Recent Progress of the NHM-4DVAR towards a Super-High Resolution Data Assimilation

Takuya Kawabata1, Kosuke Ito1,2, and Kazuo Saito1

1Meteorological Research Institute, Tsukuba, Japan
2University of the Ryukyus, Okinawa, Japan

Abstract

A new 4-dimensional variational data assimilation system with 0.5-km grid spacing (NHM-4DVAR.v3) was developed by integrating the nonhydrostatic storm-scale 4D-Var (NHM-4DVAR.v2) and the Japan Meteorological Agency (JMA) nonhydrostatic model (NHM) based Variational Data Assimilation System (JNoVA). Both systems are based on the JMANHM, but horizontal resolutions, their formulations, adjoint models of physical processes, and observation operators are different. NHM-4DVAR.v3 comprises advantages of both systems: a penalty term, optimization of lateral boundary conditions, and observation operators for advanced observations. This development aimed at improving the forecast accuracy of hazardous weather at meso-γ-scales (5–20 km). In this paper, the characteristics of NHM-4DVAR.v3 and some results, including the integrated formulations, are presented. An assimilation experiment of actual observations using NHM-4DVAR.v3 with 2-km grid spacing was found to show improvement over NHM-4DVAR.v2 at the same resolution. As a final goal, NHM-4DVAR.v3 was applied with a 0.5-km resolution. The comparison between assimilation results by NHM-4DVAR.v3 with 0.5- and 2-km horizontal resolutions indicates that analyses with super high resolutions can reproduce more detailed atmospheric features such as convective clouds.

(Citation: Kawabata, T., K. Ito, and K. Saito, 2014: Recent progress of the NHM-4DVAR towards a super-high resolution data assimilation. SOLA, 10, 145–149, doi:10.2151/sola.2014-030.)

1. Introduction

Recently, severe and small-scale phenomena such as tornados have been studied numerically in real situations owing to the increase in computer power (e.g., Mashiko et al. 2009). Though the horizontal grid spacings are approaching a few ten to several hundred meters (sub-kilometer resolution), there might be no information on these horizontal scales if the initial conditions are obtained by spatial-interpolation of operational numerical prediction systems. When the analysis data have no information on such phenomena due to their coarse resolutions, relatively low quality of their assimilation systems, and spatiotemporally coarse observation densities, considerable spatiotemporal lags are inevitable. Owing to the recent development of innovative observational instruments such as Doppler wind lidars and dual polarimetric radars, assimilating these observations at sub-kilometer resolutions have become more realistic strategy for providing precise initial conditions to high-resolution simulations.

Thus far, high-resolution assimilation systems have been applied at grid spacings of a few kilometers for predicting high-impact weather conditions (Sun and Crook 1997; Aksoy et al. 2010). Recently, a resolution of 1 km was utilized with a 3-dimensional variational system (Xue et al. 2014) and an ensemble Kalman filter (EnKF) system (Tanamachi et al. 2013) for the prediction of supercell storms. Furthermore, Cheng and Xue (2012) tried to utilize an EnKF with 0.5-km grid spacing for the prediction of tornados. Their successes were obtained with high-resolution assimilation systems, but only Doppler radar observations were assimilated without other kinds of observations. For more precise forecasts of thunderstorms, it is necessary to assimilate observations representing their environmental fields with both dynamical and thermodynamical information.

Kawabata et al. (2007) developed a cloud-resolving 4D-Var (NHM-4DVAR.v1), and expanded to assimilate observations of radar reflectivity, GPS slant total delay, and Doppler lidar (NHM-4DVAR.v2; Kawabata et al. 2011; 2013; 2014). These studies showed that the NHM-4DVAR.v2 with these various observation operators has the ability to predict a thunderstorm with a scale approximately less than 50 km. However, the 2-km resolution is insufficient to represent a cumulonimbus itself or a supercell in detail, in both numerical predictions and high-resolution observations.

In 2010, the Tokyo Metropolitan Area Convective Study (TOMACS) started a field campaign for localized intense rains and tornados using dense and advanced observational networks (e.g., Ku band radar, dense surface observation network, Doppler wind lidar) in Tokyo (Nakatani et al. 2013). Further, in 2012, the Strategic Programs for Innovative Research program started to study ultra-high precision mesoscale weather predictions using a “K computer” which is the fastest supercomputer with 10-peta flops in Japan (Saito et al. 2011). These two big projects enabled the assimilation of innovative observations at a sub-kilometer grid spacing in severe weather events. In this study, a nonhydrostatic 4-dimensional variational assimilation system at 0.5-km grid spacing was developed as the first sub-kilometer 4D-Var in the world.

