Atmos. Meas. Tech. Discuss., doi:10.5194/amt-2016-253, 2016
Manuscript under review for journal Atmos. Meas. Tech.
Published: 15 August 2016

Atmospheric Measurement Techniques
Discussions
Open Access

Uncertainties of ground-based microwave radiometer retrievals in zenith and off-zenith methods under snow conditions

Wengang Zhang[1], Guirong Xu[1,*], Yuanyuan Liu[2], Guopao Yan[3], Shengbo Wang[4]

[1] Hubei Key Laboratory for Heavy Rain Monitoring and Warning Research, Institute of Heavy Rain, China Meteorological Administration, Wuhan, China

[2]Hubei Meteorological Information and Technological Support Center, Wuhan, China

[3]Wuhan Meteorological Bureau of Hubei Province, Wuhan, China

[4]Mewbourne School of Petroleum & Geological Engineering, University of Oklahoma, Norman, USA

[*]Correspondence to: Guirong Xu (grxu@whihr.com.cn)

Abstract. This paper is to investigate the uncertainties of microwave radiometer (MWR) retrievals in snow conditions and also explore the discrepancies of MWR retrievals in zenith and off-zenith methods. The MWR retrievals were averaged in the ±15 min period centered at sounding times of 00:00 and 12:00 UTC and compared with the radiosonde observations (RAOBs). In general, the MWR retrievals have a better correlation with RAOB profiles in off-zenith method than in zenith method, and the biases (MWR observations minus RAOBs) and root mean square errors (RMSEs) between MWR and RAOB are also clearly reduced in off-zenith method. The biases of temperature, relative humidity, and vapor density decrease from 4.6 K, 9 %, and 1.43 g m^{-3} in zenith method to -0.6 K, -2 %, and 0.10 g m^{-3} in off-zenith method, respectively. The discrepancies between the MWR retrievals and the RAOB profiles along with the altitude present the same situation. Case studies show that the impact of snow on accuracies of the MWR retrievals is more serious in heavy snowfall than that in light snowfall, but the off-zenith method can mitigate the impact of snowfall. The MWR measurements become less accurate in snowfall is mainly due to the retrieving method which does not consider the effect of snow, and the accumulated snow on the top of radome increases the signal noise of MWR measurement. As the snowfall drops away by gravity in the sides of the radome and the off-zenith observations are more representative of the atmospheric conditions for RAOBs.

Key words: Microwave radiometer, Retrieval uncertainties, Off-zenith method, Snowfall

1. Introduction

Atmospheric profiles of temperature, relative humidity, and vapor density can be retrieved from ground-based microwave radiometer (MWR) measurements (Sánchez et al. 2013; Ware et al. 2013). These profiles are available nearly continuously and are extensively utilized in the forecasting and analysis of intense convective weather, also they have been assimilated into numerical weather prediction models (Marzano et al. 2005; Knupp et al. 2009; Löhnert et al. 2012; Madhulatha et al. 2013). The instability indices calculated from the MWR-retrieved thermodynamic atmospheric profiles are

Atmos. Meas. Tech. Discuss., doi:10.5194/amt-2016-253, 2016
Manuscript under review for journal Atmos. Meas. Tech.
Published: 15 August 2016

also employed in operational meteorology (Chan et al. 2010; Cimini et al. 2015; Leena et al. 2015). However, since the radiative transfer model used in the MWR does not consider the impact of precipitation on the MWR brightness temperature measurements, the MWR retrievals become less accurate under precipitation conditions (Ware et al. 2004; Xu et al. 2014). To improve the accuracy of MWR retrievals in rainy conditions, some methods are performed to minimize the influence of liquid water on MWR measurements. The MWR is equipped with a hydrophobic radome and a special blower system, which can sweep water beads and snow away from the radome (Chan 2009). A method based on linear regression is also employed to reduce the discrepancy between the MWR retrievals and the radiosonde observation (RAOB) profiles (Sánchez et al. 2013). Recently, the off-zenith method is applied in MWR observations and off-zenith retrievals provide higher accuracy during precipitation by minimizing the effect of liquid water on the radiometer radome (Cimini et al. 2011, 2015; Ware et al. 2013; Xu et al. 2014).

Snow, a special type of precipitation, has distinct scattering characteristics in the microwave. Some methods are explored to investigate these characteristics and discuss their utilization on the snow measurements (Matrosov et al. 2008; Löhnert et al. 2011; Xie et al. 2012). The scattering signal of snow is highly dependent on the assumption of snow shape and snow size distribution (SSD), especially for large-sized parameters (Kneifel et al. 2010). Some studies have demonstrated that snowfall can significantly reduce the measurement accuracy of MWR (Knupp et al. 2009; Cimini et al. 2011; Ware et al. 2013). However, few studies are reported on the improvements of MWR measurement accuracies in snow conditions. Moreover, in contrast with rain, snow usually freezes on the top of the radome, and it is not easily blown away from the radome by the blower system attached on the MWR. Since MWR retrieval accuracies generally are better in off-zenith method than in zenith method under precipitation conditions (Xu et al., 2014) and snow does not easily accumulate on the sides of a radome, we attempt to employ off-zenith method to improve the MWR retrieval accuracies during snowfall.

This paper is organized as follows: Section 2 will briefly describe the data and methodology employed in this study; Section 3 compares the MWR-retrieved atmospheric profiles of temperature, relative humidity and vapor density with RAOB profiles obtained at Wuhan station, then discusses the accuracies of MWR retrievals under snow conditions and the effect of off-zenith method on it; and Section 4 gives some conclusions.

2. DATA AND METHODOLOGY

The data used in this study are collected in the Wuhan operational station (30.6 ° N, 114.1 ° E, and 23 m above sea level), including RAOB data, meteorological observation data and MWR data. The distances between them are all less than 30 m. RAOB data is the operational data, which is obtained at 00:00 and 12:00 UTC every day. The profiles of temperature and relative humidity are obtained by the Chinese GTS1-2 digital radiosonde at a high vertical resolution of 10 m, and the profiles of vapor density can be calculated from them. The meteorological observation data are used to confirm the snowfall cases. The MWR data used in this paper is provided by a MP-3000A unit manufactured by Radiometrics, observing at 2 elevation angles (zenith and 15° elevation) up to 10 km. The MWR data has a higher temporal resolution of ~3 min, and the vertical intervals are 50 m from the surface to 500 m, 100 m to 2 km, and 250 m to 10 km (Ware et al. 2013; Xu et al. 2014).

