Effect of the off-zenith observation on reducing the impact of precipitation on ground-based microwave radiometer measurement accuracy in Wuhan

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Abstract

Microwave radiometer (MWR) can be useful for the detection of mesoscale phenomena because of its thermodynamic profiles in a minute time scale. These profiles are mainly used in non-precipitation conditions due to the less accurate of the MWR measurements in precipitation. Recently, the Radiometrics Corporation retrieved the temperature and humidity profiles from off-zenith (15° elevation) radiometer observations to provide higher accuracy during precipitation. In this paper, using the MWR-retrieved temperature and humidity profiles with collocated radiosondes from June 2010 to September 2013 in Wuhan, the impact of precipitation on the MWR measurement accuracy as well as the effect of off-zenith observation on it is investigated. In precipitation, the correlation coefficients of the MWR temperature and vapour density profiles against radiosondes are smaller than that in non-precipitation, and the bias and RMS against radiosondes also increase, especially around 2 km heights. For the MWR relative humidity profile, the correlation coefficient in precipitation is obvious smaller than that in non-precipitation below 4.5 km, and the bias and RMS against radiosondes are clear larger above 5.5 km.
Compared with the results of the zenith observation, the off-zenith observation makes a positive effect on reducing the impact of precipitation on the accuracy of MWR temperature and vapour density retrievals. On a whole, the MWR temperature bias and RMS against radiosondes in precipitation are reduced from 3.6 and 4.2 K to 1.3 and 3.1 K, respectively, and the MWR vapour density bias is also reduced from 1.10 g/m³ to 0.18 g/m³ with the RMS decreasing from 2.90 g/m³ to 1.91 g/m³. The temperature correlation coefficient between the MWR and radiosonde in precipitation is clearly improved above 3 km heights, and the temperature bias and RMS are significantly reduced at most heights. For the MWR vapour density retrievals in precipitation, the correlation coefficient, bias and RMS against radiosondes are clearly improved above 2 km heights. However, the off-zenith observation does not make a clear positive effect on improving the accuracy of the MWR relative humidity retrievals in precipitation.

**Keyword:** Microwave radiometer; off-zenith observation; precipitation; accuracy

### 1. Introduction

Atmospheric temperature and humidity profiles are significant for meteorological research, and commonly obtained with traditional radiosondes, which are launched only twice each day in operation. Many of the meteorological phenomena occurring at meso-γ require observations sufficiently close together in time and space. However, the lack of observations necessary to define mesoscale systems is a critical meteorological problem. Ground-based microwave radiometers (MWR) retrieve the temperature and humidity profiles up to 10 km by measuring the radiation intensity at a number of frequency channels in the microwave spectrum that are dominated by atmospheric water vapor, cloud liquid water and molecular oxygen emissions. These profiles are available nearly continuously, at intervals of several minutes (Chan, 2009). The high temporal resolution is able to resolve detailed mesoscale thermodynamic and limited microphysical features of various rapidly changing mesoscale and/or hazardous weather phenomena (Knupp et al. 2009). Gradually, MWRs are installed in many countries and applied in nowcasting.
Continuous measurements done using MWR can be very useful for the detection of mesoscale phenomena that require very high spatial and temporal scales. However, this measurement technology is based on an indirect measurement and, as such, it is necessary to know the uncertainty of these measurements, especially in comparison with radiosonde. It is found in studies that since the measurement principles of MWR and radiosonde are different (Volume integral above a fixed location on the ground for MWR vs. point measurement of a drifting balloon for radiosonde), there are biases and spreads of the data points, but the two data sets are following the similar trends in the evolution of the temperature and humidity inside the troposphere (Güldner and Spänkuch, 2001; Zhao et al. 2010; Chan and Hon, 2011; Madhulatha et al. 2013). Some studies show that MWR is mainly suited for continuous observations in the low troposphere (Liu 2011; Löhnert and Maier, 2012), and corrector measurements should be applied to reduce the system bias between MWR and radiosonde observations before obtaining the MWR potential benefits in operational activities (Calpini et al. 2011; Tan et al. 2011; Yao et al. 2011; Sánchez et al. 2013).

