Observation System Simulation Experiments of Water Vapor Profiles Observed by Raman Lidar Using LETKF System

Satoru Yoshida, Sho Yokota, Hiromu Seko, Tetsu Sakai, and Tomohiro Nagai
Meteorological Research Institute, Ibaraki, Japan

Abstract

We conducted observation system simulation experiments (OSSE) to investigate the effects of water vapor vertical profiles observed by Raman lidar (RL) on forecasts of heavy precipitation in Hiroshima, Japan, on August 19, 2014 using a local ensemble transform Kalman filter. We employed a simulation result similar to reality as nature-run (NR) and performed two OSSEs. In the first experiment (DaQv), conventional observation data and vertical profiles of water vapor mixing ratio in air ($q_v$) estimated from NR were assimilated. In the second experiment (CNTL), only conventional observation data were assimilated. In DaQv, we assumed that the RL was in the low-level inflow that supplied water vapor to the heavy precipitation in Hiroshima. Assimilating $q_v$ for several hours increased $q_v$ around the RL observation station, especially at low level. The regions modified by the assimilation of $q_v$ moved to Hiroshima by low-level inflow, resulting in 9-hour precipitation being approximately 28% greater than that of CNTL, and was thus closer to that of the NR. The OSSEs suggest that water vapor RL observations on the windward side of the heavy precipitation are a useful approach for improving precipitation forecasts.

(Citation: Yoshida, S., S. Yokota, H. Seko, T. Sakai, and T. Nagai, 2020: Observation system simulation experiments of water vapor profiles observed by Raman lidar using LETKF system. SOLA, 16, 43–50, doi:10.2151/sola.2020-008.)

1. Introduction

Atmospheric water vapor strongly influences thunderstorm initiation and development (e.g., Wulfmeyer et al. 2015). Thus, knowledge of atmospheric water vapor distribution is vital for accurate precipitation prediction. Over the decades, research has demonstrated positive effects on data assimilation from water vapor data obtained using Global Navigation Satellite System (GNSS; Saito et al. 2017; Seko et al. 2011; Shoji et al. 2009), microwave radiometers (Caumont et al. 2016; Kazumori 2019), and lidar systems (e.g., Kaminem et al. 2003) for forecasting humidity field. In this paper, we focus on water vapor lidar data assimilation because water vapor lidar is the only active remote sensing system that provides water vapor vertical profiles.

There are two types of water vapor lidars; one is Raman lidar (RL) and the other is Differential Absorption Lidar (DIAL). The RL emits laser pulses and receives Raman backscatter signals from water vapor and nitrogen. Water vapor mixing ratio in air ($q_v$) is estimated from ratio of the Raman backscatter signal and the laser pulse. The water vapor DIAL emits laser pulses at two wavelengths having different absorption cross-sections, and it receives the backscatter from aerosols and air molecules. It estimates water vapor number density from difference of water vapor absorption between the two wavelengths. An advantage of the RL compared to the DIAL is relatively easy to develop and operate, while the disadvantage is that observation depth of RL is lower during daytime and twilight compared to nighttime due to sunlight interference.

Kaminem et al. (2003), carrying out an observation campaign with a water vapor DIAL on a research aircraft, demonstrated that water vapor assimilation succeeded in reducing hurricane track and intensity forecast errors. Wulfmeyer et al. (2006) and Harnish et al. (2012) also assimilated vertical water vapor profiles obtained aircraft-based DIALs and showed improvements in forecasts of humidity field for a frontal system and a typhoon, respectively. Grezschik et al. (2008) assimilated water vapor vertical profiles observed using ground-based three water vapor RLs and showed improvement of humidity field forecasts. Bielli et al. (2012) observed water vapor vertical profiles using an airborne RL and ran multiple analysis and forecast cycles, demonstrating that the capabilities of precipitation forecasts increased.

Previous studies indicated that assimilation of water vapor vertical profiles improved humidity field forecasts, in a few cases, precipitation forecast. However, assimilation impact for meso-scale severe events has not been paid attention in spite that meso-scale severe events sometimes cause heavy damages and are very important for disaster mitigation. In this study, OSSEs were conducted for comprehensive understanding the assimilation impact of vertically distributed water vapor on meso-scale heavy precipitation forecast.

