend is used for stratospheric measurements and contains a digital FFT spectrometer (Acqiris AC 240) for the two emission lines centered at 52.5424 and 53.0669 GHz. Stratospheric retrievals are not addressed in this paper. A detailed description of this backend and about the stratospheric retrievals can be found in Stähli et al. (2013).

The measurements are performed in periodic cycles of 60 s. Each cycle starts with a hot load calibration in combination with a noise diode for 9 s followed by the atmosphere measurements. They consist of two parts: first a 15 s period at a zenith angle za = 30° to observe with the FFT spectrometer and simultaneously with the filterbank, and second, a tipping curve in 3 s periods and angular steps in 5° up to za = 70°. After calibration, the output of each measurement cycle is a set of 108 brightness temperatures of the filterbank at 12 frequencies and at 9 zenith angles. For the tropospheric retrieval we use a mean of 15 measurement cycles leading to a time resolution of 15 min (Stähli et al., 2013).

The cloud characterization has been performed using different instrumentation. Integrated Liquid Water (ILW) was measured by means of the radiometer TROWARA that is installed next to TEMPERA. This radiometer measures the radiation from the sky in the same direction at 21, 22 and 31 GHz. A detailed description about this instrument and the inversion algorithms is presented by Matzler and Morland (2009). Moreover, a Vaisala CT25K ceilometer was used to measure the cloud base heights.

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This instrument employs a pulsed diode laser that emits at 905 nm. The backscatter radiation caused by haze, fog, mist, precipitation and clouds is measured as the laser pulses traverse the sky. The resulting backscatter profile, i.e. signal strength vs. height, is stored and processed and the cloud bases are detected. The elevation angle of the ceilometer has been set to 40° to guarantee the observation of clouds in the same direction as TEMPERA is measuring.

Independent in-situ temperature measurements performed by means of radiosondes have been used in this study. These radiosondes are regularly launched twice a day at 11:00 and 23:00 UTC in the atmospheric survey station in Payerne (46.82° N, 6.95° E; 491 m a.s.l. and 40 km W of Bern). The station belongs to MeteoSwiss.

3 Methodology

3.1 Retrieval

TEMPERA radiometer measures thermal radiation from 51–57 GHz on the wing of the 60 GHz oxygen-emission region of the microwave spectrum. Oxygen is a well-mixed gas whose fractional concentration is independent of altitude below approx. 80 km. Therefore the radiation contains information primarily on atmospheric temperature.

A ground-based microwave radiometer measures a superposition of emission and absorption of radiation at different altitudes. The received intensity at ground level can be expressed in the Rayleigh–Jeans limit ($h\upsilon \ll kT$) as a function of the brightness temperature T_B. In these conditions the radiative transfer equation is given by

$$T_B(h_0,\theta) = T_0 e^{-\tau(h_1)} + \int_{h_0}^{h_1} T(h) e^{-\tau(h)} \alpha \frac{1}{\cos(\theta)} dh \qquad (1)$$

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where $T_B(\theta)$ is the brightness temperature at zenith angle θ, T_0 is the brightness temperature of the cosmic background radiation, $T(h)$ is the physical temperature at height h, h_0 is the Earth surface, h_1 is the upper boundary in the atmosphere, α is the absorption coefficient and τ is the opacity. The opacity is defined as

$$\tau(h) = \int_{h_0}^{h} \alpha(h')\mathrm{d}h' \quad (2)$$

From Eq. (1) we see that it is possible to calculate the estimated brightness temperature just knowing the state of the atmosphere (forward modeling). A more difficult task is to solve the *inverse problem*: given the measured brightness temperatures, what is the physical temperature profile that gave rise to them.

In this study the measured spectrum is inverted to a temperature profile by the optimal estimation method (OEM) (Rodgers, 2000) using the radiative transfer model ARTS/QPack (Eriksson et al., 2011). This principle is based on Bayes' probability theorem. A detailed description of this method applied to our system can be found in Stähli et al. (2013).

To solve the inverse problem we use the Gauss–Newton iterative method, whose solution can be expressed in a matrix notation as follow:

$$\boldsymbol{x}_{i+1} = \boldsymbol{x}_i + \left(\mathbf{S}_a^{-1} + \boldsymbol{K}_i^{T}\mathbf{S}_\epsilon^{-1}\boldsymbol{K}_i^{-1}\right)\left[\boldsymbol{K}_i^{T}\mathbf{S}_\epsilon^{-1}(\boldsymbol{y} - F(\boldsymbol{x}_i)) - \mathbf{S}_a^{-1}(\boldsymbol{x}_i - \boldsymbol{x}_a)\right] \quad (3)$$

where the vector $\boldsymbol{x}$ is the true temperature profile, $\boldsymbol{y}$ is the measured spectrum (brightness temperature), $\boldsymbol{x}_a$ is the a priori temperature profile, $\mathbf{S}_a$ is the a priori covariance matrix and $\mathbf{S}_\epsilon$ is the observation error-covariance matrix. The use of the forward model in this equation is noted by F and the vector $\boldsymbol{K}$ is the weighting function ($\boldsymbol{K} = \partial F/\partial \boldsymbol{x}$).

