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Radar Data Assimilation for the Mesoscale Analysis at Japan Meteorological Agency

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1. Introduction

As the supercomputer becomes more powerful, the resolution of numerical weather prediction (NWP) system becomes finer. Nowadays, many operational numerical weather centers operate mesoscale NWP systems for short-range forecast. The forecast time of a mesoscale NWP system is short in general, so that the quality of forecasts depends much on initial fields. It is important whether mesoscale phenomena are reproduced in the initial fields or not. In this regard, radar data is one of most valuable observation data to capture this kind of weather phenomena in both spatial and temporal resolution. Therefore, the assimilation of radar data is one of major challenges issued on operational mesoscale analyses.

The Japan Meteorological Agency (JMA) has operated a mesoscale NWP system (MSM) since March 2001 for the disaster information and aviation forecasts. Radar data have been assimilated from the beginning of its operation and played a crucial role in the mesoscale analysis.

In this paper, we present the history of radar data assimilation in mesoscale analysis at JMA and also show some of latest works on radar assimilation.

2. Radar Network in Japan

The JMA operates two radar networks. One is the weather radar observation network that covers the entire Japan territory with 20 radars. All of them used to be weather radars that could measure only reflectivity. The network has been currently being innovated and five radars have been replaced with Doppler radars. More radars plan to be upgraded till next March.

Another radar observation network is a Doppler radar network for aviation use. These Doppler radars are installed at 8 major airports, for example Narita international airport.

For the operational mesoscale analysis, radial velocities observed by Doppler radars and analyzed precipitation data are assimilated. The latter is a precipitation data analyzed using composite reflectivity of weather radars and in-situ precipitation amount data by rain-gauges of surface observation networks. This data is called “Radar/Raingauge Analyzed Precipitation” (R/A).

3. Operational Mesoscale Data Assimilation System

The MSM has been operated since March 2001. An analysis system called “PRE-RUN” was used till March 2002. The PRE-RUN was an hourly update cycle which adopted optimal interpolation method (OI). A physical initialization (PI) was also used simultaneously to assimilate the R/A data.

In March 2002, a four-dimensional variational data assimilation system (Meso 4D-Var, Ishikawa and Koizumi, 2002) began to be used in operational. This was the first operational 4D-Var for mesoscale analysis. The Meso 4D-Var adopts a hydrostatic spectral model as time-integration operator, which was a forecast model of the MSM at that time. This Meso 4D-Var has been operated since then.

The forecast model of the MSM, the hydrostatic spectral model, has been replaced with a nonhydrostatic grid model (JMA-NHM) in September 2004 (Saito et al. 2006). Since the cost function defined in the 4D-Var includes a forecast model, an optimal solution that minimizes the cost function

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depends on the forecast model. Considering this theoretical aspect of 4D-Var, there occurs the inconsistency of models between the forecast and the analysis.

To solve this problem, a new 4D-Var system (JNoVA, Honda et al. 2005) has been developed to replace the Meso 4D-Var in near future. The JNoVA adopts the JMA-NHM as time-integration operator. The JMA-NHM of the JNoVA has two options of moist physics. One option is the simplified physics that consists of the large-scale condensation and the moist convective adjustment scheme. Only the mixing ratio of the water vapor is considered. This version of the JNoVA has been developed mainly for the purpose of the operational use. The other option is the cloud microphysics which is the 2-ice bulk scheme. The predictable variables are mixing ratios of not only water vapor but also cloud water, cloud ice, rain and snow. The moist process of this version of the JNoVA is much more sophisticated than that of the other version of the JNoVA. This JNoVA is used mainly for the purpose of the research to investigate the potential of the 4D-Var.

4. Brief History of Operational Radar Data Assimilation

4.1 Radar / Raingauge Analyzed Precipitation

Besides the ordinal surface observation sites, the JMA owns the dense network of around 1500 automated surface observation sites which cover the Japan with average special interval of about 17km. This network is called “Automated Meteorological Data Acquisition System” (AMeDAS). At all stations of AMeDAS, the precipitation amount is measured. In addition, the JMA currently obtains the precipitation amount data from other observation networks operated by River Bureau, Road Bureau and other local governments. The total number of in-situ precipitation data increases 3 to 5 times by adding these data.

The Radar / Raingauge Analyzed Precipitation (R/A) data is a pseudo surface precipitation data. The low-level composite radar reflectivity data are calibrated using the in-situ precipitation data to produce hourly surface precipitation data. The R/A data is produced every 30 minutes with horizontal spacing of 2.5km.