2. Design of OSSE

In this study, we examined a severe precipitation event in Hiroshima, Japan, on 19 August 2014. During this event, a stationary front approximately 300 km north of Hiroshima led to an intermittent low-level southerly warm and humid inflow over Hiroshima. Under these conditions, from 10 UTC to 21 UTC a back-building convective precipitation system consisting of several groups of thunderstorms passed over Hiroshima from southwest to northeast, which resulted in severe precipitation in Hiroshima that exceeded 200 mm over 3 hours (Otani et al. 2019).

We employed a forecast result reported in Otani et al. (2019) as the nature-run (NR), which is considered “truth” in this OSSE. Otani et al. (2019) conducted 20-member ensemble forecasts of the event using the Japan Meteorological Agency Non-Hydrostatic Model (JMA-NHM; Saito et al. 2006) with a 2-km horizontal grid, and selected an ensemble member that was most similar to reality as the best forecast. We employed this best forecast, which was the tenth member in their paper, as our NR (Otani et al. 2019).

Figures 1a and 1b show 9-hour accumulated precipitation (from 1200 UTC to 2100 UTC) of Radar/Raingauge-Analyzed Precipitation (RA) (Ishizaki and Matsuyama 2018) and NR, respectively. Precipitation area locations and shapes of the RA and NR data resemble each other. The RA and NR 9-hour accumulated precipitations, averaged in a polygon means areal-averaged precipitation amount within the polygon. The maximums of 9-hour accumulated precipitation in the red polygon of RA and NR, respectively, are 251.2 mm and 263.1 mm. Figure 1c shows one-hour RA and NR precipitation averaged in the red polygons, indicating that peak of precipitation in NR appeared 2 hours before that in RA. Figures 2a and 2c show $q_v$ and horizontal wind at 530 m at 1200 UTC in NR. In this paper we focus on values at the altitude of 530 m. This is because the $q_v$ flux at an altitude of 500 m is closely related to heavy precipitation (Kato 2018) and the level of 530 m is the closest to the 500 m in our simulation. These figures clearly show low-level humid inflow from Bungo Channel to Hiroshima, with

Corresponding author: Satoru Yoshida, Meteorological Research Institute, 1-1 Nagamine, Tsukuba 305-0052, Japan. E-mail: syoshida@mri-jma.go.jp.

©The Author(s) 2020. This is an open access article published by the Meteorological Society of Japan under a Creative Commons Attribution 4.0 International (CC BY 4.0) license (http://creativecommons.org/licenses/by/4.0).
Yoshida et al. OSSE of Water Vapor Raman Lidar

We first carried out JMA-NHM-LETKF cycles in an outer domain with horizontal grid intervals of 15 km (hereafter, 15km-LETKF) from 0000 UTC on August 17 using meso-scale model forecasts and the global forecast as initial and boundary conditions (Fig. 3). After that, JMA-NHM-LETKF cycles in an inner domain were carried out with horizontal grid intervals of 5 km (hereafter, 5km-LETKF) from 0000 UTC on August 19 using the 15-km LETKF analyses.

This result is consistent with a previous study (Hirota et al. 2016). They reported that humid inflow contributed to heavy precipitation in Hiroshima. NR reproduced precipitation location and amounts and low-level inflow well, although the precipitation timing was 2 hours before RA.

In this paper, we employed JMA-NHM local ensemble transform Kalman filter (JMA-NHM-LETKF) system (Kunii 2014) with 50 ensemble members as data assimilation. We first carried out JMA-NHM-LETKF cycles in an outer domain with horizontal grid intervals of 15 km (hereafter, 15km-LETKF) from 0000 UTC on August 17 using meso-scale model forecasts and the global forecast as initial and boundary conditions (Fig. 3). After that, JMA-NHM-LETKF cycles in an inner domain were carried out with horizontal grid intervals of 5 km (hereafter, 5km-LETKF) from 0000 UTC on August 19 using the 15-km LETKF analyses.
as initial and boundary conditions.

