Answers to the referee 2 (AMTD-7-C355-C358,2014)

The study presents a method to include clouds in the retrieval of tropospheric temperature profiles from ground based microwave measurements in the range from 50 to 60 GHz. The effect of clouds on passive microwave measurements of water vapor and temperature is an important topic and the presented paper makes a valuable contribution. I recommend to accept the paper after major revisions.

GENERAL COMMENTS

1) The chosen title promises a more general and in depth study of the effect of clouds on microwave measurements and the retrieved temperature profiles. However, the paper presents a straight forward method to represent clouds in the forward model using cloud base and ILW data and a comparison of the method with a reference method (retrieval with channels f > 53 GHz) and radiosondes. The authors may consider to change the title into something like "Integrated approach to represent clouds in the temperature retrieval from microwave measurements".

Following the referee's suggestion we have modified the title of our manuscript in order to be more consistent with the content of this work. The title reads now as:

"An integrated approach toward the incorporation of clouds in the temperature retrievals from microwave measurements"

2) Based on the presented material the authors conclude that their method to include clouds in the retrieval leads to a general improvement, though the improvement is relatively modest. This is illustrated by Figure 8. They further highlight that the major improvement is for thick clouds (ILW > 0.1 mm) with a cloud base between 1 and 3 km above ground and that for the other cases the improvement is not clear. However, in the case of thin low and high clouds the method performs equal or worse than the reference method (retrieval with channels f > 53 GHz) as it is illustrated in figure 9 and 10. Possible explanations are insufficiently good representation of the clouds coming from the simple assumption of the LWC profile or the fact that cloud information is only known under one zenith angle while 9 zenith angles are used for the retrieval (inhomogeneous cloud cover) or systematic errors in modeling the clouds or biases in the measured brightness temperatures in the transparent channels. The authors need to provide a more thorough discussion of these possibilities. The paper would further benefit from some comparisons on the level of the brightness temperatures instead of retrievals.

We would like to point out that the retrievals without clouds were performing with all the channels (f>51 GHz). We apologize for this mistake. This point has been clarified in the manuscript. Since all the points referred in this general comment are treated in the specific comments we will answer in the next sections.

SPECIFIC COMMENTS

3) P1307,l10: The authors claim that clouds are not properly addressed. However, regression or neural network retrievals do consider clouds in the calculation of the coefficients. This should be mentioned here. See also p1311,l15; p1317,l3.

We agree with the referee's comment and we have changed this part in order to evidence that this is not the first study that deals the incorporation of the clouds to the retrievals. New references have been included. The corresponding paragraph in the introduction section reads now as (lines

51-63):

"Many studies have addressed the characterization of the temperature in the troposphere using microwave radiometer measurements (Basili et al., 2001; Stähli et al., 2013; Löhnert and Maier, 2012). However, despite the presence of clouds in many atmospheric observations, only few studies have dealt the incorporation of clouds in the temperature retrievals (Löhnert et al., 2004; Solheim et al. 1998; Ware et al., 2003). A better knowledge on the cloud characterization as well as on the assessment of its effect on the temperature under different cloudy conditions is still needed. The work presented here addresses the characterization of clouds and its incorporation in the temperature retrievals for almost one year of measurements."

And in the conclusions (lines 490-494):

"This work presents a study about the cloud effect on temperature profiles retrieved from microwave radiometry. So far, few studies have treated the clouds in the forward models and big errors are found for some cloudy conditions. Cloud characterization was carried out using different instrumentation ...."

4) P1308,l24: The geometry of the TROWARA instrument should be given here and I strongly assume it looks under the same zenith angle as the ceilometer. In general, it should be discussed what the consequences are from the fact that TEMPERA (za = 30 - 70º) and TROWARA / ceilometer (za = 40º) do not observe under the same zenith angle (za). Are the cloud cases chosen such that the cloud layer was homogeneous?

We would like to point out that the elevation angle of TROWARA was the same as for the ceilometer. The cloudy cases presented in this study were always selected looking for those cases with homogeneous cloud layers. In order to check this we checked that the cloud base heights from the ceilometer were more or less constant during a considerable period of time. For this reason we consider that the differences in the observational angles between TROWARA and TEMPERA are not very critical under homogeneous cloudy conditions.

