30-second-Update 100-m-Mesh Data Assimilation Experiments: A Sudden Local Rain Case in Kobe on 11 September 2014

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Abstract

This study aims to investigate the impacts of 30-second-update and 100-m-resolution data assimilation (DA) on a prediction of sudden local torrential rains caused by an isolated convective system in Kobe city on 11 September 2014. We perform a Local Ensemble Transform Kalman filter (LETKF) experiment with the Japan Meteorological Agency non-hydrostatic model (JMA-NHM) at 1-km and 100-m resolution using every 30-second radar reflectivity observed by the phased array weather radar (PAWR) at Osaka University. The 1-km-mesh experiment shows that 30-second-update PAWR DA has positive impacts on the analyses and forecasts. Moreover, the 100-m-mesh experiment shows significant advantages in representing the rainfall intensity and fine structure of the convective system. The promising results suggest that 30-second-update, 100-m-mesh DA have a great potential for predicting sudden local rain events.

(Citation: Maejima, Y., M. Kunii, and T. Miyoshi, 2017: 30-second-update 100-m-mesh data assimilation experiments: A sudden local rain case in Kobe on 11 September 2014. SOLA, 13, 174–180, doi:10.2151/sola.2017-032.)

1. Introduction

In modern numerical weather prediction (NWP), improvement for predicting hazardous phenomena is one of the central issues. Among others, much attention has been paid to skillful NWP for severe weather (e.g., Kain et al. 2006, Hohenegger and Schär 2007a, b; Kawabata et al. 2007; Roberts and Lean 2008). Recently, the ensemble Kalman filter (EnKF, Evensen 1994, 2003) has become a major method in data assimilation (DA), and has contributed to investigate convection-permitting regional NWP (e.g., Zhang et al. 2007; Stensrud et al. 2009, 2013; Clark et al. 2010; Schwartz et al. 2010; Baldauf et al. 2011; Melhauser and Zhang 2012; Yussolf et al. 2013, Kunii 2014a, Weng and Zhang 2016).

Recently, Miyoshi et al. (2016a, 2016b) reported an innovation of the “Big Data Assimilation” (BDA) technology, implementing a 30-second-update, 100-m-mesh local ensemble transform Kalman filter (LETKF; Hunt et al. 2007) to assimilate data from a Phased Array Weather Radar (PAWR) at Osaka University (Ushio et al. 2014) into regional NWP models known as the Japan Meteorological Agency non-hydrostatic model (JMA-NHM, Saito et al. 2006, 2007) and the Scalable Computing for Advanced Laboratory and Environment-Regional Model (SCALE-RM, Nishizawa et al. 2015). The PAWR captures the rapid development of convective activities every 30 seconds at approximately 100-m resolution. The 100-m-mesh NWP models can resolve the internal structures of convective cells. The BDA system combines these two to enable NWP resolving each cumulonimbus explicitly.

This study provides details of a case study shown in the review paper by Miyoshi et al. (2016b) and aims to investigate the benefits of the BDA system for predicting an isolated convective system. We apply the BDA system described by Miyoshi et al. (2016a, 2016b) for a sudden local severe rainstorm that occurred in the morning of 11 September 2014 local time in Kobe. In this event, an isolated convective system suddenly initiated and rapidly developed near the center of Kobe city, and reached rainfall intensity over 50 mm h$^{-1}$ within 10 minutes. The current operational forecasting systems are not designed to capture this type of event, while the PAWR at Osaka University observed the sudden initiation and rapid development well. This study performs 30-second-update NHM-LETKF (Miyoshi and Aranami 2006) experiments at 1-km and 100-m resolution. Some of the first results were already shown by Miyoshi et al. (2016b), and this study further investigates the details. We discuss the impact of the rapid update and high-resolution DA targeted for the isolated convective system. Section 2 describes the experimental settings, and Section 3 presents the results and discussion. Finally, Section 4 provides the concluding remarks.

2. Experimental settings

To evaluate the impacts of the model resolution and observational density, a series of DA experiments was performed as illustrated in Fig. 1. First, we performed 6-hourly-update, 15-km-mesh NHM-LETKF initialized at 0900 JST (Japan Standard Time) 1 September 2014 with 100 ensemble members (A in Fig. 1a). The observations from the JMA operational mesoscale analysis (JMA-MANAL) were assimilated, including radiosondes, surface stations, wind profilers, aircraft, ships, buoys, and satellite-based winds. To initialize, the ensemble-mean initial condition was taken from the JMA Global Analysis (JMA-GANAL), and the initial ensemble perturbations were taken from the 24-h (12-h) JMA global ensemble forecasts initialized at 0900 (2100) JST 31 August 2014, all valid at 0900 JST 1 September 2014. The ensemble-mean boundary conditions came from the JMA Global Spectrum Model (GSM) forecast initialized at 0900 JST 1 September 2014, and the boundary ensemble perturbations came from the ensemble perturbations of the JMA global ensemble forecasts. The computational domain consists of 273 by 221 grid points in the horizontal (A in Fig. 1c).