In the inner domain calculation, two OSSEs were conducted. The first experiment (DaQv) assumes water vapor RL observations at the windward side of low-level inflow (indicated by the black circles in Fig. 2). We assume that the RL observes \(q_v\) vertical profiles at 1000 UTC, 1100 UTC, and 1200 UTC. The observation depth during daytime and twilight is lower than during nighttime due to sun light interference. The water vapor RL presented in Sakai et al. (2019) observed \(q_v\) profiles up to approximately 1.5 km during daytime and up to 5–6 km at nighttime. The sunset time on 19 August 2014 at the RL station was about 0950 UTC and it was twilight at 1000 UTC. We assume that the RL in this OSSE provides \(q_v\) vertical profiles from 300 m to 900 m at 1000 UTC and from 300 m to 3.9 km at 1100 UTC and 1200 UTC, with an observation error of 1 g kg\(^{-1}\). The \(q_v\) vertical resolutions are set to be 150 m below 1 km and 300 m above 1 km. We set these RL observation parameters as actual RL presented in Sakai et al. (2019) could realize. The \(q_v\) vertical profile is then estimated from NR.

Because the cloud water mixing ratio below 4 km at the observation station in NR from 1000 UTC to 1200 UTC was 0 g kg\(^{-1}\), the RL observes \(q_v\) vertical profile without cloud droplet attenuation. These RL data are then assimilated in the 5km-LETKF. The other experiment (CNTL) assumes that no RL observation is assimilated. We term 5km-LETKF for DaQv and CNTL as 5km-LETKF-Daqv and 5km-LETKF-CNTL, respectively. In 15km- and 5km- LETKFs, the Kain-Fritsch scheme (Kain and Fritsch 1993) was adapted as the convective parameterization.

In 15km- and 5km- LETKFs, conventional observation data were assimilated. Temperature, pressure, horizontal winds, precipitable water vapor (PWV), relative humidity, and raindrop Doppler velocity obtained using conventional observation systems (e.g., surface observations, ships, buoys, radiosondes, aircraft, wind profilers, radars, GNSS, microwave scatterometers, and visible/infrared imagers) were assimilated up to 0900 UTC on 19 August. After 1000 UTC, conventional observation data were estimated using NR. The temporal and spatial distribution of the assimilation data are determined according to the real conventional data but their positions are arranged to the NR grids closest to the actual observation locations. Note that the observation data are available all over the domains before 0900 UTC on 19 August, while observation data are limited to the domain of NR after 1000 UTC.

Finally, we performed 50-member ensemble forecasts of this event with a 2-km horizontal grid interval (hereafter, 2km-Fcst)
with JMA-NHM using 5km-LETKF-DaQv or 5km-LETKF-CNTL analysis as initial and boundary condition. The forecast results using 5km-LETKF-DaQv and 5km-LETKF-CNTL as initial and boundary conditions are termed as 2km-Fcst-DaQv and 2km-Fcst-CNTL, respectively. The domains of the 2km-Fcst-DaQv and 2km-Fcst-CNTL are identical to that of NR. The details of the experimental set up is available in Fig. 3b.

Figure 2 shows the comparison of NR and 2km-Fcst-CNTL at 1200 UTC on 19 August at 530 m. In this paper, all variables associated with 5km-LETKFs and 2km-Fcsts, such as q, and precipitation, are evaluated by ensemble means. This figure clearly shows that the inflow into Hiroshima in 2km-Fcst-CNTL is clearly dryer and weaker horizontal wind compared to NR.

3. Results

To investigate the effects of RL data assimilation, Fig. 4 shows a comparison between 5km-LETKF-DaQv and 5km-LETKF-CNTL from 1000 UTC to 1200 UTC. All variables associated with 5km-LETKFs in Fig. 4 are obtained in analysis field. Figures 4a–4e show vertical profiles of q in 5km-LETKF-CNTL, 5km-LETKF-DaQv, and NR at the RL station. Figures 4b and 4c show that 5km-LETKF-CNTL has a clearly drier low-level q than NR at 1100 UTC and 1200 UTC. These figures of RL data assimilation increases q, with q in 5km-LETKF-DaQv approaching that of NR. These results indicate that RL assimilation improves the q, vertical profile at the station.