Although MWR has an advantage of high temporal resolution, it is mainly used in non-precipitating conditions because the radiometer measurements become less accurate in the presence of a water film on the outer housing (radome) of the equipment. Moreover, the radiometer retrieval normally does not include the scattering and emission/absorption effects of rain. Recently there are some progress in applying rain-effect mitigation methods to the radiometer, such as a hydrophobic radome and forced airflow over the radome surface (Chan, 2009). In addition, the Radiometrics Corporation retrieved the temperature and humidity profiles from off-zenith (15° elevation) radiometer observations to provide higher accuracy during precipitation by minimizing the affect of liquid water and ice on the radiometer radome (Cimini et al. 2011; Ware et al. 2013). In this study, the impact of
precipitation on MWR measurement accuracy is evaluated against radiosonde using about 3 year data set of MWR-retrieved temperature and humidity profiles with collocated vertical soundings of the atmosphere in Wuhan, China, and the effect of off-zenith observation on reducing the impact of precipitation is also explored.

2. Instruments and methods

Wuhan (30.6°N, 114.1°E, 23 m above sea level) is an operational radiosonde station in central China. A MWR is installed in Wuhan in June 2010. This paper focuses on the period from June 2010 to September 2013. The data used in this paper were collected by continuous MWR (at near 3-min intervals) and by radiosonde ascents (at 12-h intervals). The MWR is a Radiometrics MP-3000A unit, which observes 21 K-band (22 - 30 GHz) and 14 V-band (51 - 59 GHz) microwave channels at multiple elevation angles, one zenith infrared (9.6 - 11.5 μm) channel, and surface temperature, humidity and pressure sensors (Cimini et al. 2011; Ware et al. 2013). Vertical retrieval intervals are 50 m from the surface to 500 m, 100 m to 2 km, and 250 m to 10 km. To minimize such errors caused by liquid water on the MWR antenna radome, the radome is made hydrophobic to repel liquid water, and a special blower system is used to sweep water beads and snow away from the radome (Chan, 2009). A rain sensor is companied with the MWR, which is used to provide a “Rain Flag” for data that is potentially contaminated by some liquid water on the Radome. The Rain Flag data is 0 (Rain=0) and 1 (Rain=1) in non-precipitation and precipitation, respectively.

The MWR receives roughly a picowatt of Planck radiation emitted by atmospheric oxygen and water vapour molecules and liquid water, in multiple frequency channels. The atmosphere is semi-transparent in the K-band and lower V-band channels during non precipitating conditions, receiving emission from the atmosphere in addition to cosmic background radiation. The microwave, infrared and surface meteorological observations are automatically converted into continuous temperature, humidity and liquid profiles using radiative transfer equations and neural
networks. 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). Five years of historical Wuhan radiosondes were used for neural network training.

Radiosondes launched from the Wuhan station are L-band radio sounding systems, providing vertical pressure, temperature, relative humidity, dew point temperature, and wind profiles at 1-s resolution. Two radiosonde soundings were obtained daily at standard synoptic hours of 00 and 12 UTC. The radiosonde profiles are used for validating the MWR temperature and humidity profiles. For comparison, the water vapour density profiles are also calculated by using radiosonde temperature and pressure profiles.

The temperature and humidity profiles to 10 km height were retrieved from zenith MWR observations during June 2010 to April 2013, which are used to compare with collocated radiosondes to evaluate the impact of precipitation on MWR measurement accuracy. During April to September in 2013, the temperature and humidity profiles were retrieved from zenith and off-zenith (15° elevation; downslope) MWR observations, respectively, and are used to explore the effect of off-zenith observation on reducing the impact of precipitation on MWR measurement accuracy. Since the radionsondes are launched twice at 00 and 12 UTC each day and the MWR profiles are retrieved at near 3-min intervals, only the MWR profiles which the closest in time of 00 and 12 UTC are used for comparison against the radiosonde ascent.

