Ensemble Data Assimilation and Forecast Experiments for the September 2015 Heavy Rainfall Event in Kanto and Tohoku Regions with Atmospheric Motion Vectors from Himawari-8

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Abstract

Himawari-8, a next-generation geostationary meteorological satellite that has been in operation since July 2015, incorporates significant improvements in resolution, scan frequency, and number of bands, bringing new capabilities to weather forecasting. By taking advantage of the availability of high-frequency data with high spatial resolution, an ensemble Kalman filter implemented with a mesoscale regional model assimilated rapid-scan atmospheric motion vectors (RS-AMVs) from Himawari-8. Data assimilation and ensemble forecast experiments were conducted for a heavy rainfall event that occurred in September 2015 in the Kanto and Tohoku regions of Japan. The results showed that the inclusion of RS-AMVs improved precipitation scores, especially for weak and moderate rainfall. In addition, the subsequent model forecast simulated successfully the band of heavy rainfall. Ensemble-based probabilistic forecasts showed that when RS-AMVs from Himawari-8, derived from image triplets at 5-min intervals, were assimilated, the results captured the occurrence of torrential rainfall with a relatively high probability. The ensemble-based correlation analysis indicated that the strong rainfall was related to advection of moisture at low to mid levels and moisture flux convergence at lower levels. Simulations with a higher resolution model initialized by nested data assimilation showed that the assimilation of frequent RS-AMVs improved the forecast results.

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1. Introduction

The Himawari-8 geostationary meteorological satellite, a successor to the Multi-functional Transport Satellite (MTSAT) series of the Japan Meteorological Agency (JMA), has been in operation since July 2015. In Himawari-8, significant improvements have been achieved in resolution, scan frequency, and number of bands (Bessho et al. 2016); thus, Himawari-8 is expected to contribute to the improvement of JMA's meteorological services, including weather prediction. For operational weather forecasting, JMA uses satellite observations, such as radiance, Global Navigation Satellite System radio occultation, and atmospheric motion vectors (AMVs), to generate accurate initial conditions through data assimilation for numerical weather prediction (NWP) models. Because observation data are generally more scarce over the ocean than over land areas, effective utilization of satellite observations in data assimilation for NWP has been an important challenge.

AMVs are wind observations derived by tracking cloud and water vapor imagery acquired by geostationary satellites (Velden et al. 2005). In contrast to other satellite-based products, AMV data contain three-dimensional wind information and require no additional observation operator to be assimilated, enhancing their utility in data assimilation for NWP. The assimilation of AMVs, especially rapid-scan AMVs (RS-AMVs), which are derived from images acquired at more frequent intervals, has been shown to be advantageous for modeling tropical cyclones (e.g., Langland et al. 2009; Berger et al. 2011; Wu et al. 2014). Moreover, Otsuka et al. (2015) applied the assimilation of RS-AMVs from MTSAT-1R to a mesoscale rainfall event and showed that the frequent assimilation of RS-AMVs led to improved precipitation forecasts compared with forecasts based on the assimilation of operational AMVs with a coarser temporal resolution.

The rapid-scan imaging mode of MTSAT-1R was activated only during the daytime in summer, but Himawari-8 performs a rapid regional scan every 2.5 min and a full disk scan every 10 min. JMA operational global and regional analyses currently assimilate hourly AMVs derived from the full disk scan data. In addition to the operational configuration, the use of RS-AMVs for future application in high-resolution NWP has been tested. RS-AMVs from Himawari-8, derived from image triplets at 5-min intervals, are available at 15-min intervals. These RS-AMVs are generated by a new algorithm designed for effective utilization of high spatial and temporal resolution data (Shimoji 2014). Although various studies have explored the advantages of assimilating RS-AMVs for NWP of tropical cyclones, the advantages of applying RS-AMV assimilation to mesoscale phenomena have been less investigated. The main objective of this study, therefore, was to investigate the impact of ensemble Kalman filter-based assimilation of RS-AMV data derived from Himawari-8 on mesoscale forecasts. Data assimilation experiments using RS-AMVs were conducted for the case of a severe rainfall event that occurred in September 2015 in Japan. This paper is organized as follows: Section 2 describes the experimental settings; Section 3 presents the results; and Section 4 presents a summary and our conclusions.