To explore the horizontal and vertical effects of RL data assimilation, Figs. 4d–4f show q, differences (5km-LETKF-DaQv minus 5km-LETKF-CNTL) at an altitude of 530 m and Figs. 4g–4i show the vertical cross-section of q, differences (5km-LETKF-DaQv minus 5km-LETKF-CNTL) along the pink lines shown in Figs. 4d–4f. This figure demonstrates that the assimilation of RL data increases q, around the observation site, with a distinct modification up to 4 km around the observation site at 1100 UTC and 1200 UTC and a strong modification below 1.5 km around the observation site at 1200 UTC. To investigate improvements in the humidity field from assimilating RL data, Figs. 4j–4l show the difference between the absolute difference between NR and 5km-LETKF-DaQv and the absolute difference between NR and 5km-LETKF-CNTL of PWV (NR = 5km-LETKF-DaQv - NR - 5km-LETKF-CNTL) in PWV). The negative value in Figs. 4j–4l indicates an improvement in PWV over 5km-LETKF-CNTL from assimilating RL data. This PWV improvement is seen around the RL station. These results indicate that a series of RL data assimilation increases humidity, especially below 1.5 km, and improves the humidity field around the station. Figures 4m–4o show horizontal wind speed differences (5km-LETKF-DaQv minus 5km-LETKF-CNTL) at 530 m. These figures indicate that q, vertical profile assimilation modified horizontal wind; horizontal wind in the east (west) side of the RL station in the inflow is intensified (weakened).

To show the effects of RL data assimilation on forecasts, Fig. 5 shows the difference (2km-Fcst-DaQv minus 2km-Fcst-CNTL) in q, (Figs. 5a–5f) and meridional wind component (Figs. 5g–5i) at 530 m every 40 minutes from 1200 UTC to 1520 UTC. Figures 5a–5f show that the positive area (q, increased by data assimilation of the RL) moves northerly, indicating that the increased water vapor from assimilation moved along wind vector. These results are consistent with previous research (e.g., Wulfmeyer et al. 2006). They reported that the effect of q, assimilation moved along horizontal wind and changed humidity field on the leeward side of the observation site. Figures 5g–5i show that a pair of positive and negative regions (meridional wind component increased and decreased by the data assimilation) moves along the horizontal wind up to 1320 UTC.

Figure 6 shows a precipitation comparison between 2km-Fcst-CNTL and 2km-Fcst-DaQv. Figures 6a and 6b show 9-hour accumulated precipitation (from 1200 UTC to 2100 UTC) of 2km-Fcst-CNTL and 2km-Fcst-DaQv, respectively. Heavy precipitations that are not seen in NR (Fig. 1b) are recognized in the Sea of Japan (left side of the panels) and Kochi prefecture (33.6°N and 133.6°E). These are forecast errors in 2km-Fcst-CNTL and were not corrected in 2km-Fcst-DaQv. The 9-hour accumulated precipitation averaged in the pink polygons in 2km-Fcst-CNTL and 2km-Fcst-DaQv are 8.1 mm and 10.4 mm, respectively, indicating that 2km-Fcst-DaQv had a 9-hour accumulated precipitation approximately 28% greater than 2km-Fcst-CNTL. Note that two domains (the pink polygons in Fig. 6 and red polygons in Fig. 1) are of the same size but are shifted to cover the entire strong precipitation region. Considering that the 9-hour accumulated precipitation averaged in the red polygon in NR is 47.6 mm, RL assimilation improves the 9-hour accumulated precipitation forecast. Figure 6c shows time variations in precipitation per 10 minutes in the polygons. The precipitation per 10 minutes of all three experiments show similar trends. Note that the precipitation in NR is much larger than 2km-Fcst-CNTL and 2km-Fcst-DaQv, and peaked 20 minutes after the peaks in 2km-Fcst-CNTL and 2km-Fcst-DaQv.