In the radiative transfer calculations we use the model of Rosenkranz and the model of Liebe for the absorption coefficient calculations: Rosenkranz (1998) for H_2O, Rosenkranz (1993) for O_2 and Liebe et al. (1993) for N_2 (Stähli et al., 2013). Moreover,

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a tropospheric water-vapor profile with an exponential decrease is included. This profile is calculated with the measured surface water vapor density from the ExWi Weather station (placed next to TEMPERA) and assuming a scale height of 2000 m (Bleisch et al., 2011). For other species like oxygen (O_2) and nitrogen (N_2) we used standard atmospheric profiles for summer and winter, which are incorporated into ARTS2 (middle latitude FASCODE (Fast Atmospheric Signature CODE) Anderson et al., 1986).

Figure 3 shows the absorption coefficient for oxygen, water vapor, liquid water and nitrogen for 5 different frequencies between 51 and 57 GHz. From this plot we observe that the spectral dependency in this range is very small for water vapor, liquid water and nitrogen. This is not true for oxygen, which is strongly dependent on frequency. Moreover, we observe that under cloudless conditions (ILW = 0), most of the absorption and emission in the atmosphere comes from oxygen dominating the contribution from water vapor and nitrogen. This is not true when clouds are present (ILW $\neq$ 0), since they have a strong influence in the frequency range from 51 to 53 GHz.

Despite its importance, the influence of liquid water in the forward model has not been sufficiently treated due to the difficulty of characterizing the clouds. Stähli et al. (2013) proposed to reduce its effect on the forward model using only the measured frequencies larger than 53 GHz, which are less affected by clouds. This improved the temperature retrievals as showed a comparison with radiosondes. However the discrepancies between temperature profiles from microwave radiometers and from radiosondes were still considerable.

3.2 Cloud characterization

A multi-instrumental approach has been used in order to characterize the clouds. All the instruments used for this purpose are collocated at the ExWi Building of the University of Bern. Cloud base altitudes (CBA) were detected using a Vaisala CT25K ceilometer that is continuously operated. The base of the cloud is detected using a derivative method, which identifies a maximum gradient in the backscattered signal at the base cloud altitude.

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The ILW was measured by TROWARA radiometer. The presence of clouds was assumed for those cases with ILW larger than 0.025 mm.

An important parameter to characterize the clouds is the Liquid Water Content (LWC). This parameter indicates the mass of liquid water per unit volume of air and usually is expressed in $\mathrm{g\,m^{-3}}$. Different authors have characterized the LWC for different kind of clouds (Hess et al., 1998; Korolev et al., 2007; Rosenfeld and Lensky, 1998). Cirrus and fog present much lower water content than other kind of clouds, with values around 0.03 and $0.06\,\mathrm{g\,m^{-3}}$, respectively. In a continental environment, the LWC values are around $0.26\,\mathrm{g\,m^{-3}}$ for cumulus, $0.28\,\mathrm{g\,m^{-3}}$ for stratus and between 1.0 and $3.0\,\mathrm{g\,m^{-3}}$ for cumulonimbus, depending if they are growing or dissipating (Hess et al., 1998; Rosenfeld and Lensky, 1998). In this study we have assumed a constant LWC value of $0.28\,\mathrm{g\,m^{-3}}$ inside the clouds. This value is characteristic to stratus, which are the most typical clouds found in this study. Moreover, it is important to note that the value of this parameter was not critical for the microwave retrievals, since the differences in the retrieved temperature when different LWC values were included in the algorithms were within the uncertainties of the method.

Knowing the ILW and the LWC values it is possible to get directly the cloud thickness (Δz) from the next expression:

$$\mathrm{ILW} = \mathrm{LWC} \times \Delta z \tag{4}$$

Moreover, using the information of the cloud base altitude retrieved from the ceilometer and the cloud thickness it is possible to provide a LWC profile (Fig. 4) to the forward model in order to study its effect on the temperature retrievals.

4 Results

As it was indicated in the previous sections continuous radiometer and ceilometer measurements are performed at the ExWi Building of the University of Bern. Moreover, radiosondes launched twice a day at 11:00 and 23:00 UTC at Payerne (40 km W of Bern)

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were available. In this study temperature profiles retrieved from TEMPERA radiometer have been compared with in-situ temperature measurements performed by radiosondes. Due to the limitations in the radiosonde launches just two profiles are compared per day.

Almost one year of data, from February to December of 2012, has been analyzed in this study. A total of 60 no-precipitating cloud cases were found. In order to study the cloud effect on the temperature retrievals, the profiles have been calculated including and not including a LWC profile in the forward model. When the LWC profile was not considered the retrievals were performed just using the channels with frequencies larger than 53 GHz as it was indicated in Stähli et al. (2013).

4.1 Cases of study

From the 60 cases 3 clear situations have been identified regarding the location and thickness of the clouds. The first one corresponds to the presence of thick clouds at medium and high altitudes. The second one is when the cloud are thin and are located at medium and high altitudes and the third one is when there is presence of low clouds.

Figure 5a shows the temperature profiles retrieved from radiosonde and from TEMPERA radiometer using and without using cloud information in the forward model. The measurements were done on 21 November 2012. Figure 5b presents the absolute temperature deviation between the radiosondes and the radiometer retrievals. For this case the cloud base altitude was detected at 2450 m a.s.l. and the cloud thickness was 1670 m. From the figure we observe a very good agreement between radiosonde and radiometer retrievals when the cloud was considered. The mean absolute temperature deviation in the first kilometer reached an averaged value of 0.8 ± 0.6 K. Although the discrepancies increased a little bit above this altitude, the mean absolute deviation was always below 3 K in the whole profile. However, we can observe that the discrepancies between the radiosonde and the microwave profile retrieved without cloud information are much larger. Although the agreement was reasonable in the lower profile, the discrepancies increased considerably above 1300 m a.s.l., reaching a maximum absolute

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deviation of 9.2 K at 4480 m a.s.l. This example evidenced a clear improvement in the temperature retrievals when cloud information was provided to the forward model.