The development of a new assimilation system is introduced in Section 2. Some results are shown in Section 3, and summary and discussion are described in Section 4.

2. Assimilation systems

2.1 NHM-4DVAR

NHM-4DVAR is a storm-scale 4D-Var based on the JMA nonhydrostatic model (JMANHM; ver. 2002). This system was designed to reproduce mesoscale convective systems (MCSs) at a cloud-resolving resolution (2 km). The full model of JMANHM (Saito et al. 2006; 2007; 2012), which includes three-ice cloud microphysics without cumulus convection parameterization, was adopted as the forward model. The first version (v1) of the NHM-4DVAR considered perturbations only to dry dynamics and advection of water vapor (Kawabata et al. 2007). Moreover, the second version (v2; Kawabata et al. 2011) was implemented an additional warm rain process in the adjoint model (ADM). The control variables are the three-wind components, potential temperature, surface pressure, nonhydrostatic pressure, total water (water vapor and cloud water), the relative mixing ratio of rain water, and the pseudo-relative humidity for which the saturation mixing ratio of water vapor was given by the background (only for lateral boundary conditions: LBCs). Its cost function is as follows:

\[ J(x_{x_i}, x_{x_0}) = \frac{1}{2} (x_i + x_0)^T B^{-1} (x_i + x_0) + \frac{1}{2} (x_{x_i} + x_{x_0})^T B_{x_i}^{-1} (x_{x_i} + x_{x_0}) + \frac{1}{2} (H(x) - y)^T R^{-1} (H(x) - y), \]

where \( x \) denotes initial fields consisting of the control variables.
2.2 JNoVA

The JNoVA (Honda et al. 2005; Honda and Sawada 2008; 2009) had been operated as a JMA operational system since 2009. It is also based on the JMANHM (ver. 2004), but the physical processes in the ADM are large-scale condensation, eddy diffusion, and surface processes. The cost function of the JNoVA is given by the following equation:

\[ J(x_b) = \frac{1}{2} (x_b + x_{bc})^T B^{-1} (x_b + x_{bc}) + \frac{1}{2} (H(x) - y)^T R^{-1} (H(x) - y) + J_p, \]

where \( J_p \) is a penalty term with an incremental digital filter (Polarvarapu et al. 2000). Control variables of the JNoVA are horizontal wind, potential temperature, surface pressure, and pseudo-relative humidity. Observation operators for operational observation networks are implanted. In addition, the JNoVA adopts the incremental method (Coutier et al. 1994), where an inner loop ADM with a horizontal resolution of 15 km to minimize the cost function and an outer-loop model to compute analysis increment with a horizontal resolution of 5 km are employed.

2.3 Design of a new 4D-Var

We integrated the ADMs and formulations of the NHM-4DVAR.v2 and JNoVA, whereas the control variables of the NHM-4DVAR.v2 were adopted for a new 4D-Var system (NHM-4DVAR.v3). Both sets of observation operators of the NHM-4DVAR.v2 and JNoVA are available in the NHM-4DVAR.v3.

The forward model (JMANHM ver. 2004) had been sophisticated as an operational model after ver. 2002 and has been used in a couple of studies at sub-kilometer scales (e.g., Mashiko et al. 2009). Therefore, the new forward model is expected to provide accurate background fields and accurate trajectory in an assimilation window at sub-kilometer scales. Since the ADM was upgraded with a lot of physical processes in JNoVA and a warm rain process in NHM-4DVAR.v2 (see Table 1), it is also expected to produce more accurate gradient in convective cases. Finally, implemented observational operators for high-resolution observations were enough to apply to sub-kilometer assimilations after minor modifications like as quality controls and thinning.

### Table 1. Specifications of the nonlinear model of the NHM-4DVAR.v3, the formulations and adjoint models of the JNoVA, NHM-4DVAR.v2, and NHM-4DVAR.v3.