4. Discussion

Many observational results and simulation experiments indicated that strong low-level humid inflow was essential for formation and development of thunderstorms and heavy precipitation (e.g., Kawabata 2014; Otani et al. 2019). Kawabata et al. (2014) examined forecast results produced by the NHM four-dimensional variational data assimilation system in Japan’s Kanto Plain, and reported that q, flux (product of q, air density, and horizontal velocity) flowing into thunderstorms plays an important role in heavy precipitation. The results indicate that latent heat released by low-level humid inflow accounts for thunderstorm formation and development and results in heavy precipitation.

To discuss the relationship between low-level inflow and precipitation, Figs. 7a, 7b, and 7c show the q, flux at 530 m with the rainwater mixing ratio (q) at 3858 m in 2km-Fcst-CNTL, 2km-Fcst-DaQv, and NR at 1400 UTC, respectively. These figures all demonstrate that a strong q, flux (> 200 g m\(^{-2}\) s\(^{-1}\)) flows from the south into Hiroshima, where heavy precipitation occurs in each experiment. High q, regions shown by pink contour lines in Figs. 7a–7c appear on the leeward side of the strong q, flux, which indicates that low-level water vapor from the south is lifted by orographic effects around 34.5°N and then develops thunderstorms. Figure 7d shows the difference (2km-Fcst-DaQv minus 2km-Fcst-CNTL) in the northern component of the q, flux difference at 530 m, and clearly shows that the q, flux’s northern component is intensified by RL data assimilation.

To explore reasons why q, flux differs between 2km-Fcst-CNTL and 2km-Fcst-DaQv, Figs. 7e and 7f, show vertical profiles of q, and horizontal wind speed, respectively. The vertical profiles shown in Figs. 7e and 7f are above red circles in Figs. 7a and 7b for 2km-Fcst-CNTL and 2km-Fcst-DaQv, and above a white circle in Fig. 7c for NR. The red and white circles are located at the maximum q, flux at an altitude of 530 m in 2km-Fcst-DaQv and NR, respectively. Figure 7e shows that q, vertical profile in 2km-Fcst-DaQv is larger than that in 2km-Fcst-CNTL at most of altitudes. The q, in 2km-Fcst-DaQv is 0.85% larger at altitude of 530 m compared to that in 2km-Fcst-CNTL, while horizontal wind speed in 2km-Fcst-DaQv is 0.26% larger than that in 2km-Fcst-CNTL in Fig. 7f. It seems that moisture correction made larger contribution than wind correction to the q, flux difference between 2km-Fcst-DaQv and 2km-Fcst-DaQv in this event.

Figures 7e and 7f indicate that q, and horizontal wind speed at low level in NR are about 5% and 40%, respectively, larger than those of 2km-Fcst-DaQv. The large difference in horizontal wind speed between 2km-Fcst-DaQv and 2km-Fcst-NR mainly contributed to the large difference in q, flux and precipitation between them. Therefore, an additional assimilation of wind profile data might be effective and complementary to improve precipitation forecast.
Fig. 4. Comparison of analysis of 5km-LETKF-DaQv and 5km-LETKF-CNTL experiments from 1000 UTC to 1200 UTC on 19 August. All parameters associated with 5km-LETKF in Fig. 4 are obtained in analysis field. (a)−(c) show $q_v$ vertical profiles above the RL station for the 5km-LETKF-CNTL, 5km-LETKF-DaQv, and NR. (d)−(f) show differences (5km-LETKF-DaQv minus 5km-LETKF-CNTL) in $q_v$ at 530 m. (g)−(i) show the vertical cross-section of differences (5km-LETKF-DaQv minus 5km-LETKF-CNTL) in $q_v$ along the pink lines in (d)−(f). (j)−(l) show the difference between the absolute difference between NR and 5km-LETKF-DaQv and the absolute difference between NR and 5km-LETKF-CNTL in PWV. (m)−(o) show the differences (5km-LETKF-DaQv minus 5km-LETKF-CNTL) in horizontal wind speed (color contour) and horizontal wind vector analysis (arrows) at 530 m. Black circles in (d)−(f) and pink circles in (m)−(o) represent the observation site location. Northerly arrows in (m)−(o) indicate that meridional wind component of 5km-LETKF-DaQv is larger than that of 5km-LETKF-CNTL at the point.
5. Conclusion

We conducted OSSEs to evaluate the effects of assimilating vertical water vapor profile data obtained by the RL on the ground for a severe precipitation event in Hiroshima. Assimilation of the RL data increases water vapor, especially at low level, and improves the humidity field around the observation site. In forecast, the increased water vapor from assimilation is transported along wind vector, influencing \( q_v \) and \( q_v \) flux on the leeward side. Data assimilation intensifies the low-level \( q_v \) flux into thunderstorms, facilitating their formation and/or development. As a result, assimilating RL data contributes to increased precipitation in the forecast, indicating a precipitation forecast improvement.