The MP-3000A unit observes brightness temperature at up to 35 channels, including 21 K-band (22—30 GHz) and 14 V-band (51—59 GHz). Moreover, an infrared radiation thermometer (IRT) is equipped on the MWR, which measures sky infrared temperature at one zenith infrared (9.6–10.5 μm) channel and gives information on cloud-base temperature (Ware et al. 2013; Cimini et al. 2015; Xu et al. 2015). Meteorological sensors attached to the MWR can obtain ambient temperature, pressure, and relative humidity at the instrument level. The retrieved algorithm developed by the factory can automatically convert the microwave, infrared, and surface meteorological measurements into temperature, humidity, and liquid profiles using radiative transfer equations with the aid of neural networks (Xu et al. 2015). The neural network retrieval method uses historical radiosondes to characterize states of the atmosphere that commonly occur at a particular location (Ware et al. 2013). A five-year data set of historical radiosondes in Wuhan was used for neural network training (Xu et al. 2014).

Three snow cases (shown in Table 1) are selected to present the comparison of the profiles between MWR and RAOB under snow conditions, and the effect of off-zenith method on improving the MWR measurement accuracy during snowfall is explored. All cases in this study include at least one RAOB profile during snowfall. Since it takes 30 minutes for the balloon from the surface to 10 km altitude in sounding, the MWR retrievals were averaged in the ±15 minute period centered at sounding times of 00:00 and 12:00 UTC and compared with the RAOB profiles. Considering the vertical resolution of the RAOB profiles is not consistent with that of MWR retrievals, the RAOB profiles are interpolated to the height levels of the MWR retrievals. Based on the above process, there are eight temporal pairs of MWR and RAOB profiles for comparison in this study. Methods used in this study are simply employed to calculate the correlation coefficients, bias (MWR observation minus RAOB), and root mean square error (RMSE) between the MWR and the RAOB for each parameter in zenith and off-zenith methods. The discrepancies between MWR retrievals and RAOB profiles at different heights are also calculated to explore how the MWR retrievals accuracies vary with height.

3. RESULTS ANALYSIS

3.1 Uncertainties of MWR retrievals in zenith and off-zenith methods under snow conditions

To explore the effect of off-zenith method on MWR measurement accuracy, the simultaneous MWR zenith and off-zenith retrievals around the time of 00:00 and 12:00 UTC are compared with the RAOB profiles. Table 2 presents the comparison of MWR retrievals against RAOB profiles in zenith and off-zenith methods under snow conditions without considering the level division in altitude. All the MWR retrievals have a better correlation in off-zenith method than that in zenith method especially for relative humidity, and the biases and RMSEs are also clearly reduced in off-zenith method. For temperature, the MWR zenith observations have a warm bias of 4.6 K against RAOBs while in off-zenith method the bias decrease to -0.6 K, with RMSE also decreasing from 5.7 K to 2.0 K. The MWR-retrieved relative humidity has poor agreement with RAOB relative humidity in zenith method but reasonable in off-zenith method, and the bias and RMSE also decrease from 10 % and 33% in zenith method to -2 % and 20 % in off-zenith method, respectively. For vapor density, the correlation coefficient between MWR observations and RAOBs increases from 0.7130 in zenith method to 0.9389 in off-zenith method. In zenith method, the bias is 1.43 g m^{-3} with a RMSE of 2.14 g m^{-3}, while in off-zenith method both of them decrease to 0.10 g m^{-3} and 0.66 g m^{-3}, respectively. Obviously, the MWR retrievals have better accuracies against RAOBs in off-zenith method than in zenith method.

To further compare the uncertainties of MWR retrievals against RAOBs in zenith and off-zenith methods, the discrepancies between the MWR retrievals and the RAOB profiles along with the altitude under snow conditions are also investigated. As shown in Fig. 1, the temperature correlation coefficients in zenith method are smaller than those in off-zenith method below 6 km especially around 3.75 km where the correlation coefficient rapidly increases from 0.01 to 0.92, but the situation is opposite above 6 km. The MWR temperature shows a warm bias against RAOB in zenith method and the bias is larger than 3 K at most heights, while in off-zenith the bias becomes cold and within -1 K at most heights. Both the MWR temperature

RMSEs in zenith and off-zenith methods approximately increase with height, but the RMSE is clear smaller in off-zenith method. The MWR temperature RMSE is greater than 4 K above 0.5 km in zenith method while in off-zenith method it is within 2 K at most heights.

Fig. 2 presents the results for the relative humidity profiles. The correlation coefficients between MWR observations and RAOBs are negative at most heights below 2.5 km. Compared with zenith observations, off-zenith observations have well agreement with RAOBs above 4.5 km. The correlation coefficient cannot be calculated in some altitudes because the compared RAOB relative humidity remains constant at these altitudes, so some breakpoints are shown in the Fig. 2a. The biases of zenith and off-zenith observations are negative below 5 km and there are no distinct differences between them. Above 6 km, both the biases in zenith and off-zenith methods increase with height, but the bias is clear smaller in off-zenith method. It is the same situation for the RMSE, the RMSE differences between zenith and off-zenith observations are not evident below 5 km, while above 5 km the RMSE is clearly smaller in off-zenith observations.

The comparison results for the vapor density profiles are shown in Fig. 3. It can be seen that the correlation coefficient in zenith observation is positive below 3.5 km but mostly negative above 3.5 km, while in off-zenith observation it is positive except around 3 km. In general, the correlation coefficient is more reasonable in off-zenith method than in zenith method. The bias of vapor density in zenith observation increases from 0 g m^{-3} at surface to 5.51 g m^{-3} at 2 km and then decreases to near 0 g

m^{-3} at 10 km again, but in off-zenith observation the bias is clear smaller with a value within ±1.0 g m^{-3}. Both the RMSEs in zenith and off-zenith observations vary similarly with height, in which the RMSE in zenith (off-zenith) observation firstly increases to 3 km (2.3 km) and then decreases to near 0 g m^{-3} at 10 km. Although the RMSE has a close value in zenith and off-zenith observations, it is also clear smaller in off-zenith observation. The RMSE in zenith observation is mostly greater than 1.0 g m^{-3} with a peak of 2.60 g m^{-3}, yet it is generally smaller than 1.0 g m^{-3} with a peak of 1.47 g m^{-3}.