2. Experimental settings

2.1 Heavy rainfall in September 2015

In September 2015, torrential rainfall was observed in the Kanto and Tohoku regions of Japan. Linear convective systems were generated over Kanto and Tohoku from 9 to 11 September by a moist southerly airflow from an extratropical cyclone over the Japan Sea and southeasterly winds from Typhoon Kilo, which was located east of Japan (Fig. 1a). These systems caused heavy rainfall and widespread flooding at Joso city in Ibaraki Prefecture. Record-setting precipitation exceeded 400 mm in a 24-h period at Nikko city and Kanuma city in Tochigi Prefecture. Flooding and landslides associated with the rainfall killed eight people and destroyed or damaged over 7000 houses.

2.2 NHM-LETKF system

JMA's nonhydrostatic model (NHM; Saito et al. 2006, 2007) was employed with a local ensemble transform Kalman filter (LETKF; Hunt et al. 2007) used for data assimilation (NHM-LETKF; Kunii 2014). The LETKF algorithm, which has high
efficiency in parallel implementations, has been applied in numerous atmospheric data assimilation studies (e.g., Kang et al. 2011; Greybush et al. 2012; Miyoshi and Kunii 2012; Yang et al. 2012, 2013; Kunii 2014; Seko et al. 2015).

Here a 100-member NHM-LETKF was carried out with a 10 km horizontal resolution and 50 vertical levels covering the area around Japan (D1 in Fig. 1a). The data assimilation cycle was initialized at 0000 UTC 25 August 2015 using initial perturbations from JMA global ensemble forecasts based on singular vectors. For spin-up of the ensemble-based error covariance as well as for evaluating the general impact of RS-AMVs, relatively longer data assimilation cycles were carried out before analyzing the heavy rainfall in Kanto and Tohoku. The system assimilated observations from radiosondes, surface stations, pilot balloons, wind profilers, aircraft, ships, and buoys with a horizontal observation localization scale of 200 km and a vertical localization scale of 0.2 \text{ln} p$, where $p$ is pressure. The data assimilation cycle interval was 3 h, and observations collected into 1-h time slots were assimilated.

The NHM configuration included the Kain-Fritsch convective parameterization scheme (Kain and Fritsch 1993) combined with a three-ice bulk cloud microphysics scheme (Lin et al. 1983). For the turbulence scheme, the Mellor and Yamada level 2.5 closure model was adopted. Throughout the data assimilation cycles, lateral boundary perturbations derived from JMA global ensemble simulations were added to account for lateral boundary uncertainties. This treatment of lateral boundaries helps to prevent underestimation of the ensemble spread near boundaries (Kunii 2014).

After the 10-km LETKF assimilation described above, one-way nested data assimilation cycles with a horizontal resolution of 2 km were started from 1200 UTC 8 September, focusing on the heavy rainfall region over Kanto (D2 in Fig. 1a). In these inner 2-km LETKF cycles, the initial and boundary conditions were provided by the outer 10-km LETKF, and basically the same observational data were assimilated, but with 15-min time slots in hourly data assimilation cycles. A tighter horizontal localization parameter of 50 km was chosen for effective elimination of spurious noise in the higher resolution system. The NHM configuration was mostly similar to that in the 10-km experiment except that larger numerical diffusion and damping parameters were adopted.

2.3 Assimilation of the AMV data

As of September 2015, the JMA global and mesoscale data assimilation systems assimilated AMVs from MTSAT-2 after a thinning procedure in which observations were selected within 200 km $\times$ 200 km $\times$ 100 hPa grid boxes. As a baseline experiment, we assimilated the JMA operational AMVs with the 10-km LETKF (CTRL). Then a TEST experiment that assimilated RS-AMVs derived from Himawari-8 initialized with the analyses of the CTRL experiment was carried out from 0000 UTC 1 September 2015. For effective utilization of the higher resolution RS-AMVs, a super-observation procedure was performed in which the data were averaged over 60-km grids with uniform weighting. The observation errors assigned to the RS-AMVs from Himawari-8 were the same as those used in the JMA operational configuration.

In the outer TEST experiment described above, only hourly RS-AMVs were used because the 10-km LETKF-assimilated observations were collected into 1-h time slots. To examine the impact of the utilization of more frequent RS-AMV data, twin inner LETKF cycle experiments with a horizontal resolution of 2 km were performed in which observations in 15-min time slots were assimilated with an hourly data assimilation cycle. In the “15MIN” experiment, RS-AMVs were assimilated every 15 min, taking advantage of the rapid-scan operation of Himawari-8, whereas in the “60MIN” experiment RS-AMVs were assimilated hourly. Both the 60MIN and 15MIN experiments were nested within the TEST experiment, which had a horizontal resolution of 10 km. All experiments are summarized in Table 1.