For this event, assimilating \( q_v \) vertical profiles obtained with the RL provides useful but mild improvement to the moisture, wind analysis and thus precipitation prediction. For further improvement, additional data assimilation of horizontal wind obtained with a Doppler lidar might improve precipitation forecast.

As we stated in Introduction, there are several types of water vapor lidar (airborne DIAL, and so on). Different types of observation at different observation sites produce different impacts on precipitation forecast. In future, we will perform other OSSEs to discuss relationship between various lidar observations and precipitation forecasts.
Fig. 6. Comparison of precipitation in 2km-Fcst-CNTL and 2km-Fcst-DaQv experiments. (a) and (b) show 9-hour accumulated precipitation (1200 UT−2100 UT) for 2km-Fcst-CNTL and 2km-Fcst-DaQv, respectively. (c) shows time variation of precipitation per 10 minutes averaged in the pink polygons for 2km-Fcst-CNTL and 2km-Fcst-DaQv, and in the red polygon for NR. Note that 2km-Fcst-CNTL and 2km-Fcst-DaQv correspond to the left axis, whereas NR corresponds to the right axis.

Fig. 7. Comparison of qv flux at 530 m at 1400 UTC on 19 August. (a)−(c) show qv flux at 530 m with qr at 3858 m in 2km-Fcst-CNTL, 2km-Fcst-DaQv, and NR, respectively. Arrows indicate vectors of qv flux. The color contours represent qv flux amplitude exceeding 200 g m⁻² s⁻¹. The pink contour lines indicate qr at 3858 m exceeding 0.1 g kg⁻¹. (d) shows the difference between 2km-Fcst-DaQv and 2km-Fcst-CNTL in the northern component of qv flux at 530 m. (e) shows the vertical profiles of qv at 530 m. (f) shows the vertical profiles of horizontal wind speed at the red circles for 2km-Fcst-CNTL and 2km-Fcst-DaQv, at the white circle for NR.
Acknowledgements

This work was supported by JSPS KAKENHI grants 19H01983 and 17H00852.

Edited by: C.-C. Wang

References

Bielli, S., M. Grzeschik, E. Richard, C. Flamant, C. Champollion, C. Kiemle, M. Dörninger, and P. Brousseau, 2012: Assimilation of water-vapour airborne lidar observations: impact study on the COPS precipitation forecasts. Qua. J. Roy. Meteor. Soc., 138, 1652–1667.

Caumont, O. D., and co-authors, 2016: Assimilation of humidity and temperature observations retrieved from ground-based microwave radiometers into a convective-scale model. Qua. J. Roy. Meteor. Soc., 142, 2692–2704.

Grzeschik, M., H.-S. Bauer, V. Wulfmeyer, D. Engelbart, U. Wandinger, I. Mattis, D. Althausen, R. Engelmann, M. Tesche, and A. Riede, 2008: Four-dimensional variational data analysis of water vapor Raman lidar data and their impact on mesoscale forecasts. J. Atmos. Oceanic Technol., 25, 1437–1453, doi:10.1175/2007JTECHA974.1.

Harnisch, F., M. Weissmann, C. Cardinali, and M. Wirth, 2011: Experimental assimilation of DIAL water vapour observations in the ECMWF global model. Qua. J. Roy. Meteor. Soc., 137, 1532–1546, doi:10.1002/qj.851.

Hirota, N., Y. N. Takayabu, M. Kato, and S. Arakane, 2016: Roles of an atmospheric river and a cut-off low in the extreme precipitation event in Hiroshima on August 19, 2014. Mon. Wea. Rev., 144, 1145–1160.