<table>
<thead>
<tr>
<th>Nonlinear model of NHM-4DVAR.v3</th>
<th>JNoVA</th>
<th>NHM-4DVAR.v2</th>
<th>NHM-4DVAR.v3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Penalty term</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Optimization of LBC</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Incremental method</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.5 km (2 km)</td>
<td>15 km</td>
<td></td>
</tr>
<tr>
<td>Moisture process</td>
<td>Liquid bulk</td>
<td>Large scale condensation</td>
<td>Warm rain</td>
</tr>
<tr>
<td>Radiation</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>
When the penalty term was switched off, a noisy pattern was seen downstream of the assimilation point (the right figure). When the penalty term was included, the noisy pattern was suppressed (the left figure).

Further, we examined the effect of optimizing LBCs with the same set of observations, but the assimilating point was shifted to the vicinity of the lateral boundary. As a result, a large departure is seen mainly near the lateral boundary areas (right and bottom edges in Fig. 2). The area surrounding the assimilation point is modified to be closer to the observation. Therefore, it can be concluded that these two expansions of the cost function work effectively as expected.

3.3 Assimilation experimentation with actual observations

As a final step of the verification process, we performed an assimilation experiment using actual observations in a heavy rainfall setting with the NHM-4DV AR.v2 and NHM-4DV AR.v3 with 2-km grid spacing. Details of this rainfall, which occurred on 5 July 2010, can be found in Kawabata et al. (2014). The 10-min assimilation window were set from 1000 JST, and assimilated observations were Doppler radar radial velocity (RV) and reflectivity, GPS PWV, and Doppler lidar RV. We conducted the following 3 experiments: 1. simulation without data assimilation; 2. assimilation with the NHM-4DV AR.v2; and 3. assimilation with the NHM-4DV AR.v3. We recognize that there are three intense rainfall regions in Fig. 3a from north to south over the Kanto plain, while in Fig. 3c, only weak and sporadic rainfall regions are seen. Intense rains are simulated in the NHM-4DV AR.v2 and NHM-4DV AR.v3 (Figs. 3b, d) and their scales are comparable to the observation. The intense rain on the north area, which is seen in the observation, was not simulated in every case as this exists in a lateral boundary area. On closer inspection, the result of the NHM-4DV AR.v3 is closer to the observation than that of the NHM-4DV AR.v2 in terms of the number of cores in the major intense rain region and intensity.

3.4 Toward super-high resolution 4D-Var

One of the aims of our development was to apply the NHM-4DV AR.v3 to a sub-kilometer resolution. The trial with 0.5-km grid spacing was performed with actual observations (RV) and reflectivity observations by a Doppler radar, GPS-derived PWV, and RV observations by a Doppler wind lidar installed by Hokkaido University). The 5-min assimilation window was set from 1300 to 1305 JST on 24 July 2013. The same background error statistics, observational operators, and errors were used as in the NHM-4DV AR.v2 with 2-km grid spacing for simplicity. The performance may be further improved by adjusting them to the sub-kilometer scale, which is a research study for the future.

Before the assimilation experiment, we examined linearity using Eq. (4) in this case and found that the results for 0.5- and 2-km systems were 1.025 and 1.032, respectively.

From the assimilation results (Fig. 4), we first recognize an impact of the very fine structure of orography in the higher resolution experiment. Using the 0.5-km grid spacing, a large river, an airport, small coves, and man-made structures can be observed. This suggests that the 0.5-km resolution has the ability to represent realistic urbanization effects in the assimilation more accurately. This fine structure affected the potential temperature ($\theta$) field. We also see that patterns of horizontal distribution of $\theta$ in both the 2- and 0.5-km systems are almost the same, but a small-scale structure along the river was reproduced only in the 0.5-km experiment and other several small-scale structures in the $\theta$ field are seen (Fig. 4b). This comparison suggests that a high-resolution distribution provides a more realistic representation of effects of urbanization in the assimilation.
In this study, initial conditions are given only for cloud and of complex cloud microphysics because of its high nonlinearity. However, it is not easy to develop an adjoint (Section 2.3). Furthermore, ice phase is often important for meso-scale predictions. Comparison of the nonlinear and TLMs of NHM-4DV AR.v3 showed that the TLM was accurately developed and had enough linearity. The ADM is consistent with the TLM within a rounding error. These results illustrated that the NHM-4DV AR.v3 was successfully coded with enough accuracy.

Effects of expanded formulation of the NHM-4DV AR.v3 were examined. Through a single-observation assimilation experiment, we confirmed that the penalty term contributed to making the analysis field smooth and optimizing lateral boundaries made proper increments near the lateral boundaries.