Other atmospheric situations found in this study corresponded to the presence of thin clouds at medium and high altitudes. Figure 6 shows an example measured on 14 October 2012 at 23:01 UTC. For this night a cloud with a thickness of 108 m was detected at the altitude of 4304 m a.s.l. From this figure a good agreement between the temperature profiles retrieved from radiometer measurements and from the radiosonde is observed (Fig. 6a). We can observe that under these conditions there is not a clear difference in the retrievals when the LWC profile is incorporated in the forward model. The mean absolute temperature deviations in the whole profile were 1.3 ± 0.7 K and 1.0 ± 0.6 K with clouds and without cloud information in the retrievals, respectively. These results evidence that thin clouds at medium and high altitudes do not modify significantly the brightness temperature measured at ground base.

Figure 7 shows an example of low clouds. The measurements were performed on 26 October 2012 at 11:06 UTC. At this time a cloud of 481 m of thickness was detected at the altitude of 110 m a.g.l. In this situation the profiles retrieved from radiometer measurements showed different behaviour. While in the near range (below 1700 m a.s.l.) both showed relatively good agreement with the radiosonde profile (maximum absolute deviation was lower than 1.9 K), above this altitude the profile retrieved using cloud information (blue line) showed bigger discrepancies with the radiosonde than the other one. The mean absolute temperature deviation between the radiosonde and the microwave profiles above 1.7 km were 3.1 ± 0.4 K with cloud and 0.8 ± 0.5 K without cloud information. This example show that the incorporation of cloud information in the forward model does not improve the temperature retrievals at medium and high altitudes. It could be due to the difficulty of characterizing low clouds. The variability in the altitudes of low clouds is larger and in this sense the differences with the radiosonde could be important. Moreover, to provide a wrong LWC profile in the forward model in the near range where the retrievals are more sensitive could increase the differences in the solutions.

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4.2 Statistical study of temperature profiles

In this section a statistical analysis using the 60 cases of no precipitating clouds is performed. Figure 8 presents the mean absolute temperature deviation between radiosondes and microwave measurements using and without using the cloud information in the retrievals (blue and red lines, respectively). This figure shows that on average the differences in the temperature profiles from radiosondes and microwave radiometer are smaller when the clouds are incorporated in the forward model. Moreover, we also observe that the agreement for both radiometer retrievals are better at the lower than in the upper part of the troposphere. The mean absolute deviation is 0.88 ± 0.14 K below 2 km a.s.l., while it reaches 2.0 ± 0.4 K above this altitude for the retrievals with cloud information. The good agreement in the lower part evidences that the thermal structures in Payerne and Bern are very similar and it is reasonable to compare both instruments although they are located in different places. The bigger discrepancies in the upper part could be due to the lower resolution of the microwave radiometer in the far range. Similar discrepancies in the temperature were found in other studies where co-located radiosondes and microwave radiometers were compared. Güldner and Spänkuch (2001) reported differences of 0.7 K in the planetary boundary layer and 1.6 K at 7 km while Löhnert and Maier (2012) found discrepancies of 0.5 K in the lower boundary layer that increased to 1.7 K at 4 km height.

In order to understand better the cloud effect on the temperature retrievals we have classified the different cloud cases according to the amount of liquid water. Figure 9a shows the mean absolute deviation between radiometer and radiosondes for those cases with ILW lower than 0.04 mm. This condition was found in 13 cases. We observe that there are no significant differences between radiosondes and the microwave retrievals when clouds are or not are included in the forward model. In average the mean absolute deviation from the radisonde in the range from ground to 7 km a.s.l. were 1.5 ± 0.3 K when the clouds were incorporated and 1.4 ± 0.3 K when they were not. These results show that the retrievals are not very sensitive for those clouds with

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a low liquid water content. Figure 9b correspond to cases with ILW between 0.04 and 0.1 mm. A total of 19 cases were found in this range. We can observe that for this ILW range both microwave retrievals were almost identical below 2 km a.s.l. with a mean absolute deviation of 0.9 ± 0.2 K from the radiosonde. Above this altitude we observe that the cloud retrievals show larger discrepancies regarding the radiosondes. The mean absolute deviation in this range was 2.1 ± 0.4 K with clouds and 1.5 ± 0.2 K without clouds information in the forward model. Figure 9c shows the results for ILW larger than 0.1 mm. From this plot we observe that the cloud retrievals show a better agreement with the radiosondes in almost the whole profile. The mean absolute deviations for the whole profile were 2.1 ± 1.1 K for the retrievals with clouds and 2.5 ± 1.4 K without clouds. It is important to note the representativity of these last results, since they correspond almost to the 50 % of the cases (28 cases) and they evidence that there is an improvement in the retrievals when clouds information is incorporated into the forward model.