Based on the above analysis, it is clearly that snowfall has a significant impact on MWR measurement accuracy, and off-zenith method can improve the accuracies of MWR retrievals under snow conditions, especially for the temperature and vapor density retrievals. Snowfall, one of precipitation, does not be considered in the MWR retrieving method, so the MWR-retrieved atmospheric profiles in snow conditions are not reasonable as those in non-precipitation conditions (Xu et al, 2014). Although a special blower system is used to sweep water beads and snow away from the radome, snowfall, particularly heavy snowfall will always freeze on the radome in the low temperature situation. Snow produces a strong scattering signal in the microwave region and the snow ice will increase signal noise of MWR measurement, so the frozen snow on the radome will have great influence on the MWR measurement of brightness temperature. Compared to zenith method, off-zenith method has better measurement accuracies under snow conditions. This is mainly because that the MWR observes at 15° elevation through vertical sections of the inverted “U” shaped radome that are more readily cleared of snow/water droplets by gravity than the horizontal sections observed at zenith. Moreover, the MWR accuracies are related with the balloon drifting in sounding due to the wind in atmosphere (Xu et al., 2015), and the off-zenith observations are more representative of the conditions in which radiosonde observations are also taken (Xu et al., 2014), thus the MWR measurement accuracies are generally better in off-zenith method than in zenith method.

3.2 Case study

To better understand the effect of off-zenith method on the improvement of MWR retrieval accuracy, the comparison between the time series of the MWR retrievals in a heavy snowfall and a light snowfall are performed. The heavy snowfall happens from 00:07 UTC 5 February to 04:15 UTC 7 February in 2014 with cumulative snowfall of 28.0 mm and the light snowfall happens from 07:16 UTC 8 February to 04:22 UTC 9 February in 2014 with cumulative snowfall of 2.3 mm.

As shown in Fig. 4, the MWR-retrieved temperature in zenith method presents a clear increase at ~2.5 km in the heavy snowfall, but the increase is not clear in off-zenith method. The MWR-retrieved temperature in zenith method is about 10 K warmer than that in off-zenith method when the snowfall happens, and the greater temperature is well accordant with the snowfall time. The clearly warmer temperature disappeared in 1 h after the end of heavy snowfall. Fig. 5 illustrates the situation in the light snowfall. The MWR temperature discrepancies between zenith and off-zenith methods are not significant as those in the heavy snowfall, and the MWR temperatures in zenith method are about 3 K warmer than those in off-zenith method at ~2.5 km when the snowfall happens. The greater temperature is not obvious when light snowfall maybe due to the light snow on the radome is blown away immediately by the special blower system.

The MWR-retrieved temperatures have well agreement between zenith and off-zenith method in light snow condition, while they have poor agreement in heavy snowfall. Although a special blower system is used to sweep water beads and snow away from the radome, the heavy snowfall is hardly blown away and will easily froze on the radome. Frozen snow will have great influence on the MWR measurement of brightness temperature, so heavy snowfall has more effect on the MWR observations comparing with light snowfall. The greater temperature in zenith method is probably caused by the discrepancies of MWR-measured brightness temperature, and this will helpful to explain why the greater temperature is significant in heavy snow condition. Off-zenith method significantly minimizes contamination from ice and snow, so the MWR-retrieved temperature in zenith method is more reasonable especially when heavy snowfall.

The MWR relative humidity discrepancies in zenith and off-zenith methods are also significant in the heavy snowfall (Fig. 6). Although the MWR relative humidity presents good agreement in zenith and off-zenith methods below 2.5 km, the MWR relative humidity retrievals in zenith method are clear larger than those in off-zenith method above 5 km, about 40 % at 7 km. Greater MWR relative humidity appears above 7 km in zenith method and also well consistent with the timing of the heavy snowfall, while this situation disappears in the off-zenith method. However, the discrepancies between zenith and off-zenith methods are not clear in the light snowfall, and the variation of the relative humidity is also more stable (Fig. 7). The bottom of atmosphere is almost saturated when snowfall happens and we attribute that snow will easily sublimation in the blowing of the special thermodynamic blower system.

The situation for the vapor density is the same as the temperature. As shown in Fig. 8, the MWR vapor density retrievals in zenith method are significantly larger than those in off-zenith method at ~2.5 km in the heavy snowfall, and the time of vapor density increasing is also consistent with the heavy snowfall time. The heavy snowfall will also reduce the retrieval accuracies of vapor density by influencing the brightness temperature measurements of MWR, thus the trend of vapor density variation in zenith method is similar to that of temperature with heavy snowfall. While in off-zenith method, the MWR vapor density retrievals are more reasonable without the significantly larger area. In the light snowfall (Fig. 9), the MWR vapor density retrievals present a similar trend in zenith and off-zenith methods, but the former is clearly larger than the latter below 3 km.

Obviously, the MWR retrieval discrepancies between zenith and off-zenith methods are greater in heavy snowfall than that in light snowfall, As mentioned before, this is mainly because that the snowfall is more easy to freeze on the radome top in heavy snowfalls and the signal noise caused by snowfall increases, while in the sides of the radome the snowfall drops to the ground for gravity, so the MWR retrieval discrepancies are greater in heavy snowfalls. However, in light snowfalls,

Atmos. Meas. Tech. Discuss., doi:10.5194/amt-2016-253, 2016
Manuscript under review for journal Atmos. Meas. Tech.
Published: 15 August 2016

Atmospheric Measurement Techniques
Discussions

the blower system can sweep some snowfall away, so the impact of snowfall is not greater as that in heavy snowfalls.