Next, downscaled 100-member ensemble simulations with two nested domains were performed (B and C in Fig. 1a). The model domains for B and C were shown in Fig. 1c, consisting of 241 by 201 and 300 by 300 grid points with horizontal grid spacing of 5 km and 1 km, respectively. The experiment C at 1-km resolution provides the boundary conditions for the main DA experiments named D-1k and D-100. In these experiments, we focus on an isolated convective system. The PAWR at Osaka University observed the first echo which corresponded to the target convective system at 0758 JST, whereas weak fake rainfalls existed around Kobe city at that time in the experiment C. To correct the fake rainfalls by assimilating no precipitation data before receiving the first echo, the initial time of D-1k was set at 0745 JST. The initial condition for D-1k came from the experiment C. In D-1k, the NHM-LETKF was performed at 1-km resolution in a domain with 121 by 121...
reflectivity is defined by

\[
Z = (2.53 \times 10^3)(p QR)^{.84} + (3.48 \times 10^3)(p QS)^{.66}
+ (8.18 \times 10^3)(p QG)^{- .50},
\]

where \( \rho, Q, R, Q, S, Q, G \) are the air density \([\text{kg} \cdot \text{m}^{-3}] \), mixing ratios of rain, snow, and graupel \([\text{g} \cdot \text{kg}^{-1}] \), respectively (Xue et al. 2009). For radial velocity \( V_r \), the observation operator is described as follows:

\[
V_r = u \cos \alpha \sin \beta + v \cos \alpha \sin \beta + (w - w_t) \sin \alpha,
\]

where \( \alpha, \beta, u, v, w, \) and \( w_t \) are the elevation and azimuth angles \([\text{radian}] \), zonal, meridional, and vertical wind components, and reflectivity weighted terminal velocity of droplets \([\text{m} \cdot \text{s}^{-1}] \), respectively. The reflectivity weighted terminal velocity \( w_t \) is calculated by the following equation (cf. Eq. (4) of Tong and Xue 2008):

\[
w_t = w_t Z_r + w_t Z_s + w_t Z_g
\]

where \( Z_r, Z_s, \) and \( Z_g \) are the equivalent reflectivity factors \([\text{mm}^6 \cdot \text{m}^{-3}] \) of rain, snow, and graupel respectively; \( w_t, w_s, \) and \( w_t \) are the mass-weighted mean terminal velocities of rain, snow, and graupel, respectively. To calculate these mean terminal velocities, we employ the following equations described in Lin et al. (1983):

\[
w_r = 2115 \Gamma(4.8) \frac{\rho_r}{p} \frac{1}{2}
\]

\[
w_s = 152.9 \Gamma(4.25) \frac{4 g \rho_s}{6 \rho r^2} \frac{1}{2}
\]

\[
w_g = \Gamma(4.5) \frac{4 g \rho g}{3 C_D p} \frac{1}{2}
\]

where \( \rho_r, \rho_s, \rho_g \) and \( C_D \) is surface air density, air density \([\text{kg} \cdot \text{m}^{-3}] \), rain, snow, graupel size distributions and drag coefficient, respectively. \( \Gamma \) denotes the gamma function.

The number of terrain following vertical model levels (a.k.a. \( \zeta \)-coordinate levels) was 50 in all experiments. Sub-grid turbulence was considered by an improved Mellor-Yamada level-3 scheme (Nakanishi and Niino, 2004) in the experiments at resolution \( \geq 1 \text{ km} \) (except for D-100), and a large eddy simulation scheme of Deardorff (1973) was adopted in D-100. The 6-category single moment bulk microphysics but double moments for only cloud ice (Ikawa and Saito 1991) was used for cloud microphysical processes. In the 15-km-mesh (A) and 5-km-mesh (B) experiments, a modified Kain–Fritsch convective parameterization scheme (Ohmori and Yamada 2006) was used in addition to the cloud microphysics scheme.