Because of the resolution, the R/A data is one of most useful observation data to capture mesoscale weather phenomena. In the era of PRE-RUN, the R/A data was assimilated using the PI, which is a kind of a nudging method. The temperature and moisture fields were modified by the PI. Since the PRE-RUN was executed for 3 hours before the initial time, the R/A data were assimilated every hour between the analyses by OI.

When the Meso 4D-Var became operational, the assimilation window was set to 3 hours. So the same data set of the R/A data was assimilated using the Meso 4D-Var with other observation data together. Unlike the PRE-RUN, not only temperature and moisture fields but also dynamical fields were also modified under the consideration of model balance.

The twin experiments to compare the PRE-RUN and the Meso 4D-Var shows that quantitative precipitation forecasts from initial fields analyzed by the Meso 4D-Var have been improved significantly throughout the 18 hour forecast times (Koizumi et al. 2005).

4.2 Radial Velocity

Contrast to the fact that the R/A data has been assimilated from the beginning of the operation of the MSM, the radial velocity data began to be assimilated into the operational mesoscale analysis in March 2005 (Ishikawa and Koizumi 2006). In spite of the data available from early on, it took a long time to start to use this data after the Meso 4D-Var introduced in the MSM. This is mainly because of the noise of the data. The quality control and the appropriate thinning procedure are the key of the success of the assimilation of the radial velocity.

5. Impact Experiments using JNoVA

Since the JNoVA using simplified physics is a candidate of the next operational mesoscale data assimilation system, it is important to confirm that the impact of the assimilation of radar data using this JNoVA is same to that using the Meso 4D-Var.

5.1 Radar / Raingauge Analyzed Precipitation

First of all, the impact of the assimilation of the R/A data is investigated. The same observation operator proposed by Koizumi et al. (2005) is adopted

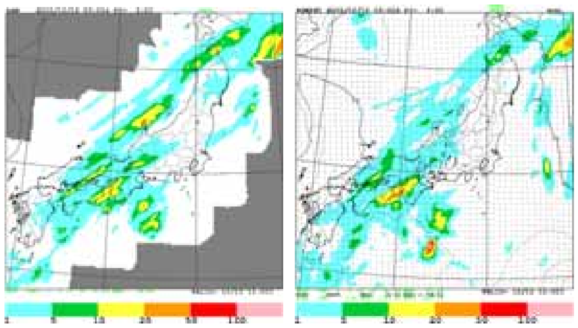

Fig.1 3 hour accumulated precipitation fields from 03 to 06 UTC on 15 Oct. 2005, which is the assimilation window. The left panel shows the R/A data and the right one the analysis by the JNoVA.

by the JNoVA, too. The analyzed precipitation pattern is similar to that of the R/A data, so that the assimilation of the R/A data is succeeded (Fig.1). Besides the cost of the observation term of the R/A data also decreases well.

To see the impact on the quantitative precipitation forecast, the forecast-analysis experiments have been conducted. The general settings of the experiments are listed in Table 1. The control is the experiment using the operational mesoscale analysis of the Meso 4D-Var. The first test, which is tagged with "JNoVA" in Fig.2, is the experiment using the analysis by the JNoVA with the same dataset of the observation used

Table 1: General Setting of Experiments

Item	Meso 4D-Var	JNoVA*
Domain size	3600x2880(km^2)	1440x1440 (km^2)
Horizontal Resolution	(Inner) 20km (Outer) 10km	(Inner) 10km (Outer) 5km
Vertical Resolution	40 layers	50 layers
Assimilation Window	6 hours	3 hours
Minimization Iteration	About 40 times	20times
Observation Data	SYNOP, SHIP, BUOY, METAR, TEMP, PILOT, AIREP, Wind Profiler, SATOB, SSM/I and R/A data	
Experiment Period	8 initials from 00UTC to 21UTC on 20 June 2006.	

* Because of the restriction of the computational resource, the data assimilation experiments with the JNoVA have been conducted with the smaller domain.

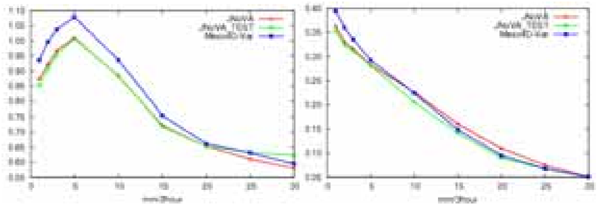

Fig.2 The bias score (left) and the equitable threat score (right) of 3 hour precipitation forecasts. The grid size of the verification grids is 10km. The x-axis indicates the threshold value.

in the control. The last test, which is referred as "JNoVA_TEST" in Fig.2, is the experiment using the analysis by the JNoVA with the same dataset of the observation except the R/A data and the polar-orbit satellite data (Precipitation intensity and total precipitable water). The comparison of these experiments wouldn't show exactly the impact of the R/A data. But the precipitation amount of the R/A data and the precipitation intensity of the polar-orbit satellite data are quite similar data, so that the satellite data (including the total precipitable water) are excluded simultaneously. So it is a kind of robust evaluation. The forecasts from all analyses are executed using the JMA-NHM with horizontal grid spacing of 5km in the smaller domain used in the tests.