4. CONCLUSIONS

In this paper, the MWR retrieval accuracies in snow conditions are discussed by comparing with the RAOBs and improvements of off-zenith method are also investigated when snowfall happens. We also present two snowfall cases to explore the MWR retrieval accuracy in heavy and light snow conditions. Based on the above analysis, we draw the following conclusions:

1. Without considering the division of altitude, all the MWR retrievals have a better correlation with RAOB profiles in off-zenith method than that in zenith method especially for relative humidity when snowfall happens, and the biases and RMSEs are also clearly reduced in off-zenith method. The temperature bias and RMSE decrease from 4.6 K and 5.7 K in zenith method to -0.6 K and 2.0 K in off-zenith method, respectively. The relative humidity bias and RMSE also decrease from 10% and 33% in zenith method to -2 % and 20 % in off-zenith method, respectively, while the correlation coefficient increases from 0.2531 to 0.7997. For vapor density, the bias is 1.43 g m^{-3} with a RMSE of 2.14 g m^{-3} in zenith method, while in off-zenith method the bias decreases to 0.10 g m^{-3} with a smaller RMSE of 0.66 g m^{-3}.

2. The discrepancies between the MWR retrievals and the RAOB profiles along with the altitude under snow conditions are also investigated. The MWR temperature

shows a warm bias against RAOB in zenith method and the bias is larger than 3 K at most heights, while in off-zenith the bias becomes cold and is within -1 K at most heights. The temperature RMSE is greater than 4 K above 0.5 km in zenith method while in off-zenith method it is within 2 K at most heights. The vapor density retrievals show the same situation, the bias and RMSE are clear smaller in off-zenith method than in zenith method at most height. The off-zenith relative humidity retrievals show a better agreement with RAOBs above 4.5 km but the correlation coefficients are negative in zenith method. Although the differences between zenith and off-zenith methods in relative humidity bias and RMSE are insignificant below 5 km, the bias and RMSE are clearly smaller in off-zenith method above 6 km.

3. Case studies show that the heavy snowfall has an obvious impact on the accuracies of MWR retrievals by influencing the MWR brightness temperature measurements, and the off-zenith method greatly mitigates the impact of snowfall. The zenith retrievals have an increase trend during heavy snowfall process, but the MWR retrievals in off-zenith method are smooth without the higher retrievals appearing in zenith method.

4. The MWR measurements become less accurate in snowfall is mainly due to the retrieving method which does not consider the effect of snow, moreover, the snowfall accumulating on the radome especially in heavy snowfalls also increases the signal noise of MWR measurement. As the snowfall drops away by gravity in the sides of the radome and the off-zenith observations are more representative of the atmospheric conditions for RAOB, the off-zenith method makes a positive effect on

mitigating the impact of snowfall,

Acknowledgements

This study was supported by the Hubei Meteorological Bureau project under Grant 2014Q03, the open project of Institute of Plateau Meteorology, CMA, Chengdu under Grant LPM2014009 and the National High Technology Research and Development Program ("863" Program) of China under Grant 2012AA120902.

References

Chan, P. W.: Performance and application of a multi-wavelength, ground-based microwave radiometer in intense convective weather. Meteorolo. Z., 18, 253-265, doi: 10.1127/0941-2948/2009/0375, 2009.

Chan, P. W. and Hon, K. K.: Performance of instability indices of the troposphere as derived from a ground-based microwave radiometer. The 11th Specialist Meeting on Microwave Radiometry and Remote Sensing of the Environment, Washington, DC, USA, 1-4 March 2010, 2010.

Cimini, D., Campos, E., Ware, R., Albers, S., Giuliani, G., Oreamuno, J., Joe, P., Koch, S. E., Cober, S., and Westwater, E.: Thermodynamic atmospheric profiling during the 2010 winter olympics using ground-based microwave radiometry. IEEE T GEOSCI REMOTE, 49, 4959-4969, doi: 10.1109/TGRS.2011.2154337, 2011.

Cimini, D., Nelson, M., Güldner, J., and Ware, R.: Forecast indices from a ground-based microwave radiometer for operational meteorology. Atmos. Meas. Tech., 8, 315-333, doi: 10.5194/amt-8-315-2015, 2015.

Kneifel, S., Löhnert, U., Battaglia, A., Crewell, S., and Siebler, D.: Snow scattering signals in ground‐based passive microwave radiometer measurements. J. Geophys. Res., 115, D16214, doi: 10.1029/2010JD013856, 2010.

Knupp, K. R., Ware, R., Cimini, D., Vandenberghe, F., Vivekanandan, J., Westwater, E., Coleman, T., and Phillips, D.: Ground-based passive microwave profiling during dynamic weather conditions. J. Atmos. Oceanic. Tech., 26, 1057-1073, doi: 10.1175/2008JTECHA1150.1, 2009.

Leena, P. P., Dani, K. K., Nath, A., Sanap, S. D., Pandithurai, G., and Kumar, V. A.: Validation of ground-based microwave radiometer data and its application in verifying atmospheric stability over Mahbubnagar during 2011 monsoon and post-monsoon seasons. Int. J. Remote. Sens., 36, 2920-2933, doi: 10.1080/01431161.2015.1051632, 2015.

Löhnert, U. and Maier, O.: Operational profiling of temperature using ground-based microwave radiometry at Payerne: prospects and challenges. Atmos. Meas. Tech., 5, 1121–1134, doi: 10.5194/amt-5-1121-2012, 2012.

Löhnert, U., Kneifel, S., Battaglia, A., Hagen, M., Hirsch, L., and Crewell, S.: A multisensor approach toward a better understanding of snowfall microphysics: the TOSCA project. Bull. Amer. Meteor. Soc., 92, 613–628, doi: 10.1175/2010BAMS2909.1, 2011.

Madhulatha, A., Rajeevan, M., Ratnam, M. V., Bhate, J., and Naidu, C. V.: Nowcasting severe convective activity over southeast India using ground-based microwave radiometer observations. J. Geophys. Res., 118, 1–13, doi: 10.1029/2012JD018174, 2013.

Marzano, F. S., Cimini, D., and Ware, R.: Monitoring of rainfall by ground-based passive microwave systems: models, measurements and applications. Advances in Geosciences, 2, 259–265, doi: 10.5194/adgeo-2-259-2005, 2005.