3. Impact of precipitation on MWR retrievals

To evaluate the impact of precipitation on MWR measurement accuracy, we compared the profiles of temperature, vapour density and relative humidity between the MWR and radiosonde in Wuhan during June 2010 to April 2013. The data set is divided into two samples of non-precipitation (Rain=0) and precipitation (Rain=1) conditions. As shown in Table 1, without considering the level division in altitude, the MWR temperature and vapour density profiles have a significant correlation with
radiosondes in both non-precipitation and precipitation, with the correlation coefficients above 0.92. The correlation of relative humidity between the MWR and radiosonde is reasonable with a correlation coefficient of 0.77 and 0.68 in non-precipitation and precipitation, respectively. The MWR temperature has a cold bias of -1.9 K against the radiosonde in non-precipitation, however, the MWR temperature bias becomes warm with 2.1 K in precipitation, and the root-mean-square (RMS) between the MWR and radiosonde also becomes larger from 3.2 K to 5.3 K. The MWR vapour density has a wet bias against the radiosonde, especially in precipitation. The vapour density bias between the MWR and radiosonde varies from 0.06 g/m$^3$ in non-precipitation to 1.31 g/m$^3$ in precipitation, with a corresponding RMS varying from 0.30 g/m$^3$ to 2.28 g/m$^3$. It is the same situation for the MWR relative humidity, the wet bias of the MWR relative humidity against radiosonde varies from 7% in non-precipitation to 10% in precipitation, with a corresponding RMS varying from 21% to 24%. It can be seen that the discrepancy between the MWR retrievals and radiosondes is larger in precipitation than in non-precipitation without considering the level division in altitude.

Table 1 Comparison of MWR zenith retrievals against radiosondes without considering the level division in altitude during June 2010 to April 2013 in Wuhan

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Rain Flag</th>
<th>Numbers</th>
<th>Correlation Coefficient</th>
<th>Bias</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>Rain=0</td>
<td>94656</td>
<td>0.9876</td>
<td>-1.9 K</td>
<td>3.2 K</td>
</tr>
<tr>
<td></td>
<td>Rain=1</td>
<td>6960</td>
<td>0.9614</td>
<td>2.1 K</td>
<td>5.3 K</td>
</tr>
<tr>
<td>Vapour Density</td>
<td>Rain=0</td>
<td>94656</td>
<td>0.9724</td>
<td>0.06 g/m$^3$</td>
<td>0.30 g/m$^3$</td>
</tr>
<tr>
<td></td>
<td>Rain=1</td>
<td>6960</td>
<td>0.9250</td>
<td>1.31 g/m$^3$</td>
<td>2.28 g/m$^3$</td>
</tr>
<tr>
<td>Relative Humidity</td>
<td>Rain=0</td>
<td>94656</td>
<td>0.7721</td>
<td>7.3%</td>
<td>21.4%</td>
</tr>
<tr>
<td></td>
<td>Rain=1</td>
<td>6960</td>
<td>0.6752</td>
<td>9.9%</td>
<td>24.3%</td>
</tr>
</tbody>
</table>

The discrepancy between the MWR retrievals and radiosondes along the altitude during non-precipitation and precipitation is also evaluated with the data set in Wuhan.
from June 2010 to April 2013. As shown in Fig. 1, the temperature correlation coefficient between the MWR and radiosonde is clearly smaller in precipitation than in non-precipitation below 8.5 km height, especially around 2 km height the correlation coefficient decreases from 0.95 to 0.70, however, above 8.5 km height the precipitation shows no distinct impact on the correlation coefficient. The MWR temperature shows a cold bias against radiosondes in non-precipitation, with a bias value varying stably from about 0 K near the surface to -3.5 K at 10 km height, but in precipitation it is opposite below 8.5 km, the temperature bias increases from 0.5 K near the surface to 5.9 K at 2.25 km and then decreases to 0.2 K at 8.5 km before becoming cold with a value within 1 K. Furthermore, the temperature RMS between the MWR and radiosonde is significant larger in precipitation than in non-precipitation. The temperature RMS increases from 1.1 K near the surface to 5.2 K at 10 km height in non-precipitation, but in precipitation it increases sharply from 1.0 K near the surface to 7.6 K at 1.8 km height and then decreases to 4.5 K at 3.5 km height before enlarging again to 6.8 K at 10 km height.

Fig. 1 The correlation coefficient, bias and RMS of temperature profiles between MWR and
raiosonde during non-precipitation (Rain=0) and precipitation (Rain=1) in Wuhan from June 2010 to April 2013.