On the other hand, following the referee's suggestion we have indicated the geometry of observation of TROWARA radiometer in this section. The text reads now as (lines 113-122):

"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. Since 2002, TROWARA is operated in a temperature-controlled room, looking into the atmosphere (elevation angle of 40º) through a styrofoam window. 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)."

5) P1311,l7: Specify the assumptions for the LWC profile in Figure 3. Since in this study a LWC value of 0.26 g/m3 has been assumed for all clouds, it would make sense to show the absorption coefficient of liquid water for a constant profile (from ground up to 10 km).

Following the referee's suggestion we have retrieved the liquid absorption coefficient for a constant liquid water profile up to 10 km. The calculus has been performed for a LWC value of 0.28 g/m3 and for the atmospheric conditions on 21 November 2012 in Bern. The Figure 3, the legend and the corresponding paragraphs regarding this plot have been modified in the manuscript. It read now as (lines 200-220):

"Figure 3 shows the absorption coefficient for oxygen, water vapor, liquid water and ni-

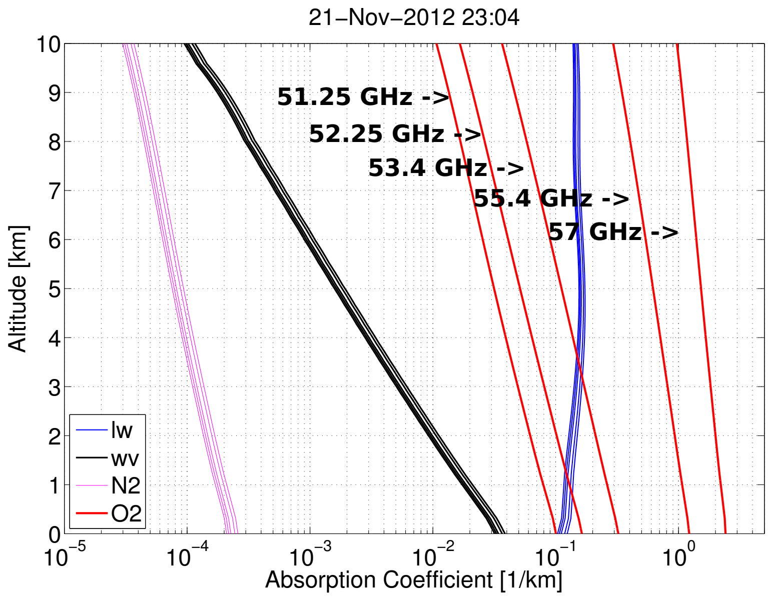

Fig. 3: Vertical profiles of Absorption Coefficients for oxygen (O_2), water vapor (wv), liquid water (lw) and nitrogen (N_2) at 51.25, 52.25, 53.4, 55.4 and 57 GHz calculated for atmospheric conditions on 21 November 2012 in Bern.

trogen for 5 different frequencies between 51 and 57 GHz. The absorption coefficient for oxygen, water vapor and nitrogen was calculated for the atmospheric conditions found at 23 UTC on 21 November 2012 in Bern. 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. For the liquid water the absorption coefficient was calculated assuming a constant liquid water profile up to 10 km in order to assess its relevance at different altitudes. From this plot we observe that the clouds have a strong influence in the frequency range from 51 to 54 GHz and their absorptions and emissions can not be considered negligible. Moreover, the liquid water absorption coefficient increases slightly with the altitude indicating that clouds get more important at higher altitudes."

6) P1312,l13: the paper concludes that the presented method to include clouds improves the retrievals for thick clouds with a base between 1 and 3 km agl. For high and low clouds no improvement could be shown. My first conclusion would be that the chosen LWC profiles are not valid for thin high and low clouds. The text states, that fog shows LWC values one order of magnitude smaller than the chosen value. It has to be shown here in a more convincing way that different LWC profiles (values and shapes) do not significantly affect the results. A comparison on the level of the brightness temperatures would be more appropriate than on the level of the retrieved profiles.

