The 1-Dimentional Variational Approach to Improve Thermodynamic Profiles in Low-Level Troposphere during Rain Conditions

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1. Introduction

Temporally and spatially high-resolution estimation of thermodynamic environments, especially in the low-level troposphere, is needed for nowcasting and forecasting severe storms. One of the methods for obtaining temporally high-resolution thermodynamic profiles is the retrieval using ground-based microwave radiometer (MWR) data (Araki et al. 2014). The MWR has been used to retrieve vertical profiles of atmospheric temperature and water vapor, and vertically integrated water vapor and liquid water at time intervals of a few minutes. Major methods for the retrieval are neural networks (NNs) and 1-dimensional variational (1DVAR) techniques, and the 1DVAR has been known to outperform other retrieval methods (Araki et al. 2015a). The retrieval using MWR data in zenith direction, however, is critically affected by raindrops on the radome and in the air during rainfall events. In this study, the effectiveness of the off-zenith observations in reducing the error due to raindrops on the radome is investigated (Araki et al. 2015b).

2. Accuracy of retrieved thermodynamic profiles during no-rain and rain conditions

The ground-based multi-channel MWR (model: MP-3000A, Radiometrics) installed on the roof of the Meteorological Research Institute of Japan Meteorological Agency (JMA) at Tateno (36.05°N, 140.13°E) is used in this study. The MWR measures the brightness temperatures of 21 K-band (22–30 GHz) and 14 V-band (51–59 GHz) microwave channels with the band width of 300 MHz in zenith direction and at an elevation angle of 15° in north and south azimuth directions. A rain sensor is also attached to the MWR. In this study, both the 1DVAR technique developed by Araki et al. (2015b) and the NN were used for retrievals using MWR data in zenith and off-zenith directions. The first guess for the 1DVAR was provided from numerical simulations by the JMA non-hydrostatic model (NHM; Saito et al. 2006) with horizontal grid spacing of 5km. The details of the model setting are given in Araki et al. (2015b). In this study, NN-, NHM-, and 1DVAR-derived profiles averaged over 30 min before each radiosonde observation at both 00 and 12 UTC at Tateno were compared with radiosonde-measured profiles of temperature and water vapor density from 25 April to 27 June 2012. To investigate the accuracy of the retrieved profiles under each weather condition, the data were classified into the following three types: No-Rain cases in which rain sensor did not detect rain for 1 h before and after the radiosonde observations (87 samples), Rain_RR<1 cases in which rain sensor detected rain and rain gauge at Tateno observed the 2-hour (1 h before and 1 h after the radiosonde observations)-averaged rainfall rates (RR) less than 1.0 mm h^{-1} (24 samples), and Rain_RR>1 cases in which the 2-hour-averaged RR was equal to or larger than 1.0 mm h^{-1} (10 samples).

Figure 1 shows the vertical profiles of mean difference (MD) and root-mean-square (RMS) error of NN-, 1DVAR-, and NHM-derived atmospheric temperature with respect to radiosonde-measured profiles. The inferiors of Z and OZ in NN and 1DVAR respectively indicate the retrievals using zenith and off-zenith observations in southern azimuth directions. Figure 2 is same as Fig. 1 but for water vapor density. The NHM- and 1DVAR-derived temperature profiles for No-Rain cases showed good agreement: the absolute MD was less than 1 K at all altitudes (Fig. 1a). The RMS errors for 1DVAR-derived temperatures were about 1 K at all altitudes, but those of NHM-derived temperatures reached 1.5 K below 0.5 km (Fig. 1b). The absolute MD for 1DVAR- and NHM-derived water vapor densities for No-Rain cases were less than 0.5 g m^{-3} at all altitudes, and the values of 1DVAR-derived water vapor densities were less than those derived from NHM (Fig. 2a). The RMS errors for 1DVAR-derived vapor density were also less than those derived from NHM at all altitudes; their maximum values for 1DVAR- and NHM-derived vapor densities reached 1.5 and 2 g m^{-3}, respectively, at around 1 km (Fig. 2b). These results show that, compared to other methods, the 1DVAR technique significantly improves the atmospheric temperature profile in the low troposphere and the water vapor profile at all altitudes.