Finally, the studied cases were also classified according to their cloud base altitudes. Figure 10a shows the mean absolute deviation for the 22 cases with cloud base altitudes below 1000 m a.g.l. Different behaviour is observed in the near range than in the far range. Below 4 km a.s.l. the no-cloud retrievals show better agreement with radiosondes than when the clouds are included in the forward model. However the behaviour is opposite above this altitude. For those cases with CBA between 1 and 3 km a.g.l. which correspond almost to the 50 % of the cases (29) (Fig. 10b), the cloud retrievals show an improvement almost in the whole profile. For cases with CBA above 3 km a.g.l. (Fig. 10c) the retrievals show an opposite behaviour than for low clouds, the cloud retrievals present a better agreement below 4.2 km a.s.l. while it is worse above this altitude.

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5 Conclusions

This work presents a study about the cloud effect on temperature profiles retrieved from microwave radiometry. So far, clouds have not been properly treated in the forward models and big errors are found for some cloudy conditions. Cloud characterization was carried out using different instrumentation. Cloud base altitude was retrieved using ceilometer measurements and the ILW was measured using TROWARA radiometer. A constant LWC value of 0.28 $\mathrm{g\,m^{-3}}$ is used inside of the cloud. A LWC profile is provided to the forward model in order to take into account the clouds in the radiative transfer equation. Microwave temperature profiles have been obtained considering and without considering this LWC profile and they have been compared with radiosonde profiles. Almost one year of data has been analyzed and a total of 60 non-precipitation cloud cases were found. Three different situations have been identified in the comparison of the microwave profiles with radiosondes. The first one corresponds to the presence of thick clouds at medium and high altitudes. For this situation a very good agreement between radiosonde and the retrievals with clouds was observed, while the discrepancies were much larger when the clouds were not considered. The second atmospheric situation found in this study corresponded to the presence of thin clouds at medium and high altitudes. In these conditions both microwave retrievals were very similar, showing that this kind of clouds do not modify significantly the measured brightness temperature at ground base. The third situation was the presence of low clouds. In this case the retrievals considering clouds did not show better results. They were even worse than the retrievals without clouds above 2 km a.s.l. This could be explained because the retrievals are more sensitive in the lowest altitudes and a possible wrong cloud characterization is more critical.

A statistical analysis of all the cases showed that on average the microwave retrievals considering the clouds showed a better agreement with radiosondes with mean absolute deviations of 0.88 ± 0.14 K below 2 km a.s.l. and 2.0 ± 0.4 K above this altitude.

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Moreover, different behaviours in the results were observed depending on the liquid water content of the clouds. For those cases with ILW lower than 0.1 mm there was not a clear improvement in the tropospheric retrievals when clouds where incorporated. However, for cases with ILW larger than 0.1 mm the retrievals with clouds showed a better agreement with the radiosondes in almost the whole profile. The mean absolute deviations from the radiosondes for the whole profile were 2.1 ± 1.1 K for the retrievals with clouds and 2.5 ± 1.4 K without clouds. These results evidenced the improvement in the temperature retrievals when clouds with high integrated liquid water are incorporated into the forward model.

The study also showed a different behaviour in the retrievals depending on the cloud base altitude. For cloud base altitudes below 1000 m a.g.l. and above 3000 m a.g.l. the there was not a clear improvement using the clouds information in the retrievals. While the results were better for those cases with cloud base between 1000 and 3000 m a.g.l. This situation corresponded to almost the 50 % of the cases.

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Table 1. Frequencies (f) and bandwidths (B) of tropospheric channels (ch1–ch12).

channel	f [GHz]	B [MHz]	channel	f [GHz]	B [MHz]
1	51.25	250	7	54.40	250
2	51.75	250	8	54.90	250
3	52.25	250	9	55.40	250
4	52.85	250	10	56.00	1000
5	53.35	250	11	56.50	1000
6	53.85	250	12	57.00	1000

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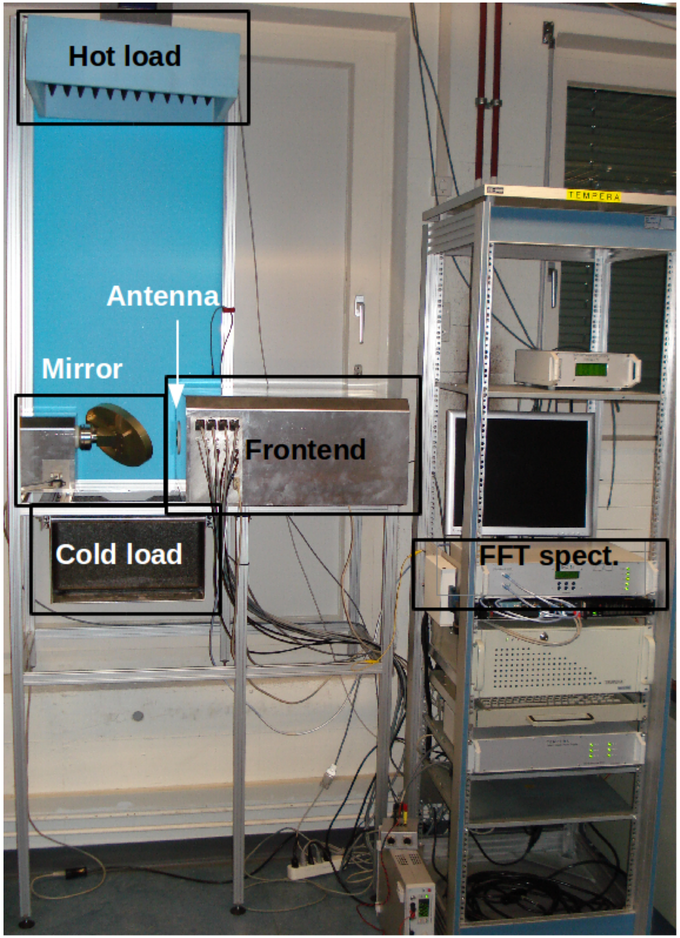

Fig. 1. TEMPERA at the laboratory at ExWi, Bern (Switzerland).