Fig. 2 presents the comparison for vapour density profiles. It can be seen that the vapour density correlation coefficient between the MWR and radiosonde decreases with altitude in both non-precipitation and precipitation. The vapour density correlation coefficient is smaller in precipitation than in non-precipitation below 6.0 km, but it is opposite between 6.0 - 9.5 km. In non-precipitation, the MWR vapour density shows a dry bias against radiosondes below 1.6 km with a peak of -0.79 g/m$^3$ at 0.8 km height, while above 1.6 km the bias becomes wet with a peak of 0.74 g/m$^3$ at 4.0 km height. However, in precipitation the MWR vapour density shows a wet bias against radiosondes; it increases sharply from 0.24 g/m$^3$ near the surface to 3.32 g/m$^3$ at 2.0 km height, and then decreases to the value of 0.08 g/m$^3$ at 10 km height. Although no distinct is found between the MWR vapour density RMS in non-precipitation and precipitation conditions below 0.5 km, the MWR vapour density RMS is clear larger in precipitation than in non-precipitation. Moreover, in both precipitation and non-precipitation, the MWR vapour density RMS varies with altitude in a similar pattern, in which the RMS firstly increases with altitude and then decreases with altitude before a maximum appearing at 1.6 km height. Most of the MWR vapour density RMS in non-precipitation is within 1.0 g/m$^3$ while that in precipitation is within 2.0 g/m$^3$, and the maximum RMS appearing at 1.6 km height in non-precipitation and precipitation are 1.91 and 4.11 g/m$^3$, respectively.
Fig. 2 Same as Fig. 1 but for vapour density profiles.

The comparison for relative humidity profiles is presented in Fig. 3. The relative humidity correlation coefficient between the MWR and radiosonde is smaller in precipitation than in non-precipitation below 4.5 km, especially from the surface to 2 km, but the discrepancy is not distinct above 4.5 km. Excluding a dry bias of -2.1% in non-precipitation at the surface level, the MWR relative humidity shows a wet bias against radiosondes in both non-precipitation and precipitation. In non-precipitation, the MWR relative humidity bias firstly increases from 0.2% near the surface to 18.1% at 5.0 km and then decreases to 5.8% at 10 km, and in precipitation the MWR relative humidity bias increases with altitude in principle, varying from 0.2% at the surface to 27.4% at 10 km. However, the MWR relative humidity bias is smaller in precipitation than in non-precipitation below 5.5 km, but it is opposite above 5.5 km and the discrepancy enlarges with altitude. The MWR relative humidity RMS in non-precipitation increases generally with altitude, which varies from 9.7% at the surface to 22.7% at 10 km height and the maximum of 26.4% appears at 5 km height. Although the MWR relative humidity RMS in precipitation also increases with altitude on a whole, a peak of 22.1% appears at 1.5 km height and the maximum of
33.7% appears at 9.0 km height. Moreover, the MWR relative humidity RMS is larger in precipitation than in non-precipitation below 1.7 km and above 5.5 km, but the former is smaller than the latter during 1.7 - 5.5 km.

Fig. 3 Same as Fig. 1 but for relative humidity profiles.

4. Effect of off-zenith observation on MWR retrievals

The MWR profiles are retrieved from the simultaneous zenith and off-zenith observations during May to September 2013 in Wuhan. To explore the effect of off-zenith observation on MWR measurement accuracy, the coupled MWR zenith and off-zenith retrievals around the time of 00 and 12 UTC are compared with the collocated radiosondes. Table 2 presents the comparison of MWR zenith and off-zenith retrievals against radiosondes without considering the level division in altitude. It can be seen that in non-precipitation the MWR temperature cold bias and RMS against radiosondes are smaller in off-zenith than in zenith, and in precipitation the MWR temperature warm bias is reduced from 3.6 K in zenith to 1.3 K in off-zenith, with RMS also reducing from 4.2 K to 3.1 K. For vapour density, the MWR bias against radiosondes in non-precipitation is lightly larger in off-zenith than
in zenith with a very close RMS, and in precipitation the MWR bias is reduced from 1.10 g/m³ in zenith to 0.18 g/m³ in off-zenith, with RMS also reducing from 2.90 g/m³ to 1.91 g/m³. Although the MWR relative humidity bias against radiosondes in non-precipitation is lightly smaller in off-zenith than in zenith with a same RMS, the discrepancy of MWR relative humidity against radiosondes in precipitation varies from a wet bias of 3.9% in zenith to a dry bias of -12.1% in off-zenith, and the corresponding RMS also increases lightly. In addition, the correlation coefficients between the MWR retrievals and radiosondes in precipitation are larger in off-zenith than in zenith, especially for vapour density it increases from 0.91 to 0.97.