Matrosov, S. Y., Shupe, M. D., and Djalalova, I. V.: Snowfall retrievals using millimeter-wavelength cloud radars. J. Appl. Meteorol. Clim., 47, 769-777, doi: 10.1175/2007JAMC1768.1, 2008.

Sánchez, J. L., Posada, R., García-Ortega, E., López, L., and Marcos, J. L.: A method to improve the accuracy of continuous measuring of vertical profiles of temperature and water vapor density by means of a ground-based microwave radiometer. Atmos. Res., 122, 43–54, doi:10.1016/j.atmosres.2012.10.024, 2013.

Ware, R., Cimini, D., Campos, E., Giuliani, G., Albers, S., Nelson, M., Koch, S. E., Joe, P., and Cober, S.: Thermodynamic and liquid profiling during the 2010 Winter Olympics. Atmos. Res. 132–133, 278–290, doi: 10.1016/j.atmosres.2013.05.019, 2013.

Ware, R., Cimini, D., Herzegh, P., Marzano, F., Vivekanandan, J., and Westwater, E.: Ground-based microwave radiometer measurements during precipitation. The 8th Specialst Meeting on Microwave Radiometry, Rome, Italy, 24-27 Feb 2004, 2004.

Xie, X. X., Löhnert, U., Kneifel, S., and Crewell, S.: Snow particle orientation observed by ground-based microwave radiometry, J. Geophys. Res., 117, D02206, doi: 10.1029/2011JD016369, 2012.

Xu, G. R., Xi, B. K., Zhang, W. G., Cui, C. G., Dong, X. Q., Liu, Y. B., and Yan, G. P.: Comparison of atmospheric profiles between microwave radiometer retrievals and radiosonde soundings, J. Geophys. Res. Atmos., 120, doi: 10.1002/2015JD023438, 2015.

Xu, G. R., Ware, R., Zhang, W. G., Feng, G. L., Liao, K. W., and Liu, Y. B.: Effect of off-zenith observations on reducing the impact of precipitation on ground-based microwave radiometer measurement accuracy. Atmos. Res., 140-141, 85–94, doi: 10.1016/j.atmosres.2014.01.021, 2014.

Tables:

Table 1. Details of three snow cases used in this study

Start time of snowfall	**End time of snowfall**	**Cumulated snowfall (mm)**
00:07 UTC 5 Feb 2014	04:15 UTC 7 Feb 2014	28.0
07:16 UTC 8 Feb 2014	04:22 UTC 9 Feb 2014	2.3
12:00 UTC 17 Feb 2014	01:38 UTC 18 Feb 2014	11.1

Table 2. Comparison of MWR retrievals against RABOs in zenith and off-zenith methods under snow conditions when not considering the level division in altitude.

Parameters	Observation mode	Number of samples	Correlation coefficient	Bias	RMSE
Temperature	Zenith	464	0.9239	4.6 K	5.7 K
	Off-zenith	464	0.9890	-0.6 K	2.0 K
Relative Humidity	Zenith	464	0.2531	8.9 %	33.1 %
	Off-zenith	464	0.7997	-2.2 %	20.2 %
Vapor density	Zenith	464	0.7130	1.43 g m^{-3}	2.14 g m^{-3}
	Off-zenith	464	0.9389	0.10 g m^{-3}	0.66 g m^{-3}

Figures:

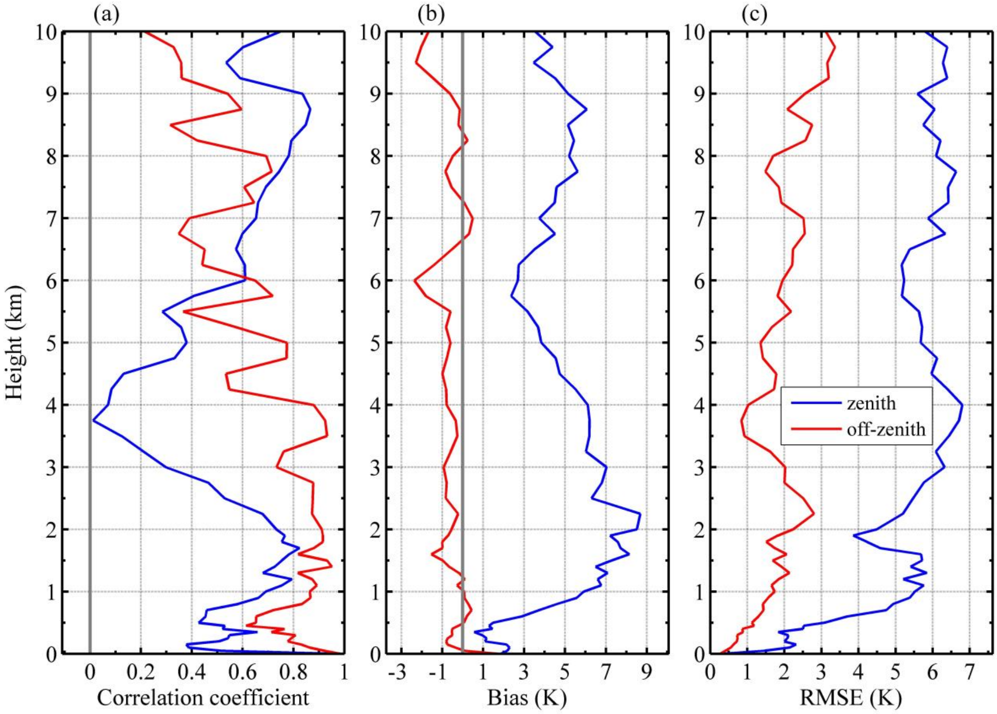
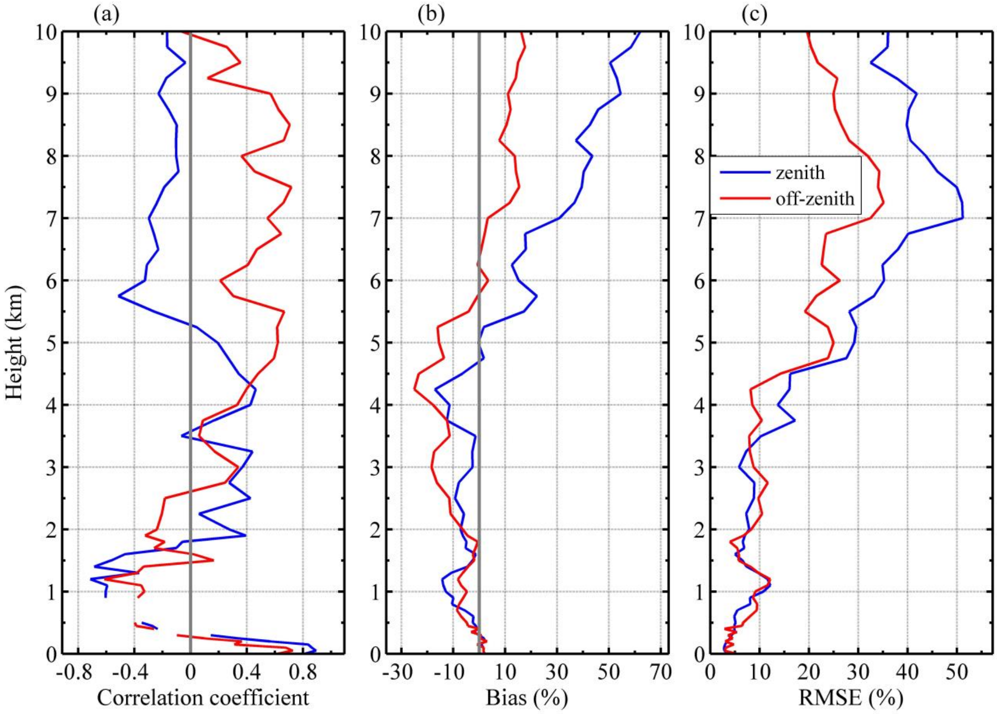