Ishizaki, H., and H. Matsuyama. 2018: Distribution of the annual precipitation ratio of radar/raingauge-analyzed precipitation to AMeDAS across Japan. SOLA, 14, 192–196.

Kamineni, R., T. N. Krishnamurti, R. A. Ferrare, S. Ismail, and E. V. Browell, 2003: Impact of high resolution water vapor cross-sectional data on hurricane forecasting. Geophys. Res. Lett., 30, 1234.

Kawabata, T., H. Iwai, H. Seko, Y. Shoji, K. Saito, S. Ishii, and K. Mizutani, 2017: Cloud-resolving 4D-Var assimilation of Doppler wind lidar data on a meso-gamma-scale convective system. Mon. Wea. Rev., 142, 4484–4498.

Kawabata, T., H. Iwai, H. Seko, Y. Shoji, K. Saito, S. Ishii, and K. Mizutani, 2018: Assimilation of Himawari-8 clear sky radiance data in JMA’s global and mesoscale NWP systems. J. Meteor. Soc. Japan, 968, 173–192.

Kain, J., and J. Fritsch, 1993: Convective parameterization for mesoscale models: The Kain–Fritsch scheme. The Representation of Cumulus Convection in Numerical Models, Meteor Monogr., No. 46, Amer. Meteor. Soc., 165–170.

Kunii, M., 2014: Mesoscale data assimilation for a local severe rainfall event with the NHM–LETKF system. Wea. Forecasting, 29, 1093–1105.

Otani, S., N. Nakada, A. Isimoto, C. Akieda, N. Kazahaya, Y. Nishimori, T. Nakamura, Y. Yorioka, T. Tatsukami, T. Íwata, H. Seko, and S. Yokota, 2019: Analysis on the relation between the heavy rainfall and its environment, especially low-level inflow, obtained by the ensemble forecast experiments. Tenki, 66, 141–160.

Saito, K., T. Fujita, Y. Yamada, J. Ishida, Y. Kumagai, K. Aranami, S. Ohmori, R. Nagasawa, S. Kumagai, C. Muroi, T. Kato, and H. Eito, 2006: The operational JMA nonhydrostatic mesoscale model. Mon. Wea. Rev., 134, 1266–1298.

Saito, K., Y. Shoji, S. Origuchi, and D. Lee, 2017: GPS PWV Assimilation with the JMA nonhydrostatic 4DVAR and cloud resolving ensemble forecast for the 2008 August Tokyo metropolitan area local heavy rainfalls. Data Assimilation for Atmospheric, Oceanic and Hydrologic Applications (Vol. III), Springer, 383–404.

Sakai, T., T. Nagai, T. Izumi, S. Yoshida, and Y. Shoji, 2019: Automated compact mobile Raman lidar for water vapor measurement: instrument description and validation by comparison with radiosonde, GNSS and high-resolution objective analysis. Atomos. Meas. Tech., 12, 131–326.

Seko, H., T. Miyoshi, Y. Shoji, and K. Saito, 2011: Data assimilation experiments of precipitable water vapor using the LETKF system: intense rainfall event over Japan 28 July 2008. Tellus A, 63, 402–412.

Shoji, Y., M. Kunii, and K. Saito, 2009: Assimilation of nationwide and global GPS PWV data on heavy rainfall in the 28 July 2008 Hokuriku and Kinki, Japan. SOLA, 5, 45–48.

Wulfmeyer, V., H. Bauer, M. Grzeschik, A. Behrendt, F. Vandenberghe, E. V. Browell, S. Ismail, and R. A. Ferrare, 2006: Four-dimensional variational assimilation of water vapor differential absorption lidar data: The first case study within IHOP. 2002. Mon. Wea. Rev., 134, 209–230.

Wulfmeyer, V., and co-authors, 2015: A review of the remote sensing of lower tropospheric thermodynamic profiles and its indispensable role for the understanding and the simulation of water and energy cycles. Rev. Geophys., 53, 819–895.

Manuscript received 15 August 2019, accepted 3 February 2020
SOLA: https://www.jstage.jst.go.jp/browse/sola/