3. Results and discussions

Figure 2 shows the side-by-side comparisons of radar reflectivity analyses at the 2-km elevation at 0810, 0820 and 0830 JST, corresponding to 50, 70 and 90 LETKF cycles, respectively. In NO-DA-1k, radar reflectivity is always less than 15 dBZ, and the target rainstorm is completely missing (Figs. 2a, 2b, and 2c). In D-1k, reflectivity corresponding to the isolated convective cell. About 8 million (0.2 million) PAWR data were available in D-100 and 1-km-by-1-km-by-100-m cells for D-1k, and took the average of the quality controlled PAWR data included in each cell. About 8 million (0.2 million) PAWR data were available in D-100 (D-1k) for assimilation at each LETKF step. The number of observations in D-1k is much smaller than that in D-100 since we cannot assimilate observation data at higher resolution than the model resolution. With the D-100’s high resolution model, we can assimilate the high-resolution PAWR data. To treat no precipitation data, the method of Aksoy (2009) was applied, so that reflectivity below 5 dBZ was replaced by 5 dBZ. The observation operator to convert the model produced hydrometeor quantities into radar reflectivity is defined by

\[
Z = (2.53 \times 10^3)(\rho QR)^{.84} + (3.48 \times 10^3)(\rho QS)^{.66}
+ (8.18 \times 10^3)(\rho QG)^{- .50},
\]

dBZ = 10 \times \log_{10}(Z),

where \( \rho, Q, R, Q, S, Q, G \) are the air density \([\text{kg} \cdot \text{m}^{-3}] \), mixing ratios of rain, snow, and graupel \([\text{g} \cdot \text{kg}^{-1}] \), respectively (Xue et al. 2009). For radial velocity \( V_r \), the observation operator is described as follows:

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where \( \rho_r, \rho_s, \rho_g \) and \( C_D \) is surface air density, air density \([\text{kg} \cdot \text{m}^{-3}] \), rain, snow, graupel size distributions and drag coefficient, respectively. \( \Gamma \) denotes the gamma function.

The observation error standard deviation for reflectivity was assumed to be 10% of the observed value or 2 dBZ when it is smaller than 2 dBZ. The observation error standard deviation for radial winds was assumed to be 3 m s\(^{-1}\). These values are somewhat larger than the instrumental errors of 2 dBZ for reflectivity and 1.5 m s\(^{-1}\) for radial velocity (Yoshikawa et al. 2013) by considering additional errors from representativeness and the observation operators. For D-1k (D-100), the Gaussian localization functions with the standard deviations of 2 km (350 m) and 1000 m were used for the horizontal and vertical covariance localization, respectively. The ensemble size was fixed at 100 for all experiments. For reference, the same procedure as D-1k but without PAWR data input was performed (NO-DA-1k).

The number of terrain following vertical model levels (a.k.a. \( \zeta \)-coordinate levels) was 50 in all experiments. Sub-grid turbulence was considered by an improved Mellor-Yamada level-3 scheme (Nakanishi and Niino, 2004) in the experiments at resolution \( \geq 1 \text{ km} \) (except for D-100), and a large eddy simulation scheme of Deardorff (1973) was adopted in D-100. The 6-category single moment bulk microphysics but double moments for only cloud ice (Ikawa and Saito 1991) was used for cloud microphysical processes. In the 15-km-mesh (A) and 5-km-mesh (B) experiments, a modified Kain–Fritsch convective parameterization scheme (Ohmori and Yamada 2006) was used in addition to the cloud microphysics scheme.

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However, D-1k underestimates the peak reflectivity compared to the observation. Apparently, 1-km resolution is not sufficient to resolve the internal structure of each convective cell captured by the PAWR (Figs. 2d, 2e, 2f, 2j, 2k, and 2l). In D-100, reflectivity shows a good agreement with the actual observation at sub-kilometer scales (Figs. 2g, 2h, 2i, 2j, 2k, and 2l), with much higher peak intensity than D-1k. Figure 3 shows the zonal-vertical cross sections of radar reflectivity at the latitude near the peak echo. Even though D-1k shows the vertical structures of the convection generally similar to the observation (Figs. 3d, 3e, 3f, 3j, 3k, and 3l), D-100 clearly shows much finer structures almost identical to the observation (Figs. 3g, 3h, 3i, 3j, 3k, and 3l).

Generally, convective activity is strongly related with the vertical stratification of the atmosphere. To clarify the impacts on the atmospheric conditions by the PAWR DA, the zonal-vertical cross sections of equivalent potential temperature (EPT) and zonal-vertical winds are shown in Fig. 4. Although the stratification is basically convectively unstable, the magnitude of the vertical motion is small, and the signals of convective initiation are hardly found in NO-DA-1k (Figs. 4a, 4b, and 4c). By contrast, we find strong disturbances in EPT and vertical motion in both D-1k and D-100. At 0810 JST, large EPT appears near the 1-km level (Figs. 4a, 4d, and 4g). The high EPT air-mass gradually propagates to upper levels with upward motion, and creates unstable stratification (Figs. 4d, 4e, 4f, 4h, and 4i). The generally unstable atmosphere contributed to activate the convection. We can find the main difference of EPT and vertical motion patterns between D-1k and D-100 in their finer structures at 100-m resolution, corresponding to the vertical cross-sections in Figs. 3 and 4.