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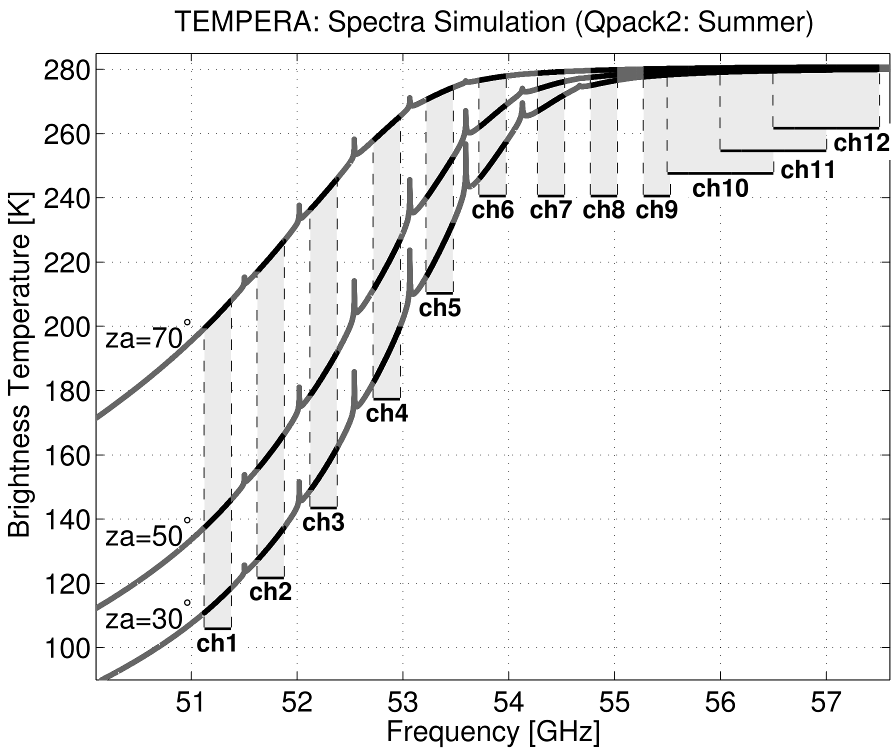

Fig. 2. TEMPERA spectrum from 51–57 GHz simulated with Qpack2/ARTS2 during summer for zenith angles at 30, 50 and 70°. The grey bars indicate the 12 channels (ch1–ch12) of the filterbank.

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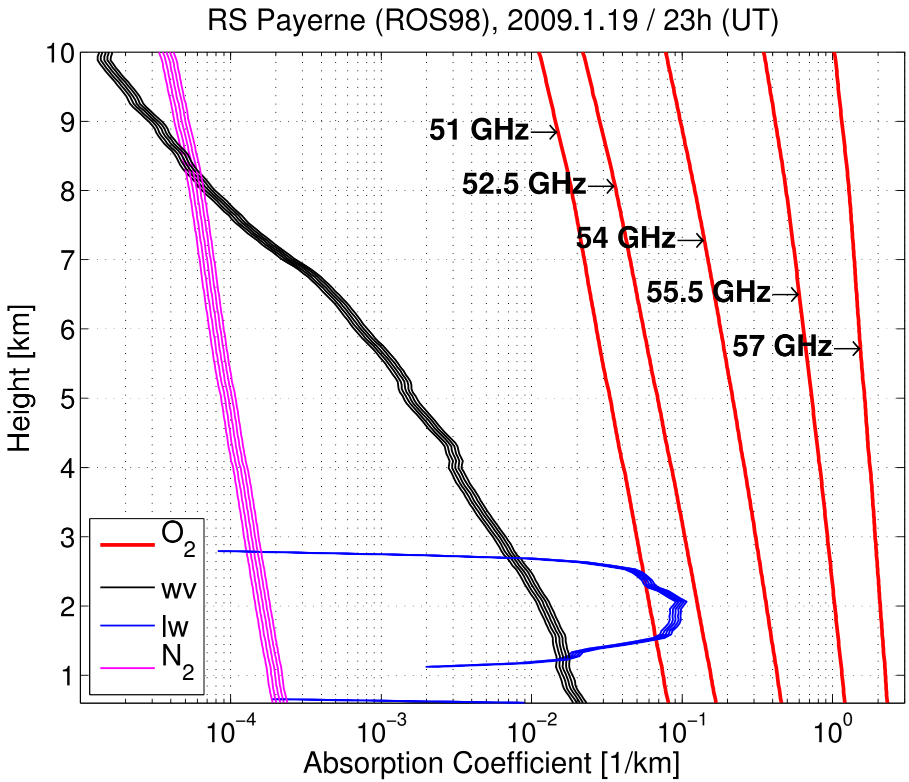

Fig. 3. Vertical profiles of Absorption Coefficients for oxygen (O_2), water vapor (wv), liquid water (lw) and nitrogen (N_2) at 51, 52.5, 54, 55.5 and 57 GHz calculated with radiosonde data from Payerne on 19 January 2009. Calculations made with the Rosenkranz (1998) model.