3. Results

3.1 General verification measures

To evaluate the influence of the RS-AMVs from Himawari-8 on the forecast results, general verification measures were calculated for the forecast outputs initialized with each LETKF analysis. We evaluated threat and bias scores for the 3-h accumulated precipitation averaged over eight different initial times from 0000 UTC 8 September to 1800 UTC 9 September 2015 (Fig. 2). For weak and moderate rains of less than 20 mm per 3 h, the threat scores of TEST were substantially better than those of CTRL.

| Experiment | Horizontal resolution | Assimilated AMVs          | Observation density for AMVs | Assimilation interval of AMVs | Horizontal localization |
|------------|-----------------------|---------------------------|------------------------------|-----------------------------|------------------------|
| CTRL       | 10 km                 | JMA operational AMVs      | 200 km                       | 60 minutes                  | 200 km                 |
| TEST       | 10 km                 | RS-AMVs from Himawari-8   | 60 km                        | 60 minutes                  | 200 km                 |
| 60MIN      | 2 km                  | RS-AMVs from Himawari-8   | 20 km                        | 60 minutes                  | 50 km                  |
| 15MIN      | 2 km                  | RS-AMVs from Himawari-8   | 20 km                        | 15 minutes                  | 50 km                  |
With a longer lead time of 36 h, the threat scores of the TEST experiment were superior to the CTRL scores even for intense rainfalls of more than 20 mm per 3 h. Although assimilation of RS-AMV data caused a positive bias in the rainfall amount at the 12 h forecast, the TEST scores were slightly improved compared with the CTRL scores for forecast times longer than 24 h.

Focusing on the forecasts of the strong rainfall over Kanto region, we compared the distributions of the 3-h accumulated rainfall, horizontal moisture flux divergence at 850 hPa, and equivalent potential temperature at 950 hPa at 1500 UTC 9 September 2015 in the CTRL and TEST experiments.
was associated with horizontal convergence (Fig. 3e) as well as with southerly and southeasterly inflows of moist air (Fig. 3f) at lower levels, which were not reproduced appropriately in the TEST experiment (Figs. 3b and 3c). However, the quantitative correspondence between the model and the RAP data was still poor, even in the TEST experiment, an indication that accurate deterministic forecasting of severe weather events remains a challenging problem.

In this study, the RS-AMVs were assimilated after the super-observation procedure to eliminate observation error correlation. The use of averaged observations with a horizontal spacing of 60 km is expected to help improve environmental fields in the model, rather than small-scale features such as convective cells, and thus should result in better threat scores for weak and moderate rainfalls. The assimilation of dense observations with an explicit consideration of spatial and temporal observation error correlations, which might improve forecasting of smaller scale events directly, is an attractive area for future research in data assimilation.

### 3.2 Ensemble forecast results and correlation analysis

To capture probabilistic information on precipitation, extended ensemble forecasts were made by using LETKF analyses. The procedure used to consider the boundary uncertainties was the same as that used in the LETKF data assimilation cycles. We then examined probability of precipitation (POP) distributions at 1500 UTC 9 September 2015 for different initial times (Fig. 4). Here, POP is defined as the percentage of ensemble members that predicted precipitation exceeding a certain threshold. When the threshold was set at 20 mm per 3 h, the features of the POP distribution approached those of the observed RAP distribution (Fig. 1b) as the lead time decreased from 33 to 21 h (Figs. 4a, 4b, and 4c). Although the orientation of the rainband was slightly different from the observation, with a lead time of 21 h, a relatively large POP was estimated over Tochigi Prefecture where the torrential rainfall actually occurred. With a larger threshold of 50 mm per 3 h (Figs. 4d, 4e, and 4f), the POP distribution became narrower and less tailed, but the 21 h forecast still successfully captured the intense rainfall observed over Tochigi Prefecture.