Figure 1. The correlation coefficient (a), bias (b) and RMSE (c) between the MWR and RAOB temperature in zenith (blue) and off-zenith (red) observations.

Atmos. Meas. Tech. Discuss., doi:10.5194/amt-2016-253, 2016
Manuscript under review for journal Atmos. Meas. Tech.
Published: 15 August 2016



1

2 Figure 2. Same as Fig. 1 but for relative humidity profiles. Some breakpoints are

3 shown in Fig. 2a because the compared RAOB relative humidity remains constant at

4 these altitudes.

Atmos. Meas. Tech. Discuss., doi:10.5194/amt-2016-253, 2016
Manuscript under review for journal Atmos. Meas. Tech.
Published: 15 August 2016

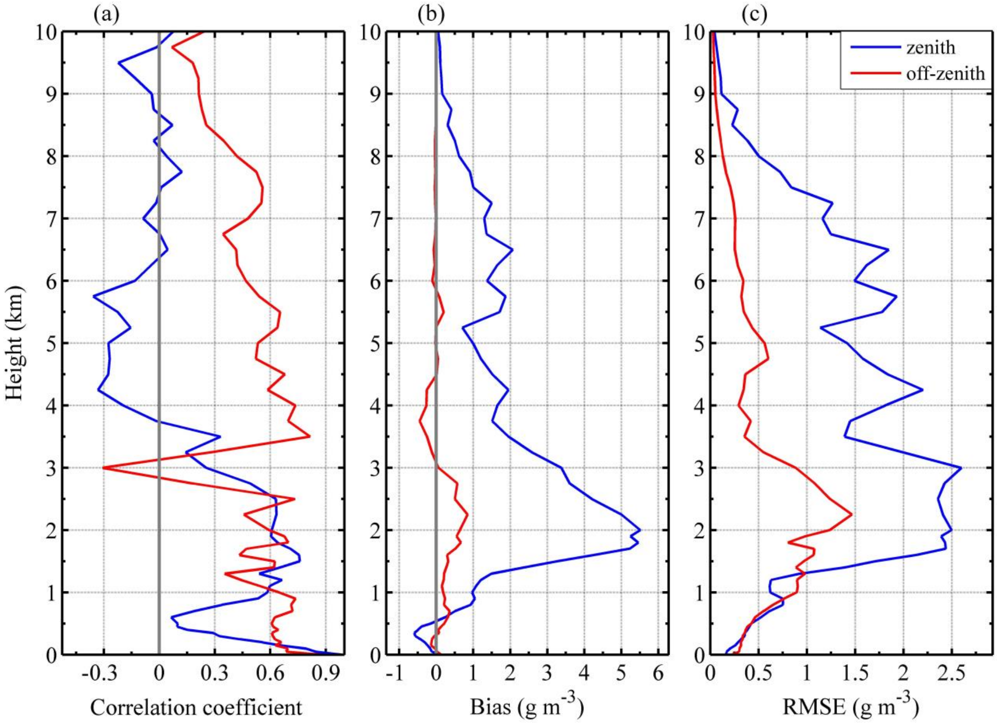


Figure 3. Same as Fig. 1 but for vapor density profiles.