Table 2 Comparison of MWR zenith and off-zenith retrievals against radiosondes without considering the level division in altitude during May to September 2013 in Wuhan

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Rain Flag</th>
<th>Observation Mode</th>
<th>Numbers</th>
<th>Correlation Coefficient</th>
<th>Bias</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>Rain=0</td>
<td>Zenith</td>
<td>14500</td>
<td>0.9911</td>
<td>-2.4 K</td>
<td>2.8 K</td>
</tr>
<tr>
<td></td>
<td>Rain=0</td>
<td>Off-zenith</td>
<td>14500</td>
<td>0.9936</td>
<td>-1.1 K</td>
<td>2.1 K</td>
</tr>
<tr>
<td></td>
<td>Rain=1</td>
<td>Zenith</td>
<td>928</td>
<td>0.9678</td>
<td>3.6 K</td>
<td>4.2 K</td>
</tr>
<tr>
<td></td>
<td>Rain=1</td>
<td>Off-zenith</td>
<td>928</td>
<td>0.9831</td>
<td>1.3 K</td>
<td>3.1 K</td>
</tr>
<tr>
<td>Vapour Density</td>
<td>Rain=0</td>
<td>Zenith</td>
<td>14500</td>
<td>0.9763</td>
<td>0.12 g/m³</td>
<td>1.62 g/m³</td>
</tr>
<tr>
<td></td>
<td>Rain=0</td>
<td>Off-zenith</td>
<td>14500</td>
<td>0.9792</td>
<td>0.37 g/m³</td>
<td>1.61 g/m³</td>
</tr>
<tr>
<td></td>
<td>Rain=1</td>
<td>Zenith</td>
<td>928</td>
<td>0.9069</td>
<td>1.10 g/m³</td>
<td>2.90 g/m³</td>
</tr>
<tr>
<td></td>
<td>Rain=1</td>
<td>Off-zenith</td>
<td>928</td>
<td>0.9657</td>
<td>0.18 g/m³</td>
<td>1.91 g/m³</td>
</tr>
<tr>
<td>Relative Humidity</td>
<td>Rain=0</td>
<td>Zenith</td>
<td>14500</td>
<td>0.7713</td>
<td>7.4%</td>
<td>19.4%</td>
</tr>
<tr>
<td></td>
<td>Rain=0</td>
<td>Off-zenith</td>
<td>14500</td>
<td>0.7759</td>
<td>6.3%</td>
<td>19.4%</td>
</tr>
<tr>
<td></td>
<td>Rain=1</td>
<td>Zenith</td>
<td>928</td>
<td>0.5648</td>
<td>3.9%</td>
<td>20.3%</td>
</tr>
<tr>
<td></td>
<td>Rain=1</td>
<td>Off-zenith</td>
<td>928</td>
<td>0.6021</td>
<td>-12.1%</td>
<td>22.0%</td>
</tr>
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</table>

The impact of off-zenith observation on MWR measurement accuracy is also...
explored in considering the level division in altitude. Fig. 4 presents the comparison of MWR temperature profiles against radiosondes in zenith and off-zenith observations during May to September 2013 in Wuhan. It can be seen that in non-precipitation the temperature correlation coefficient between MWR and radiosonde is larger in off-zenith observation than in zenith observation below 5.5 km and above 8.75 km, and it is opposite during 5.5 - 8.75 km heights. Although in non-precipitation the MWR temperature bias in off-zenith observation shows no distinct difference from that in zenith observation below 2.0 km, the cold temperature bias above 2.0 km is clearly reduced in off-zenith observation, with the peak bias varying from -4.7 K to -2.2 K. Moreover, the MWR temperature RMS in non-precipitation is obvious smaller in off-zenith observation than in zenith observation, which ranges in 1.0 - 2.6 K and 1.8 - 3.3 K, respectively. In precipitation, the temperature correlation coefficient between MWR and radiosonde in off-zenith observation is lightly smaller than that in zenith observation below 2.5 km, but the former is clearly larger than the latter above 2.5 km. The MWR warm temperature bias in precipitation is also clearly reduced in off-zenith observation, which varies in -0.2 - 3.1 K and that for zenith observation is 1.5 - 8.3 K. The MWR temperature RMS in precipitation shows no distinct difference in zenith and off-zenith observations below 2.5 km, but it is clearly smaller in off-zenith observation than in zenith observation above 2.5 km, with a peak reducing from 6.8 K to 3.7 K.
Fig. 4 The correlation coefficient, bias and RMS of temperature profiles between MWR and radiosonde in zenith and off-zenith observations during May to September 2013 in Wuhan. The up panel is for non-precipitation (Rain=0), and the down panel is for precipitation (Rain=1).