The equitable treat score shows that the assimilation of the R/A data (and the polar-orbit satellite data) has a positive impact on quantitative precipitation forecasts. Another comparison of the run "JNoVA" and the run "Meso 4D-Var" shows that the score of the JNoVA is slightly better than that of the Meso 4D-Var in the range of 10-25mm/3hours.

However, it is not that the assimilation of precipitation data always gives the positive impact on analyses and forecasts. The R/A data we use is a kind of super observation in the format of the 2-dimensional grid data with the same spacing to the analysis model of inner step. So as the analysis resolution becomes finer, the resolution of the assimilated R/A data also becomes higher. Since the Meso 4D-Var and the JNoVA don't consider the spatial correlation of the observed precipitation data, non-diagonal elements of the observation error covariance matrix are set to 0. The weight of the precipitation data gets larger as the density of this data is higher unless the error variance is adjusted to be larger. Unlike the Doppler radial velocity or satellite data, this effect of this problem has not been evaluated using the Meso 4D-Var.

To investigate the effect of the weight of the R/A data, two data assimilation experiments have been done using different observation error variances of the R/A data. One experiment named “CostRainx0.1” is the same error variance used in the previous forecast-analysis experiments. This one is already adjusted by multiplying 0.1. The other run named “CostRainx1” is the observation error variance used in the operational mesoscale data assimilation system. Fig.3 shows the vertical cross sections of the analysis increment of potential temperature. The difference of figures in Fig.3 is concentrated on the left side of the figures where the rain is observed in the R/A data. Since the precipitation amount of the first guess is smaller than the observed amount, the model produces more precipitation to fit to the R/A data. As a result, the atmosphere is stabilized by cooling the lower atmosphere and heating the upper atmosphere. The reason of this increment might be because the rain is produced thought the moist convective adjustment scheme, which has a character to remove the unstable status of the atmosphere. In the case of the experiment “CostRainx1”, the atmosphere is more stabilized than that of the experiment “CostRainx0.1” although the reproduced precipitation of the analysis seems to be better (not shown). This affects on the precipitation forecasts because the forecasted precipitation is suppressed when the atmosphere is stable. The bias score of the precipitation forecast of experiment “CostRainx1” is lower than that of experiment “CostRainx0.1” in the range of the thresholds more than 10mm/3h. The equitable threat score also indicates the score of the forecast becomes worse.

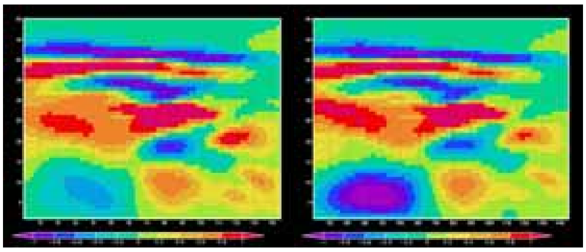

Fig.3: Vertical cross section of analysis increment of potential temperature. The left one is the result of the experiment “CostRainx0.1” and the right one that of the experiment “CostRainx1”.

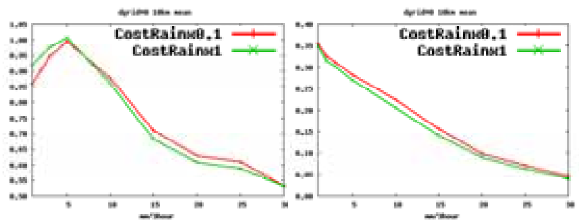

Fig.4: The bias score (left) and the equitable threat score (right) of 3 hour precipitation forecasts. The grid size of the verification grids is 10km. The x-axis indicates the threshold value.

These results suggest that even 4D-Var may degrade the analysis as the initial field of the forecast model unless the error of the observation data is appropriately treated. When the dense observation data like radar data are assimilated, the spatial correlation of the error should be taken into account in the cost function or the data itself should be thinned enough to treat each of them as independent observation. The former might be better because the information of the finer structure of mesoscale phenomena can be ingested into the analysis.