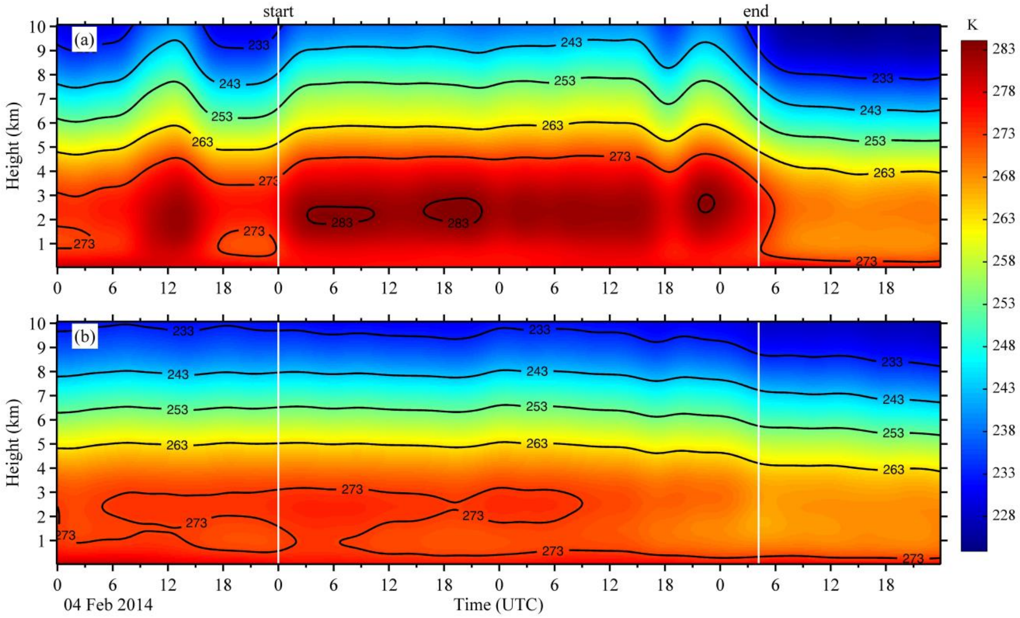


Figure 4 Comparison of temperature retrievals between zenith (a) and off-zenith (b) observation in heavy snow condition. The start and end times of snowfall are indicated by the vertical lines. The time series starts at 00:00 UTC 04 Feb 2014.

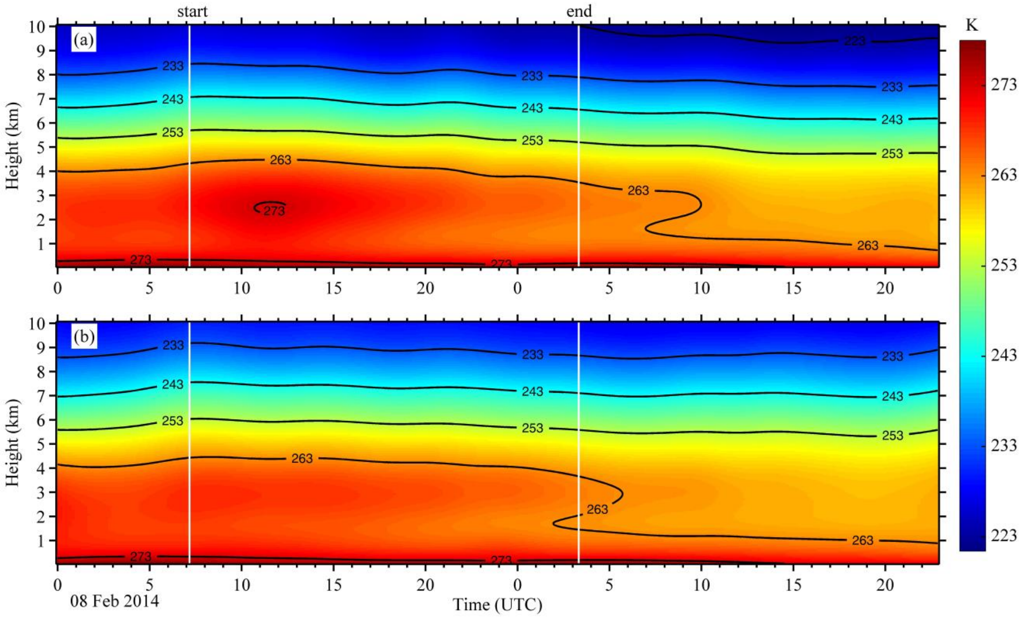


Figure 5 Comparison of temperature retrievals between zenith (a) and off-zenith (b) observation in light snow condition. The start and end times of snowfall are indicated by the vertical lines. The time series starts at 00:00 UTC 08 Feb 2014.

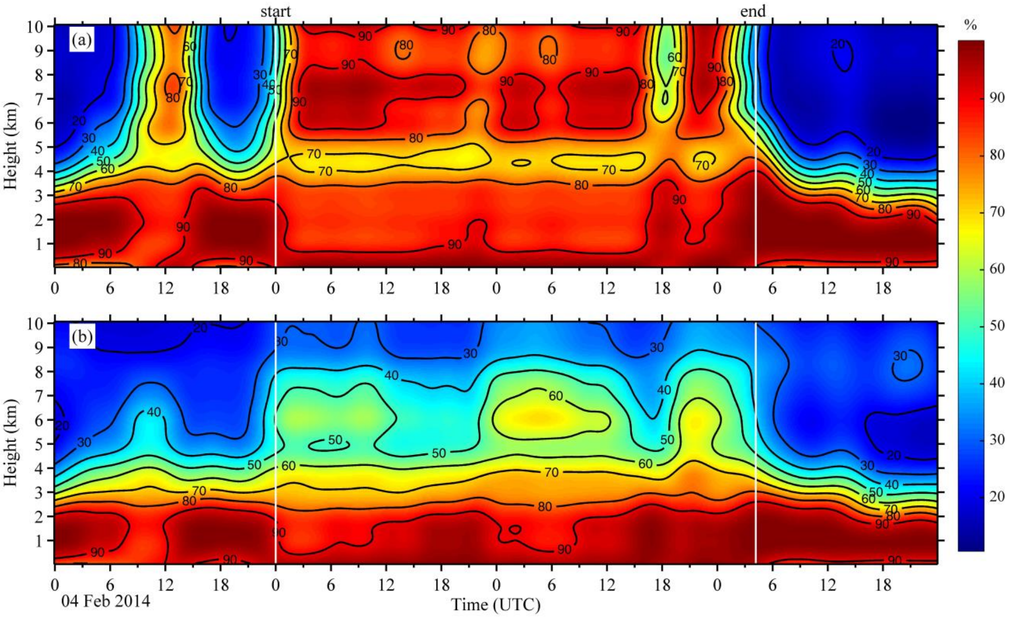


Figure 6 Same as Fig. 4 but for relative humidity retrievals.