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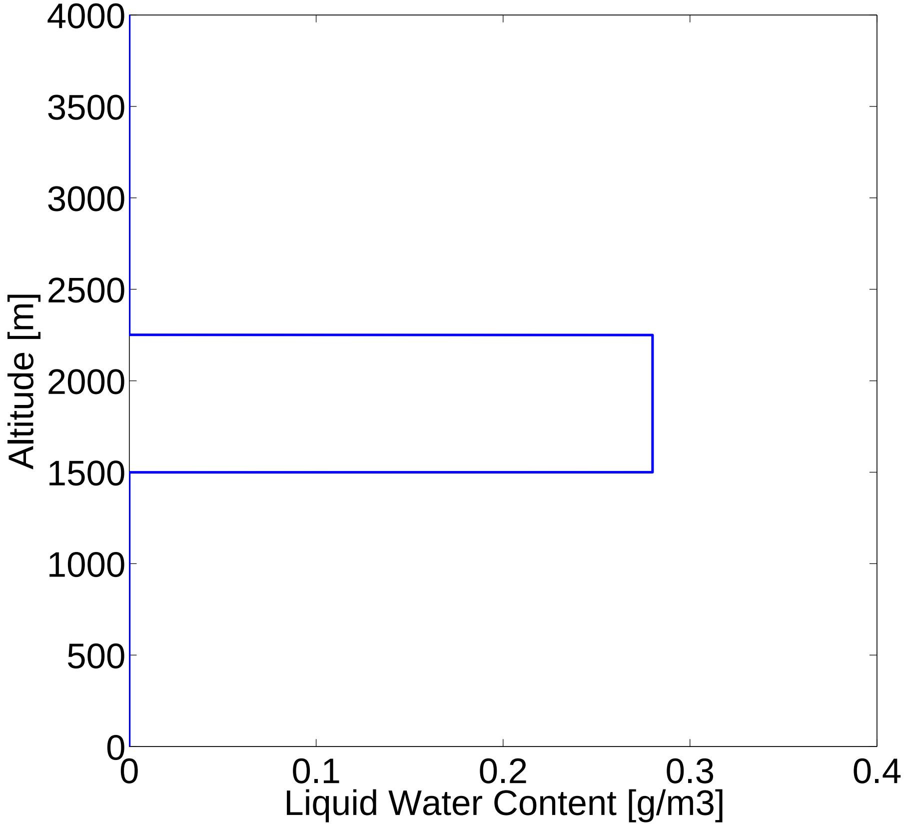

Fig. 4. Example of Liquid Water Content profile incorporated in the forward model corresponding to an ILW of 0.21 mm.

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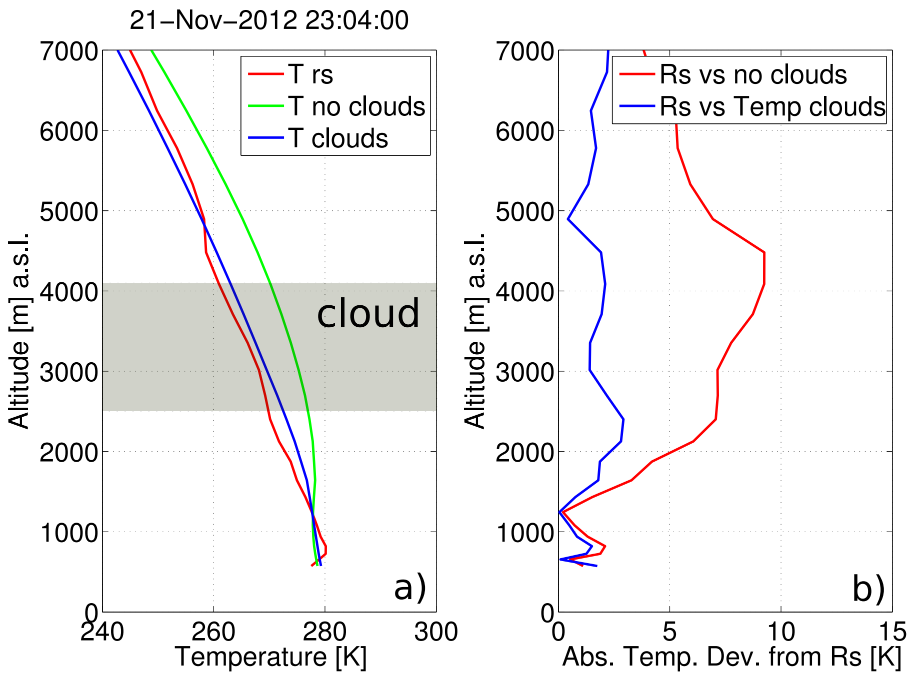

Fig. 5. (a) Temperature profiles on 21 November 2012 retrieved from radiosonde (red line) and from TEMPERA radiometer using and not using cloud information in the forward model (blue and green lines, respectively). The cloud is marked with a gray box. **(b)** Absolute Temperature Deviation for inversions with clouds (blue line) and without clouds (red line) from radiosondes.