The discussion of the three studied cases has been extended since we have included an analysis of the brightness temperature for each retrieval (Figures 5, 6 and 7). Moreover we have also included a study about how the LWC values affect on the temperature retrievals for the three cases presented here. After this major changes the section reads as (lines 285-414):

4.1 Case studies

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 clouds 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 and an ILW value of 0.47 mm was measured with TROWARA for these cloudy conditions. 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 (asl) 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 (asl), reaching a maximum absolute deviation of 9.2 K at 4480 m (asl). Figure 5c shows the corresponding brightness temperatures for the different retrievals. A total of 108 measured brightness temperatures are shown corresponding to the measurements from the 12 channels under 9 observational zenith angles (black points). In addition, the forward model brightness temperatures for the retrievals with and without clouds, blue and red circles respectively, are also presented. We can observe that the forward model brightness temperatures for the retrieval including the cloud information agree much better with the measured brightness temperature than those ones obtained without cloud information. The absolute differences between measured and forward model brightness temperatures (residuals) are between 0.003 and 7 K for the retrieval with cloud and between 0.017 and 42.6 K for the retrieval without cloud. The plot also confirms that the biggest discrepancies in the brightness temperatures between both retrievals are found for the lower frequencies (<54 GHz), as it could be predicted from the absorption coefficients (Fig. 3). It is also interesting to note that the changes in the brightness temperatures for the different zenith angles are small for the highest frequencies due to the large opacity from the oxygen at these frequencies. In conclusion, this example evidenced a clear improvement in both physical and brightness temperatures 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. The ILW value measured in this case was lower than in the previous one (0.03 mm). For this night a cloud with a thickness of 108 m was detected at the altitude of 4304 m (asl). 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 (Fig. 6c).

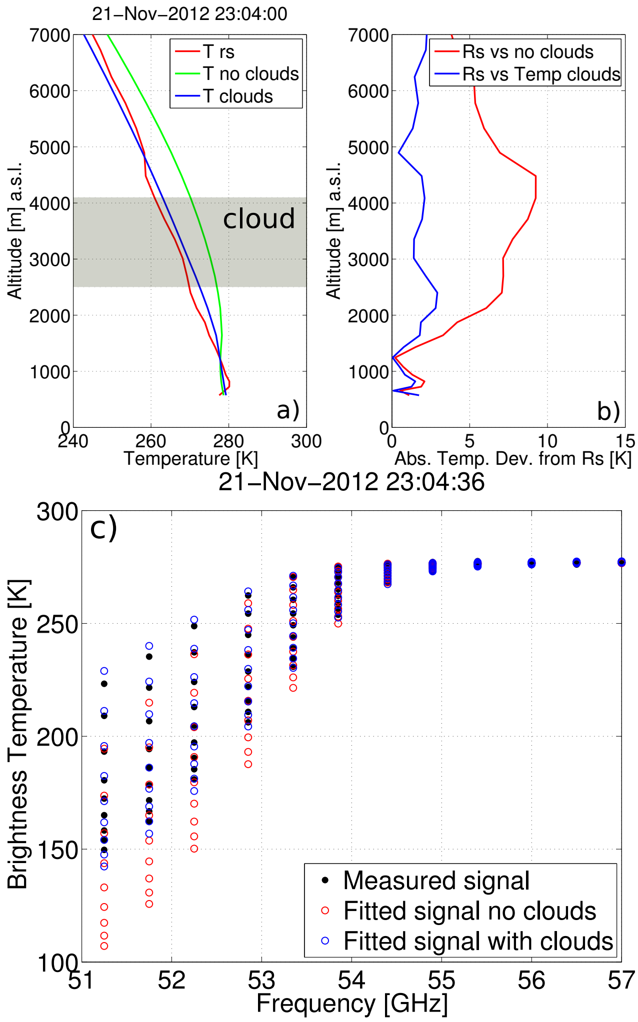

Fig. 5: a) Temperature profiles on 21 November 2012 retrieved from radiosonde (red line) and from TEMPERA radiometer using and not using cloud information in the forward model (blue and green lines, respectively). The cloud is marked with a gray box. b) Absolute Temperature Deviation for inversions with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