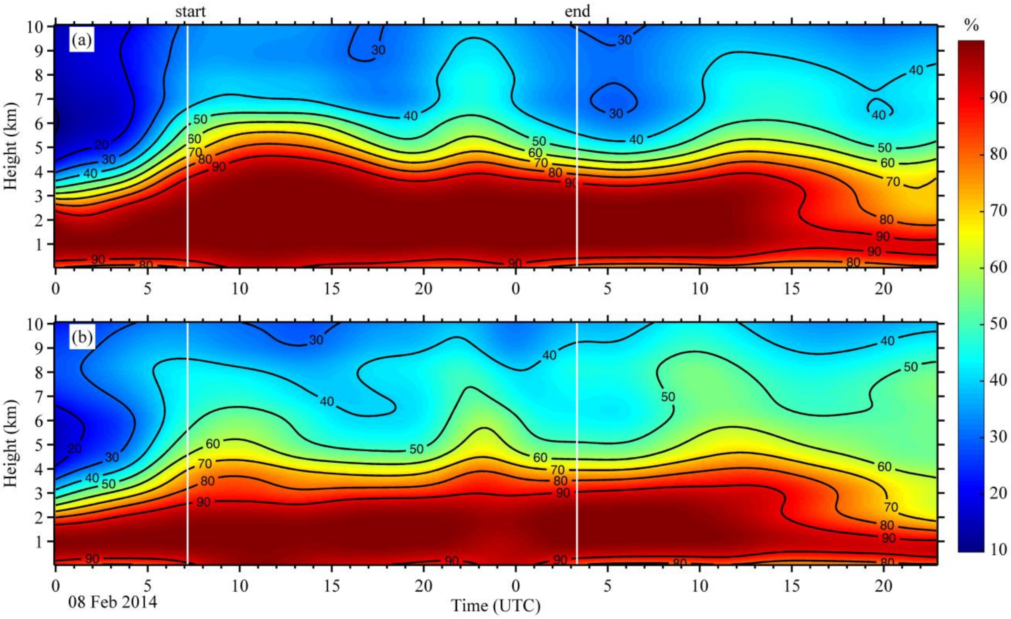


Figure 7 Same as Fig. 5 but for relative humidity retrievals.

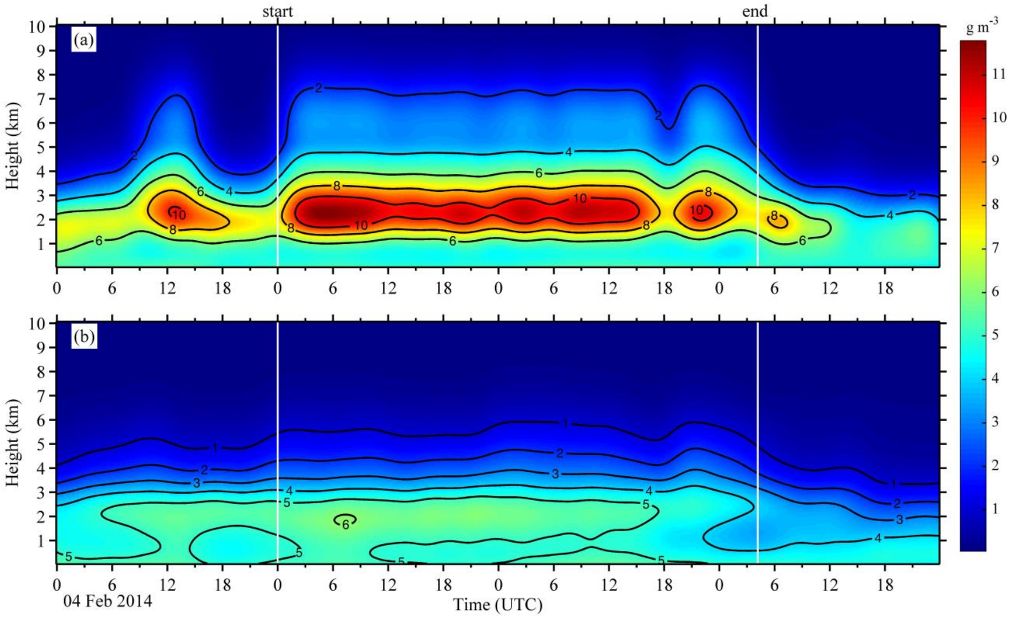


Figure 8 Same as Fig. 4 but for vapor density retrievals.

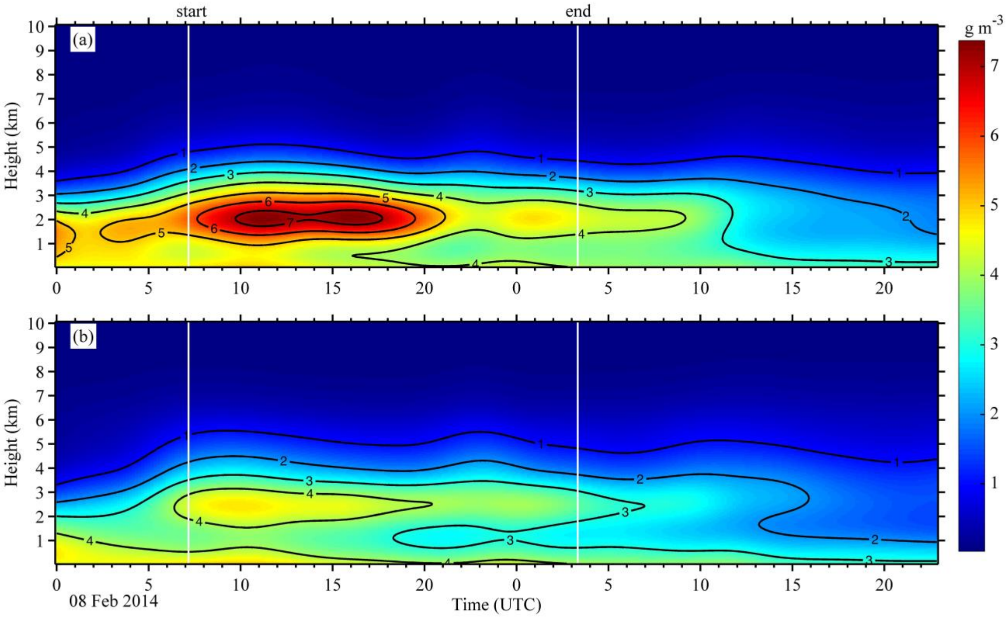


Figure 9 Same as Fig. 5 but for vapor density retrievals.