This tendency of eastward shift was also shown by the zonal-vertical cross section of radar reflectivity (Fig. 6). The upward velocity reached 20 m s\(^{-1}\) in D-100 (c1, c2, c3, c4, c5, and c6 in Fig. 6), and led to the overproduction of large ice-phase droplets indicated by high reflectivity above the freezing level. Convection and associated ice-phase droplets developed in the eastern side, the downstream of general westerly flow over 4 km high. Apparently, the heavy precipitation core occurred east of the observed echo area at 0900 JST, while the echo intensity was generally similar between D-100 and PAWR observation (c6 and d6 in Fig. 6). D-1k generally agree with D-100 about the general eastward shift,
Fig. 4. Zonal-vertical cross sections of equivalent potential temperature analyses for (a-c) NO-DA-1k, (d-f) D-1k, and (g-i) D-100. The latitude is the same as Fig. 3. Top, middle and bottom panels correspond to 0810, 0820 and 0830 JST, respectively.

Fig. 3. Similar to Fig. 2, but for zonal-vertical cross sections at 34.70°N (0810 JST) or at 34.69°N (0820 and 0830 JST).
but the location of convection showed a discontinuous jump from 0850 JST to 0900 JST (b4, b5, and b6 in Fig. 6) unlike D-100. The convection around 135.2°E rapidly decayed from 0850 JST to 0855 JST in D-1k (b4 and b5 in Fig. 6) probably because the downward drag due to heavy rain occurs at the same grid point because of low resolution. Alternatively, two new convective systems generated at 135.35°E and 135.45°E (b5 in Fig. 6). The east-most convection eventually developed to high reflectivity at 0900 JST (b6 and d6 in Fig. 6). Supplement 1 provides the every-minute transition from 0850 JST to 0900 JST for more detailed analysis of D-1k.

In summary, although D-100 showed clear advantage over D-1k, the NWP model including physical processes are not necessarily optimized for 100-m-mesh forecasts. For further improvement, developing the numerical model at this resolution would be essential.

4. Conclusion

In this study, we carried out a series of DA experiments at 1-km and 100-m resolution using the every-30-second PAWR data for a single case of a local sudden rainstorm in Kobe caused by an isolated convective system on 11 September 2014. From the comparisons of the results, D-100 showed significant advantages in representing the rainfall intensity and three-dimensional structure of the convection. In addition, the 100-m-mesh forecasts also showed improvements in surface precipitation compared to the 1-km-mesh forecasts. It indicated that rapid-update, high-resolu-
tion DA cycles contributed to create a preferable initial condition.

Simulating an isolated convective system is one of the challenging issues in the contemporary NWP, and this study suggests that the BDA system be a promising approach to sudden local severe weather prediction, following Miyoshi et al. (2016a, 2016b). This study shows more details of the second case shown by Miyoshi et al. (2016b). Although the results are generally promising, we found issues related to high-resolution microphysics modeling. In addition, this study is only a single rainfall case with forecasts initialized at a fixed time. Our future studies will investigate more cases.

Acknowledgements

We are grateful to the members of Data Assimilation Research Team, RIKEN AICS, Hiromu Seko, Tomoo Usbho, and anonymous reviewers for their fruitful comments. This study was supported by CREST, JST projects ‘Innovating “Big Data Assimilation” technology for revolutionizing very-short-range severe weather prediction’ (grant number: JPMJCR1312) and ‘EBD: Extreme Big Data – Convergence of Big Data and HPC for Yottabyte Processing’ (grant number: JPMJCR1303). The PAWR data was provided by NICT science cloud system. This research used computational resources of the K computer and FX10 of the HPCI system provided by RIKEN AICS and Information Technology Center, the University of Tokyo through the HPCI System Research Project (Project ID: hp150019, 160162).

Fig. 5. Surface rainfall intensity forecasts initialized by the ensemble-mean analyses at 0830 JST from (a−c) D-1k and (d−f) D-100. (g−i) show the JMA analysis precipitation at 1-km resolution for reference. Top, middle and bottom panels show the results at 0840 JST (10-minute forecasts), 0850 JST (20-minute forecasts) and 0900 JST (30-minute forecasts), respectively. Dashed lines denote 34.69°N latitude (a,d,g) or 34.67°N latitude (others), corresponding to the vertical cross-sections in Fig. 6.
Edited by: S.-H. Chen

**Supplement**

Supplement 1 provides every-minute details of Fig. 6 from 0850 JST to 0900 JST for D-1k.

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Manuscript received 17 May 2017, accepted 15 August 2017

SOLA: https://www.jstage.jst.go.jp/browse/sola/