As shown in Fig. 5, in non-precipitation the vapour density correlation coefficient between MWR and radiosonde in off-zenith observation shows no distinct difference from that in zenith observation below 1.5 km, but the former is lightly larger than the latter above 1.5 km. For the MWR vapour density bias in non-precipitation, it is wet against radiosondes below 1.0 km and above 4.0 km but dry at other heights in zenith observation; in off-zenith observation, the wet bias becomes larger below 1.0 km while smaller above 5.0 km, and the dry bias becomes smaller at 1.8 - 2.75 km while larger at 2.75 - 4.0 km, but at other heights the bias signs in zenith and off-zenith observations are opposite. Same as the correlation coefficient, the MWR vapour density RMS in non-precipitation shows no distinct difference between off-zenith and zenith observations below 2 km, but above 2 km the MWR vapour density RMS is smaller in off-zenith observation than in zenith.
observation, and it is more obvious at 2 - 5 km heights. In precipitation, the vapour
density correlation coefficient between MWR and radiosonde in off-zenith
observation is smaller than that in zenith observation below 2 km, but the former is
clearly larger than the latter above 2 km, with most values increasing from below 0.4
to above 0.5. The MWR vapour density in precipitation shows a dry bias against
radiosondes in zenith observation at most heights below 1.6 km while a wet bias
above 1.6 km; although in off-zenith observation the MWR vapour density bias sign
is opposite to that in zenith observation at most heights, the bias range is significantly
reduced from -2.34 - 6.04 g/m$^3$ to -1.17 - 1.42 g/m$^3$. For the MWR vapour density
RMS in precipitation, it is larger in off-zenith observation than in zenith observation
below 1.8 km, but the former is clearly smaller than the latter above 1.8 km especially at
1.8 - 5.0 km heights, and the maximum RMS is also reduced from 4.72 g/m$^3$ in zenith
observation to 3.14 g/m$^3$ in off-zenith observation.

Fig. 5 Same as Fig. 4 but for vapour density profiles.

The comparison of MWR relative humidity profiles against radiosondes in zenith
and off-zenith observations is presented in Fig. 6. In non-precipitation, except above 7 km the relative humidity correlation coefficient between MWR and radiosonde in off-zenith observation is lightly smaller than that in zenith observation, the discrepancy between them shows no distinct at other heights. For the MWR relative humidity bias in non-precipitation, it is dry against radiosondes near the surface but wet at other heights in zenith observation; while in off-zenith observation, the wet bias increases below 2 km but decreases above 4.75 km, and at other heights the bias changes its sign with a close magnitude. Moreover, the MWR relative humidity bias ranges in -5% - 21% in zenith observation, and in off-zenith observation it is during -6% - 14%. Same as the correlation coefficient, the MWR relative humidity RMS in non-precipitation shows no distinct difference between off-zenith and zenith observations below 7.5 km, except the former lightly larger than the latter above 7.5 km. In precipitation, the relative humidity correlation coefficient between MWR and radiosonde is smaller in off-zenith observation than in zenith observation at most heights below 9 km, except the former lightly larger than the latter, and note that a negative correlation coefficient appears at 3 km in zenith observation but it changes to positive in off-zenith observation. For the MWR relative humidity bias in precipitation, it is dry against radiosondes below 1.5 km and at 3.5 - 5.5 km heights but wet at other heights in zenith observation; however, it is dry at most heights except a little wet around 2.5 km in off-zenith observation, and the bias is during -29% - 1% smaller than the range of -12% - 31% in zenith observation. Although the MWR relative humidity RMS in precipitation is lightly smaller in off-zenith observation than in zenith observation above 8.5 km, the former is larger than the latter below 8.5 km especially at 4 - 6 km.
Fig. 6 Same as Fig. 4 but for relative humidity profiles.