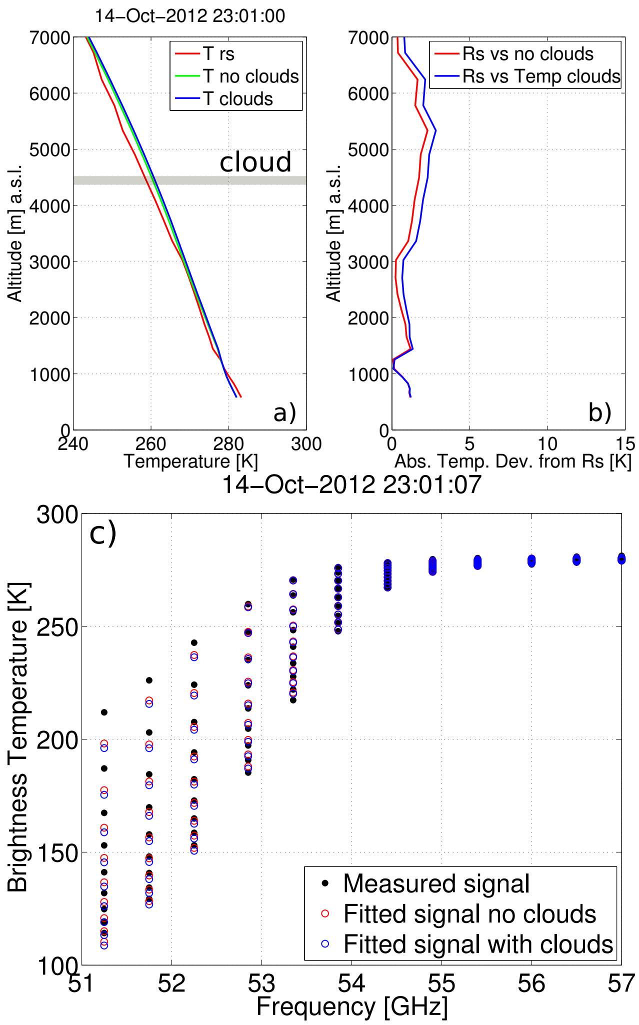

Fig. 6: As in Figure 5 but on 14 October 2012.

Figure 7 shows an example of low clouds. The measurements were performed on 26 October 2012 at 11:06 UTC. A ILW value of 0.13 mm was measured with TROWARA. At this time a cloud of 481 m of thickness was detected at the altitude of 110 m (agl). In this situation the profiles retrieved from radiometer measurements showed different behaviour. While in the near range (below 1700 m, asl) 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.

However, when the brightness temperatures were checked (Fig. 7c) we observed that the forward model brightness temperatures obtained for the retrieval with cloud agree better with the measured brightness temperatures than for the ones without cloud. It indicates that the microwave radiometer temperature retrieval also improved for this case when the cloud was incorporated although the comparison of the physical temperature with the radiosonde does not prove that. This example evidences 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, as it has been shown in this case. Moreover, to provide a wrong LWC profile (due to a mislocation of the cloud, possible stratification ...) in the forward model could be more critical because the retrievals are more sensitive in the near range.

In order to assess the sensitivity of the temperature retrievals with the LWC value the three cases presented in this section have been checked considering very different kind of clouds. The chosen LWC values for this test were 0.06, 0.28 and 1.0 g/m^3 which are typical for cirrus, stratus and cumulonimbus, respectively. Table 2 presents the ILW value for each case and the different cloud thickness which are found depending on the kind of cloud. We can observe that for the same atmospheric conditions (with a fixed ILW value) the cloud thickness can range from some hundred meters to several kilometers depending on the kind of cloud.

Date	ILW [mm]	cirrus [m]	stratus [m]	cumulon. [m]
21-Nov	0.47	7770	1665	466
14-Oct	0.03	505	108	30
26-Oct	0.13	2246	481	134

Table 2: ILW and cloud thickness for different kind of clouds.

Figure 8 shows different linear regressions obtained from temperature comparisons from radiosondes and microwave radiometer measurements for the three studied cases. The regressions presented correspond to temperatures measured in the height range between ground and 7 km. The microwave retrievals were performed using the LWC values indicated before for different kind of clouds. We can observe that despite the extreme LWC values used for the different kind of clouds the changes in the temperatures were very small. The correlation coefficients were larger than 0.99 in all regressions. The biggest discrepancies found in all the cases always were below 1 K indicating that the temperature retrievals were not very sensitive to the LWC parameter. For this reason the statistical analysis presented in the next section was performed using the LWC value of 0.28 g/m^3 which is typical for stratus. This kind of clouds was the most common found in our study.