The ensemble outputs were also used for the correlation analysis. Using the ensemble prediction initialized at 1800 UTC 8 September 2015, we investigated the correlation between the 3-h accumulated rainfall amount over the region where intense rainfall was observed (35.0°N–37.5°N, 139.0°E–140°E) at 1500 UTC 9 September 2015 and the moisture flux divergence at 950 hPa as well as the relative humidity at 700 hPa (Fig. 5). A negative correlation corresponding to moisture flux convergence was observed directly above and to the south of the rainband in both the 15-h and 21-h forecasts (Figs. 5b and 5c), but it was not clearly detected 12 h prior to the occurrence of strong precipitation (Fig. 5a). However, a positive correlation with low-to-mid-level relative humidity was observed to the south of the rainband 12 h prior to the occurrence of strong precipitation (Fig. 5d); this correlation was likely linked to the strong rainfall in the 15-h and 21-h forecasts (Figs. 5e and 5f). These results imply that the northward advection of moisture at low to mid levels, in addition to the low-level moisture flux convergence, contributed to the intense rainfall over Tochigi Prefecture.

### 3.3 Impacts of frequent RS-AMVs on higher resolution simulations

To assess the impact of assimilating frequent RS-AMVs with a one-way nested LETKF, the extended forecast outputs of the 2-km NHM were evaluated by comparing them with the corresponding RAP observations. We compared the 3-h accumulated precipitation in the 2-km NHM initialized with the nested LETKF analyses between the 60MIN and 15MIN experiments (Fig. 6). When the initial conditions were derived from the hourly assimilation of RS-AMVs (Fig. 6a), the forecast was degraded compared with the coarser resolution results (Figs. 3a and 3d). This result was probably due to the use of a tighter localization scale in the 2-km LETKF experiment, which would affect the synoptic environment of the event, namely, the southerly and southeasterly moisture inflows at lower levels, leading to the degradation of the rainfall forecast. By contrast, the assimilation of the RS-AMVs every 15 min improved the precipitation forecast, such that it corresponded better quantitatively to the RAP data.

Not only spatial correlations but also temporal correlations
associated with the assimilation of frequent observations should be considered. Because the parameters for thinning the RS-AMVs were determined empirically in this study, both spatial and temporal observation correlations may degrade the results. However, the results of the 60MIN and 15MIN experiments suggest that frequent data assimilation is essential in higher resolution simulations, and that the RS-AMVs derived from Himawari-8 should be useful for analyzing local severe weather events in future data assimilation studies.

4. Summary and conclusions

The objective of this study was to investigate the impact of RS-AMVs derived from Himawari-8 on mesoscale NWPs. To achieve this goal, we conducted data assimilation experiments and subsequent model forecasts with the NHM-LETKF system. The verification scores showed that the assimilation of RS-AMVs had positive impacts on rainfall forecasts. These impacts were

Fig. 5. Evaluated correlations between the 3-h accumulated precipitation over the region where intense rainfall was observed (35.0°N–37.5°N, 139.0°E–140°E, within the rectangle) at 1500 UTC 9 September 2015 and (a–c) the moisture flux divergence at 950 hPa or (d–f) the relative humidity at 700 hPa, at (a, d) 0300 UTC 9 September 2015 (b, e) 0900 UTC 9 September, and (c, f) 1500 UTC 9 September 2015.

Fig. 6. Simulated mean sea level pressure (contours, every 2 hPa) and 3-h accumulated rainfall (mm) by the 2-km NHM initialized with the LETKF analysis in the (a) 60MIN and (b) 15MIN experiments.
most pronounced in the case of weak or moderate rainfall because observations averaged over a horizontal spacing of 60 km mainly improved the environmental fields of the model rather than small-scale features related to strong rainfall. Probabilistic forecasts based on the ensemble forecasting results successfully captured the intense rainfall with relatively long lead times. The results of a correlation analysis between precipitation and model variables based on the ensemble results implied that the occurrence of severe rainfall is related to the advection of the moisture at low to mid levels and moisture flux convergence at lower levels. The higher resolution simulation with frequent RS-AMV assimilation improved the precipitation forecast, whereas that with assimilation of temporally scarce observations degraded the forecast.

One limitation of this study is that observation error correlations were not considered. For more effective utilization of RS-AMVs from Himawari-8, the assimilation of dense observations with explicit treatment of error correlations would include more information and likely result in more accurate analyses, as indicated by previous studies (Li et al. 2009; Miyoshi et al. 2013). The application of observation error correlation estimation methods is an important subject for future research.

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