An assimilation experiment using actual observations was also conducted. Assimilated observations were Doppler RV, reflectivity, GPS precipitable water vapor, and Doppler lidar observations.

The assimilation results showed good agreement with radar observations in rainfall intensity and distribution and illustrated that the performance of the NHM-4DV AR.v3 might be better than that of the NHM-4DV AR.v2.

As a first step towards the development of a sub-kilometer advanced data assimilation system, a super-high resolution 4D-Var experiment was performed with 0.5-km grid spacing as an assimilation experiment, again using actual observations. Detailed structures of potential temperatures along a river and over the entire domain were well resolved, which was not possible with a 2-km mesh.

We found that the linearity of the 0.5-km system was slightly better than that of the 2-km system. The reasons were that the time interval of the 0.5-km system was shorter and the grid spacing was smaller than that of the 2-km system. That is, the less discretization errors were useful in this case.

As a result, it can be concluded that the NHM-4DV AR.v2 and JNoVA were appropriately integrated and the NHM-4DVAR.v3 showed good performance. Using this system, sub-kilometer 4D-Var data assimilation can be made available, but further improvements are required. Primarily, we used the same background covariance both to 0.5- and 2-km experiments simply. At sub-kilometer scales, flow-dependency should be introduced to background error covariance, because meteorological phenomena are simulated very locally. Therefore, we are developing a hybrid system (Ito et al. 2013) to utilize flow dependency at 15- to sub-kilometer scales. Furthermore, we have carefully to optimize parameters of the penalty term only to remove spurious gravity waves but true after several impact experiments. These are important issues that need to be addressed in the future.

4. Summary and discussion

A new nonhydrostatic 4D-Var system (NHM-4DV AR.v3) was developed by integrating the existing cloud-resolving nonhydrostatic 4D-Var (NHM-4DV AR.v2) and the Japan Meteorological Agency operational nonhydrostatic 4D-Var (JNoVA). Since the NHM-4DV AR.v2 and JNoVA have their own advantages, NHM-4DV AR.v3 was designed to unify these advantages: a penalty term to suppress spurious gravity waves, optimization of lateral boundary conditions, adjoint subroutines to a couple of physical processes, and observation operators for storm scale and meso-scale systems.

In this system, the dynamics between nonlinear and TLM (ADM) are inconsistent. However, the differences between full nonlinear model and TLM were around 1% for 10-min prediction (Section 2.3). Furthermore, ice phase is often important for mesoscale predictions, however, it is not easy to develop an adjoint of complex cloud microphysics because of its nonlinearity. In this study, initial conditions are given only for cloud and

![Fig. 4. Horizontal distribution of the potential temperature at z = 686 m. Assimilation results with 2-km (a) and 0.5-km (b) grid spacing. Line A-B indicates the vertical cross section used in Fig. 5.](image)

![Fig. 5. Vertical cross section of mixing ratio of rainwater, potential temperature and winds projected on the plane of the assimilation result with 2-km (a) and 0.5-km (b) grid spacings along the line A-B in Fig. 4. Reflectivity was observed by Haneda airport radar (c).](image)
Acknowledgements

The authors would like to thank Professor Yasushi Fujiyoshi and his colleagues at Hokkaido University for providing Doppler lidar observations and Dr. Yoshimori Shoji at the Meteorological Research Institute (MRI) for GPS precipitable water vapor observations. We are grateful to Dr. Hiromu Seko at MRI for giving us useful advice to conduct this study.

This study was supported by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) through Strategic Programs for Innovative Research (SPIRE), a Grant-in-Aid for Scientific Research (21244074): “Study of advanced data assimilation and cloud-resolving ensemble technique for the prediction of local heavy rainfall”, and the project of the “Tokyo Metropolitan Area Convection Study for Extreme-Weather Resilient Cities (TOMACS)” under the funds for “integrated promotion of social system reform, research, and development”.

References


Ito, K., M. Kuni, T. Kawabata, K. Saito, and Y. Honda, 2014: Tropical cyclone forecast using a hybrid EnKF-4DVar system, JpGU Annual meeting.


Nagumo, N., Y. Yamada, T. Kawabata, and E. Sato, 2014: Simulation and verification of cumulonimbi occurred on Kanto plane in summer using NHM. Proceedings of spring annual meeting of Meteorological Society of Japan, 105, 133.


Manuscript received 27 May 2014, accepted 27 August 2014
SOLA: https://www.jstage.jst.go.jp/browse/sola/