5.2 Radial Velocity

The observation operator of the radial velocity is quite simple. As written above, the key of the success of the assimilation of the radial velocity is the quality control and the thinning procedure. In contrast to the R/A data, the assimilation of radial velocity didn’t

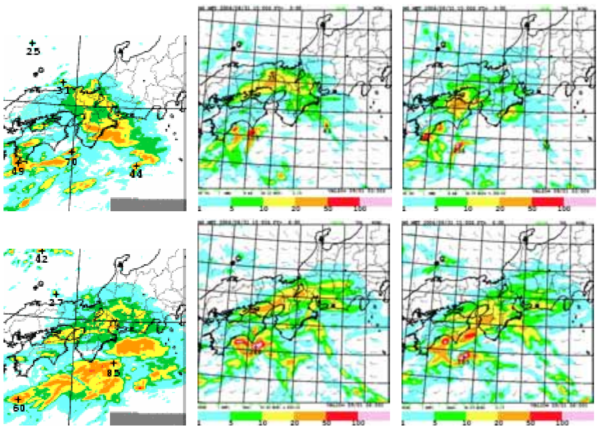

Fig.5: 3 hour accumulated precipitation at (upper) 3 hour forecast time and (lower) 6 hour forecast time. The left panels show the R/A data, the center ones are forecasts of the experiment “CostRainx0.1”, the right ones are forecasts of the experiment “CostRainx1”.

contribute to the improvement of the forecasts until the data is thinned enough even before the resolution of the analysis is raised. This might be because the radial velocity is a momentary data although the R/A data is an accumulated data.

Using the same quality control and the thinning procedure, the JNoVA also shows positive impacts on forecasts by the assimilation of the radial velocity (Fig. 5).

6. Trial of Assimilation of Radar Reflectivity

6.1 Weakness of the assimilation of the R/A data

Although the R/A data is assimilated, the radar reflectivity itself has not been tried to be assimilated by the Meso 4D-Var yet. This is simply because the moisture variable of the hydrostatic model adopted in the Meso 4D-Var is only relative humidity. The radar beam is sensitive to the precipitable water contents. It is essential that a model predicts these water contents explicitly in order to describe the observation operator of the radar reflectivity.

Although the JNoVA used in section 5 adopts the JMA-NHM using the simplified physics and the specific humidity of the water vapor is the only moist-related variable, the JMA-NHM originally predicts other hydrometeors considering the cloud microphysics. To take advantage of this sophisticated moist process, the JNoVA using 2-ice bulk microphysics scheme (JNoVA_CLD) has been developed (Honda and Yamada 2007).

Before moving on the assimilation experiments of the radar reflectivity, the character of the JNoVA_CLD is briefly described. The mixing ratios of cloud water, cloud ice, rain and snow are added to predicted variables of the JMA-NHM adopted by the JNoVA_CLD. The tangent-linear and the adjoint code of the 2-ice bulk microphysics scheme are generated in nearly straightforward manner. The accuracy of the tangent-linear model of the JMA-NHM using 2-ice bulk scheme has been evaluated by comparing the growth rate of the perturbation by the tangent-linear model and that by the nonlinear model. The results showed the acceptable accuracy, so that the cost can be minimized when this adjoint model of 2-ice bulk scheme is used in the variational data assimilation (Honda and Yamada 2007).

In this paper, the assimilation of the reflectivity data whose intensity is larger than 10dBz has been attempted using the JNoVA_CLD. First of all, the minimization of the cost function has been failed when the assimilation window is 3 hours under the same conditions shown in Table 1. However, the assimilation of the R/A data using this JNoVA_CLD with 3 hour assimilation window is succeeded reported in Honda and Yamada (2007). The exact reason why the assimilation of reflectivity fails and the assimilation of the R/A data succeeds is unclear so far. To see the impact of reflectivity, the assimilation window is shortened to 1 hour henceforth.

The weakness of the assimilation of the R/A data is that the precipitation data can be assimilated only at the place where the model predicts the precipitation. In addition, the weather phenomena, which a model adopted by 4D-Var cannot represent well, are more difficult to analyze even if the strong precipitation is observed. One example is a convection caused by the thermal instability over the sea.

Because the R/A data is a pseudo observation data generated from the reflectivity and in-situ observation data, the direct assimilation of reflectivity is expected to be more sophisticated and mitigate problems of the assimilation of the R/A data.

6.2 Assimilation of only Radar Reflectivity

The analysis by assimilating the R/A data by the JNoVA_CLD is shown in Fig.6. The convection marked with orange circle is not represented in the analysis. The observation of radar reflectivity captures this convection cell well (Fig.7). So the assimilation experiment has been done with this reflectivity data instead of the R/A data.