For the cases of Rain_RR<1, NN_Z- and $1DVAR_Z$-derived profiles were affected by rain and the errors in the profiles increased (Figs. 1 and 2). The absolute MD and RMS error for NN_{OZ}-derived temperature and water vapor density were similar to those for the No-Rain case. These results indicate that off-zenith observations reduced the error due to raindrops on the radome for Rain_RR<1 cases. The absolute MD of $1DVAR_{OZ}$-derived temperatures was about 1 K below 1 km and less than 0.5 K above 1.5 km, and the absolute MD of NHM-derived temperatures was 0–0.7 K less than those of $1DVAR_{OZ}$-derived temperature below 1 km. The RMS error was 0.5–1.3 K above 0.5 km, but the error of $1DVAR_{OZ}$-derived temperatures was about 0.5 K smaller than that derived from NHM below 0.5 km. These results suggest that mean biases in 1DVAR-derived temperature profiles, obtained from off-zenith observations, are slightly larger than those of NHM-derived temperature profiles below 1 km under rainy conditions with RR less than 1.0 mm h^{-1}. However, the 1DVAR technique using off-zenith observations could improve the temperature profiles obtained from NHM simulation when NHM simulations show large errors, especially in the lower troposphere. Similar feature was found in water vapor density profiles derived from 1DVAR. For the cases of Rain_RR>1, NN_Z- and $1DVAR_Z$-derived profiles were highly affected by rain (Figs. 1 and 2). Although the accuracies of NHM-derived temperature and vapor density were similar to the cases of Rain_RR<1, the absolute MD and RMS error for $1DVAR_{OZ}$-derived profile of both temperature and vapor density were larger below 1–2 km. The RMS error for NN_{OZ}-derived profiles was larger than that of $1DVAR_{OZ}$-derived profile for temperature at all altitudes and for vapor density above 0.5 km, respectively. These results indicate that the 1DVAR technique outperforms the NN technique in retrievals of thermodynamic profiles under conditions of heavy rain, whereas the 1DVAR technique does not improve the accuracy of thermodynamic profiles when compared with NHM simulation results.

3. Conclusions and remarks

The 1DVAR technique that uses MWR data was applied for no-rain and rainy conditions and the effect of off-zenith observations on reducing the error during rain periods was statistically investigated. Comparisons with radiosonde observations show that the 1DVAR technique used in this study successfully improves the vertical profiles of temperature in the low troposphere and those of water vapor density at all altitudes, as compared to retrievals by neural networks and the results of numerical simulation under no-rain conditions. There is also indication that the error in the retrieved profiles could be reduced by the 1DVAR technique by using off-zenith observations at an elevation angle of 15° even under rain conditions with rainfall rates less than 1.0 mm h^{-1}, especially when the numerical model does not accurately reproduce the thermodynamic environment. This result suggests that the 1DVAR technique is helpful in nowcasting severe storms.

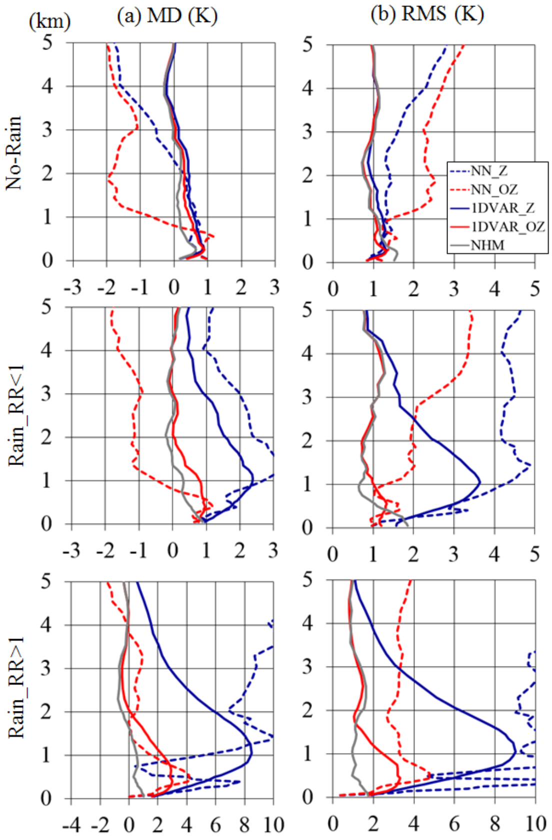

Figure 1. (a) Mean difference (MD) and (b) root-mean-square (RMS) error of NN-, 1DVAR-, and NHM-derived atmospheric temperature with respect to radiosonde soundings.

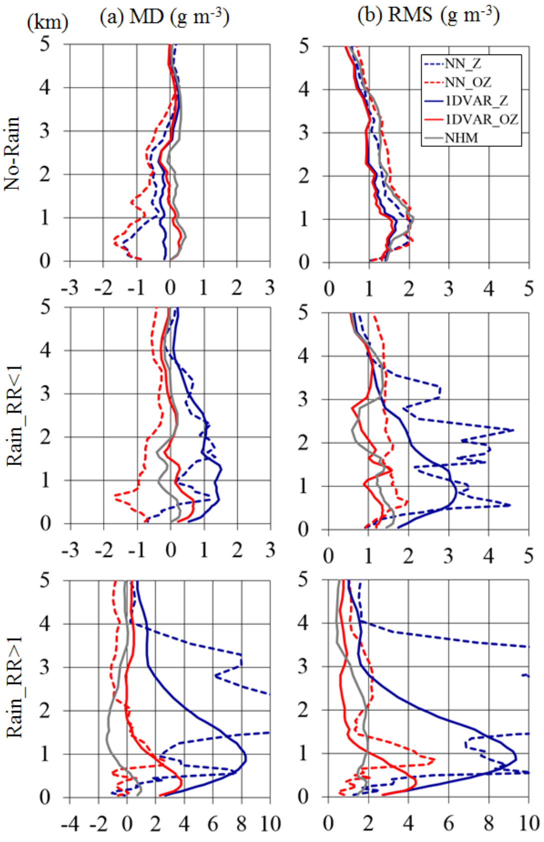

Figure 2. Same as Fig. 1, but for water vapor density.

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