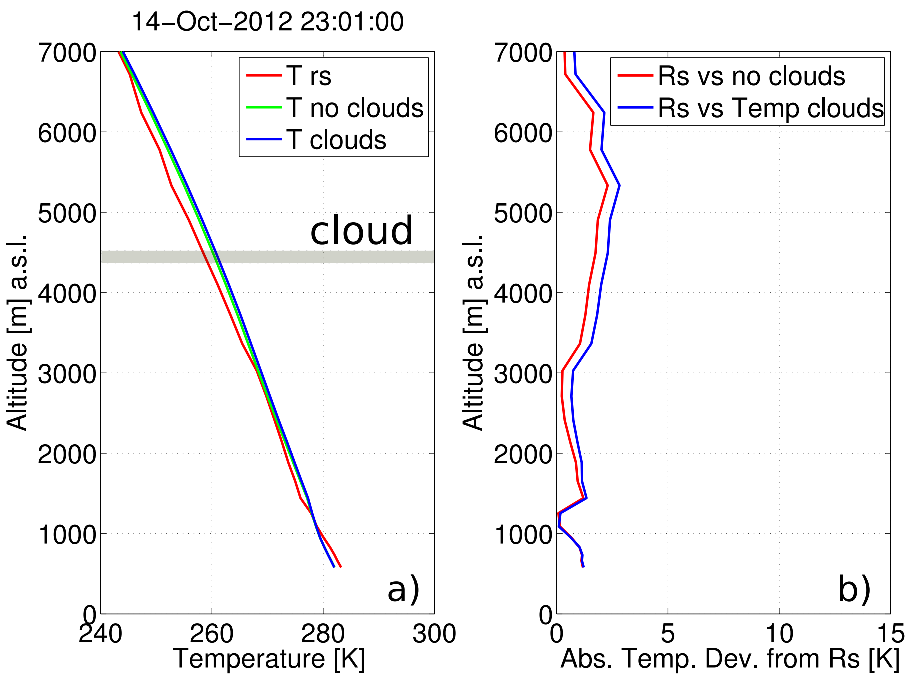

Fig. 6. (a) Temperature profiles on 14 October 2012 retrieved from radiosonde (red line) and from TEMPERA radiometer using and not using cloud information in the forward model (blue and green lines, respectively).The cloud is marked with a gray box. **(b)** Absolute Temperature Deviation for inversions with clouds (blue line) and without clouds (red line) from radiosondes.

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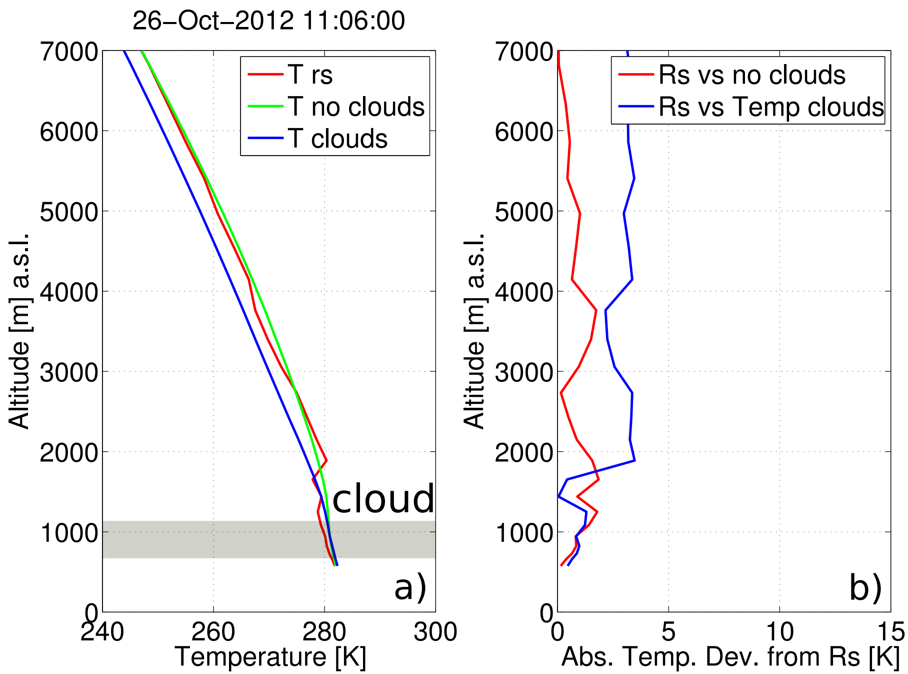

Fig. 7. (a) Temperature profiles on 26 October 2012 retrieved from radiosonde (red line) and from TEMPERA radiometer using and not using cloud information in the forward model (blue and green lines, respectively).The cloud is marked with a gray box. **(b)** Absolute Temperature Deviation for inversions with clouds (blue line) and without clouds (red line) from radiosondes.