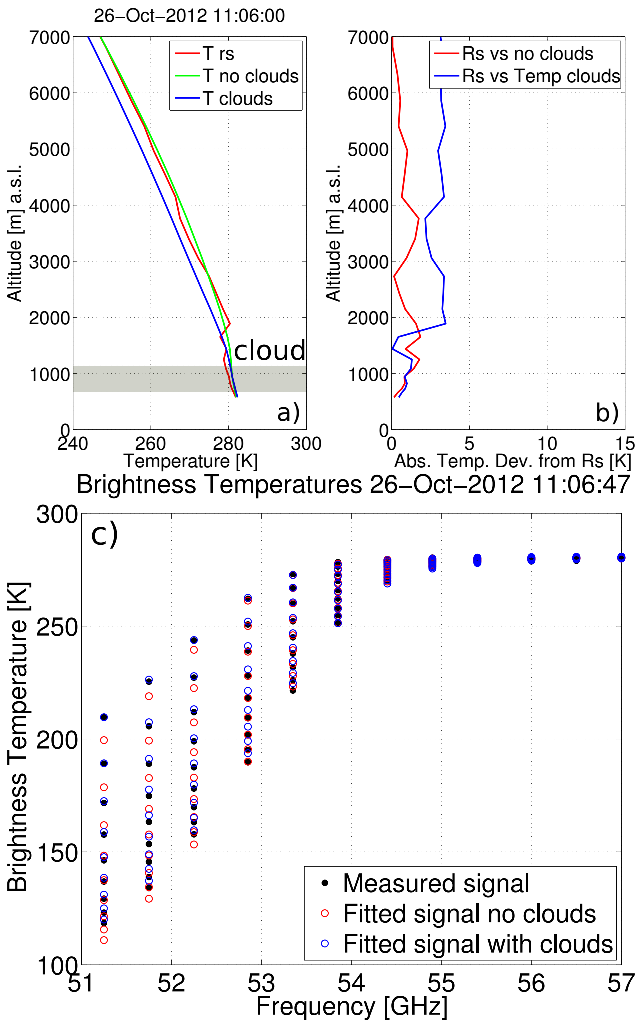

Fig. 7: As in Figure 5 but on 26 October 2012.

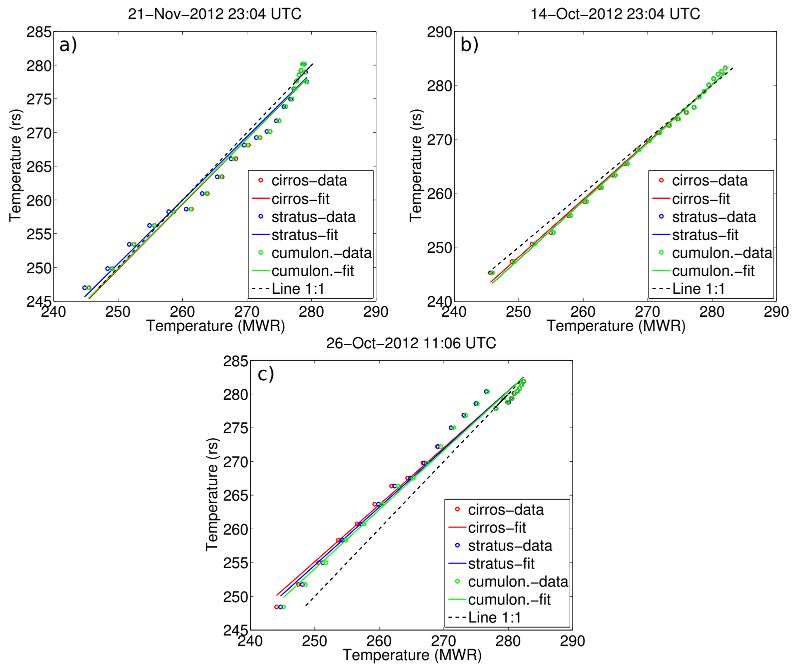

Fig. 8: Linear regressions between the temperatures from radiosondes and from microwave radiometer measurements on 21 November (a), 14 October (b) and 26 October (c). The microwave temperature retrievals incorporating clouds were calculated for typical LWC values for cirros, stratus and cumulonimbus.

Moreover, after these new studies we have modified part of the conclusions. It reads now as (lines 519-531):

"However, the analysis of the forward model brightness temperatures for the retrievals with clouds evidenced a better agreement with the measured brightness temperatures. It indicated that the temperature retrievals improved when the clouds were incorporated and the differences with the radiosonde come from a real difference in the physical temperature for both locations. This case illustrated the difficulty found in the analysis of low clouds since they present higher variability at low altitudes and the discrepancies with the radiosonde can be larger. The three cases were tested for different types of clouds (different LWC value) without showing significant differences in the retrievals."