5. Discussions and conclusions

MWR can be useful for the detection of mesoscale phenomena because of its ability to obtain constant continuous measurements of temperature and humidity profiles. These profiles are mainly used in non-precipitation conditions because the MWR measurements become less accurate in the presence of a water film on the radome of the equipment. Recently, there have been improvements in applying rain-effect mitigation methods to the radiometer, such as a hydrophobic radome and forced airflow over the radome surface. In addition, the Radiometrics Corporation retrieved the temperature and humidity profiles from off-zenith (15° elevation) radiometer observations to provide higher accuracy during precipitation by minimizing the affect of liquid water and ice on the radiometer radome.

In this paper, the impact of precipitation on the MWR measurement accuracy against radiosonde is evaluated using a 3 year data set of MWR-retrieved temperature and humidity profiles with collocated radiosondes in Wuhan. Without considering the
level division in altitude, the MWR retrievals still have reasonable correlation coefficients with radiosondes in precipitation conditions. However, the MWR retrieval accuracy against radiosondes in precipitation is not good as that in non-precipitation, in which the absolute biases for the temperature, vapour density and relative humidity are 2.1 K, 1.31 g/m$^3$ and 10%, with the corresponding RMS errors of 5.3 K, 2.28 g/m$^3$ and 24%, respectively. Considering the level division in altitude, the MWR temperature is mostly impacted by precipitation around 2 km height compared with that in non-precipitation, at which the correlation coefficient decreases from 0.95 to 0.70 while the absolute bias and RMS error increase from 1.4 and 2.5 K to 5.9 and 7.6 K, respectively. The impact of precipitation on the MWR vapour density is also most obvious around 2 km height, at which the correlation coefficient, absolute bias and RMS error vary from 0.91, 0.23 g/m$^3$ and 1.91 g/m$^3$ in non-precipitation to 0.76, 3.32 g/m$^3$ and 4.11 g/m$^3$ in precipitation, respectively. However, for the MWR relative humidity, the correlation coefficient in precipitation is obvious smaller than that in non-precipitation below 4.5 km, and the absolute bias and RMS error are clear larger above 5.5 km.

The effect of off-zenith observation on reducing the impact of precipitation on MWR measurement accuracy is also explored in this paper by comparing the MWR retrievals in zenith and off-zenith observations with collocated radiosondes. Without considering the level division at altitude, the off-zenith observation makes a positive effect on reducing the impact of precipitation on the accuracy of MWR temperature and vapour density retrievals. The MWR temperature bias against radiosondes is reduced from 3.6 K in zenith observation to 1.3 K in off-zenith observation, with the RMS error also reducing from 4.2 K to 3.1 K. For the MWR vapour density, the bias and RMS error are reduced from 1.10 g/m$^3$ and 2.90 g/m$^3$ in zenith observation to 0.18 g/m$^3$ and 1.91 g/m$^3$, respectively. Although the relative humidity correlation coefficient between the MWR and radiosonde is lightly larger in off-zenith observation than in zenith observation, the former’s bias of -12% is larger than the latter’s bias of 4% with close RMS errors. Considering the level division at altitude, the temperature correlation coefficient between the MWR and radiosonde in
precipitation conditions is clearly improved in off-zenith observation above 3 km heights, and the temperature warm bias against radiosondes is also significantly reduced from the surface to 10 km with a distinct smaller RMS error above 3 km. For the MWR vapour density retrievals in precipitation, the correlation coefficient and RMS error against radiosondes is also improved in off-zenith observation above 2 km, and the bias is also clearly reduced at most heights. However, the relative humidity correlation coefficient between the MWR and radiosonde in precipitation is only improved in off-zenith observation around 3 km height, and the relative humidity bias range is just reduced from -12% - 31% to -29% - 1% with the RMS error only reduced above 8.5 km. Note that the off-zenith observation also makes a positive effect on the MWR measurement accuracy in non-precipitation conditions especially for the temperature and vapour density profiles.

Our results suggest that the off-zenith observation makes a positive effect on reducing the impact of precipitation on the accuracy of the MWR temperature and vapour density profiles. The MWR temperature profile retrieved from off-zenith observation in precipitation conditions has a reasonable accuracy against radiosondes, which comparable to that from zenith observation in non-precipitation conditions. Moreover, the accuracy of the MWR vapour density profile retrieved from off-zenith observation is also improved on the whole in precipitation conditions. However, the effect of off-zenith observation on reducing the impact of precipitation on the MWR relative humidity accuracy is not obvious like those for the MWR temperature and vapour density profiles.

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REFERENCE