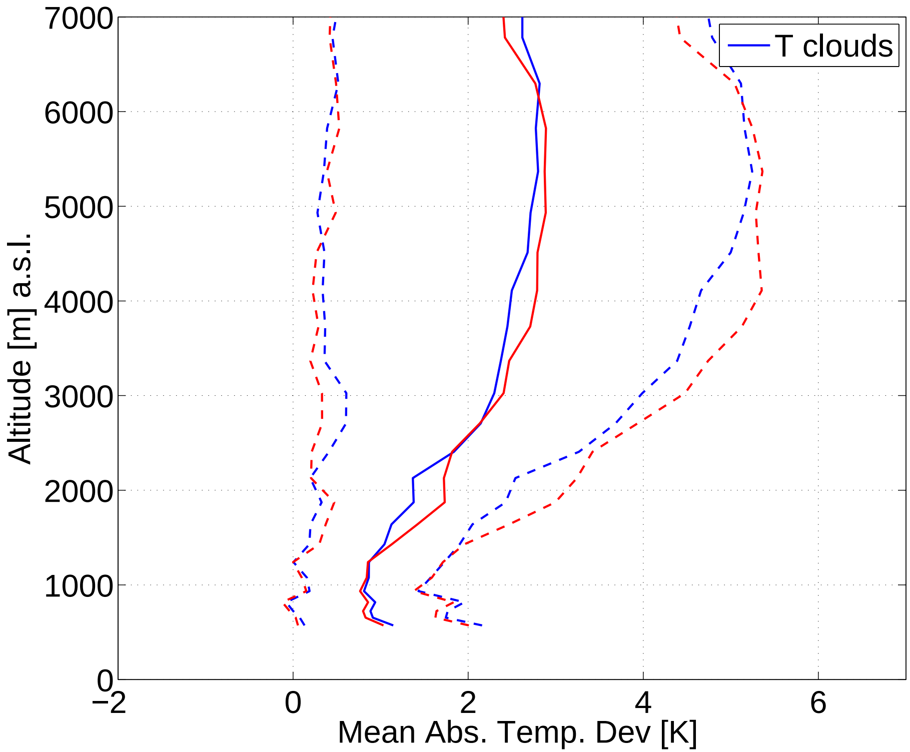

Fig. 8. Mean Absolute Temperature Deviation between radiosondes and microwave profiles. The blue line corresponds to retrievals with clouds and the red line without clouds. The standard deviations are marked by dashed lines.

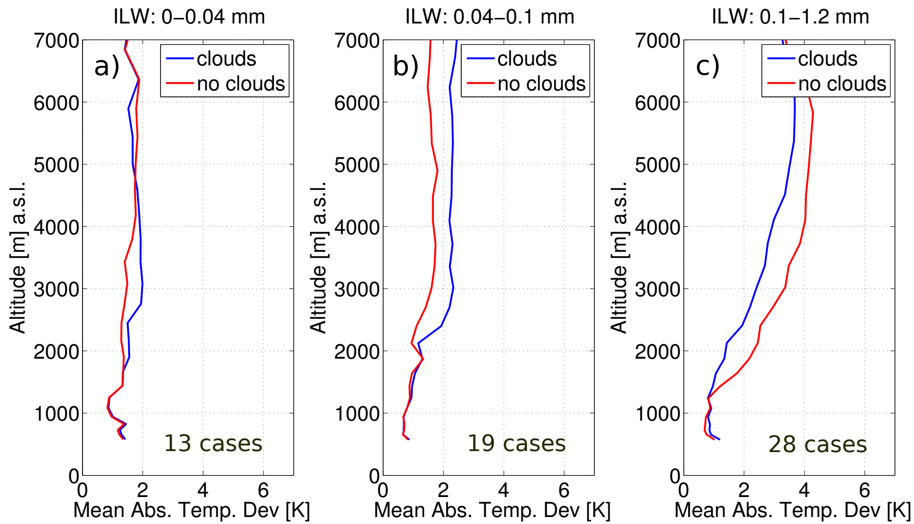

Fig. 9. Mean Absolute Temperature Deviation between radiosondes and microwave profiles for different ranges of ILW.

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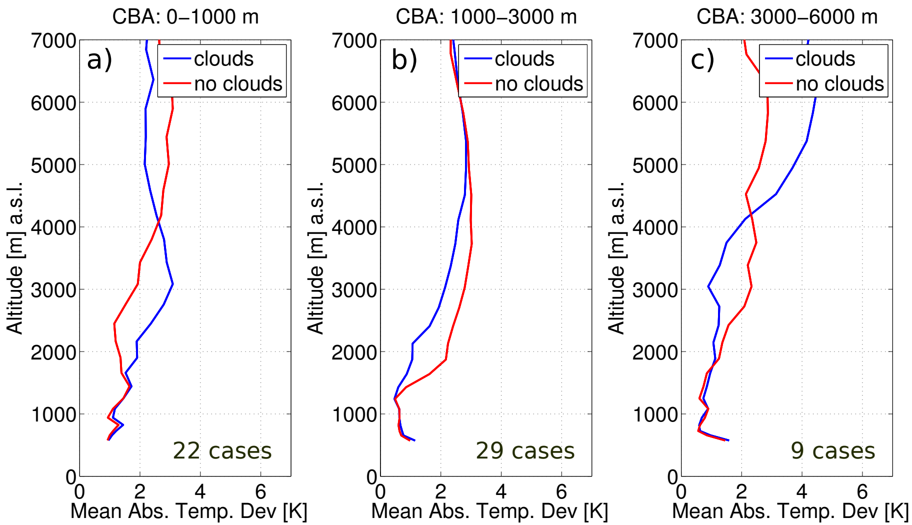

Fig. 10. Mean Absolute Temperature Deviation between radiosondes and microwave profiles for different ranges of cloud base altitudes.

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