7) P1313,l16: What are the ILW values for figures 5 to 7?

The ILW values for the three cases presented in Figure 5, 6 and 7 have been indicated in the manuscript. It read as:

Lines 294-297: **"The measurements were done on 21 November, 2012 and an ILW value of 0.47 mm was measured with TROWARA for these cloudy conditions".**

Lines 340-341: **"The ILW value measured in this case was lower than in the previous one (0.03 mm)."**

Lines 356-357: **"A ILW value of 0.13 mm was measured with TROWARA."**

8) P1314,l23: "This example . . ." this statement is a lot too general, it would be more appropriate to say that the presented method is too simple to represent low and high clouds. I appreciate the following statement about the difficulty to characterize clouds and their variability. But here

the authors should show, or at least mention provided the necessary tests have been made, that other assumptions on the LWC profile do not lead to different results.

As we have indicated in comment 6 we have included the tests where the retrievals have been checked for different LWC values (Figure 8) and the brightness temperatures have been showed for each retrievals. After this study we have modified this paragraph as follow (lines 370-385):

"However, when the brightness temperatures were checked (Fig. 7c) we observed that the forward model brightness temperatures obtained for the retrieval with cloud agree better with the measured brightness temperatures than for the ones without cloud. It indicates that the microwave radiometer temperature retrieval also improved for this case when the cloud was incorporated although the comparison of the physical temperature with the radiosonde does not prove that. This example evidences 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, as it has been shown in this case. Moreover, to provide a wrong LWC profile (due to a mislocation of the cloud, possible stratification ...) in the forward model could be more critical because the retrievals are more sensitive in the near range."

9) P1315,l5: Comment here also the difference in the standard deviation, which indicates that the presented method reduces the variability in the differences.

As the referee suggests we have indicated this result in the manuscript. It reads as follow (lines 423-426):

"It is also interesting to point out that the standard deviation is lower for the retrievals with clouds, indicating that this method reduces the variability in the differences."

10) P1317,l18: "In these . . ." It is dangerous to draw conclusions on the brightness temperatures from the retrievals. It would be more appropriate to show directly the difference in brightness temperatures.

As it has been mentioned before the brightness temperatures of each retrieval have been included in the reviewed manuscript.

11) P1318,l10: It is positive that the presented method performs well for thick mid layer clouds and that this corresponds to almost 50% of the cases. However, it has to be discussed in more depth why the method does not perform better for thin low and high clouds and how the method could be improved in future work.

Following the referee's suggestions we have extended the discussion in this point. It reads now as (lines 550-561):

"The study also showed a different behaviour in the retrievals depending on the cloud base altitude. For cloud base altitudes below 1000 m (agl) and above 3000 m (agl) there was not a clear improvement using the clouds information in the retrievals. The difficulty of characterizing the low clouds due to their larger variability in the near range and the shift of the radiosonde in high altitudes could be the reason of these unclear results. On this account, future campaigns where microwave radiometers operate at the same location as radiosondes are launched will help to improve the temperature retrievals for these atmospheric conditions. On the other hand we observed that the results were better for those cases with cloud base between 1000 and 3000 m (agl). This situation corresponded to almost the 50% of the cases."

Technical corrections

12) P1309,l19: replace "as a function of" by "in terms of"

Done (line 150).

13) P1309,l21: Equation (1) -> α must be height dependent.

Done (line 153).

14) P1310,l7: replace "just knowing" by "from".

Done (line 163).

15) P1311,l25: repeat here the geometry of the ceilometer and TROWARA.

The geometry of both instruments (ceilometer and TROWARA) has been indicated in these lines. The text read now as (lines 234-243):

"Cloud base altitudes (CBA) were detected using a Vaisala CT25K ceilometer that is continuously operated. The instrument points to the atmosphere with an elevation angle of 40º. 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.

The ILW was measured by TROWARA radiometer under the same observational elevation angle as the ceilometer (40º) . The presence of clouds was assumed for those cases with ILW larger than 0.025 mm."

16) P1313,l11: replace "case of study" by "Case studies"

Done (line 285).

17) P1315,l23: "We observe. . ." this phrase is not correct, there are significant differences between radiosonde and microwave radiometer. It should say that there are no significant differences between the two retrievals.

We have corrected this mistake. It reads now as (lines 448-449):

"We can observe that there are no significant differences between both retrievals."

18) P1318,l3: replace "where" by "were".

Done (line 541).