The observation operator of the radar reflectivity is described as follows:

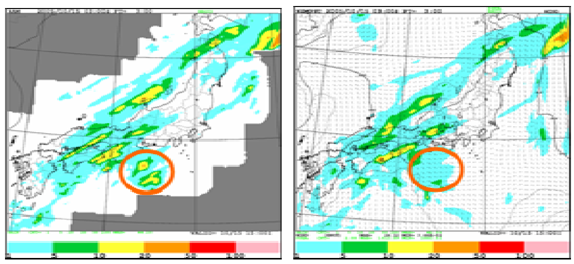

Fig.6 The same to Fig.1 except that the right panels shows the analysis of the JNoVA_CLD with the R/A data.

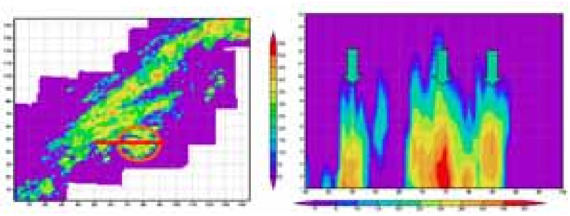

Fig.7 CAPPI data of the radar reflectivity. The left panel shows the horizontal cross section at 2km. The right panel shows the vertical cross section along the red line of the left panel. Three green arrows represent the peaks of the reflectivity, which may indicate the convective activities.

$$J_o^{Radar\_ref} = \frac{1}{2}\left[Z_{obs} - H(q_r, q_s)\right]^{\mathrm{T}} \mathbf{R}^{-1}\left[Z_{obs} - H(q_r, q_s)\right]$$

$$Z = 10 \times \log_{10}(Ze),\ Ze = Zer(q_r) + Zes(q_s)\ .$$

The functions of Zer and Zes are fundamentally based on the formulation proposed by Smith et al.(1975).

The targeted convection is succeeded to be reproduced in the analysis although it is not as strong as the observed one (Fig.8). However, it becomes apparent that spurious orographic convections are also excited at the same time. How these spurious convections are simulated can be explained as follows. First, the atmosphere in the orange circle is moistened by assimilating the radar reflectivity. Then this moisture air is advected by the ambient flow before the strong convection is organized. At last the air is lifted along the slope of the orography to organize a spurious convection.

It becomes apparent that the assimilation of radar reflectivity is useful to moisten the atmosphere where the strong reflectivity is observed, but it deteriorates the quality of the analysis by exciting spurious orographic convections.

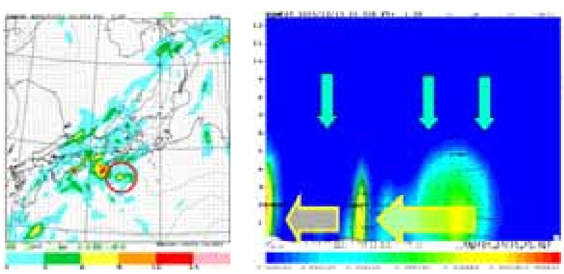

Fig.8 The left panel shows 3 hour accumulated precipitation of the analysis assimilated radar reflectivity by JNoVA_CLD. The right panel shows the simulated radar reflectivity from the analysis. The green arrows are same to those in Fig.7. Yellow accrows shows the schematic image of the ambient flows.

6.3 Simultaneous Assimilation of Radar Reflectivity with the R/A data

To resolve the above problem, the simultaneous assimilation of the radar reflectivity and the R/A data is tested. The aim of this experiment is to suppress spurious convections by ingesting the information of the precipitation pattern from the R/A data.

The analysis shows that spurious convections are removed successfully while the convection over the sea is kept. Simulated radar reflectivity of the analysis becomes similar to the observed one and the vertical circulation of the convection related to the strongest simulated reflectivity is built up.

While the assimilation experiment is succeeded, there is a fair pointed out that the simultaneous assimilation of these data is redundant since the R/A data is calculated using the low-level composite reflectivity.

7. Conclusion and Future Work

In this paper, we introduce the brief history of the radar data assimilation of the operational mesoscale analysis. And we also show the results of the assimilation experiments of various radar data using the pre-operational mesoscale variational data assimilation, JNoVA. It is reconfirmed that the assimilation of the R/A data and the radial velocity used in operational system contribute to the improvement of the quantitative precipitation forecasts. So far the spatial correlation of error of the R/A data is ignored and it works fine. But the resolution of the

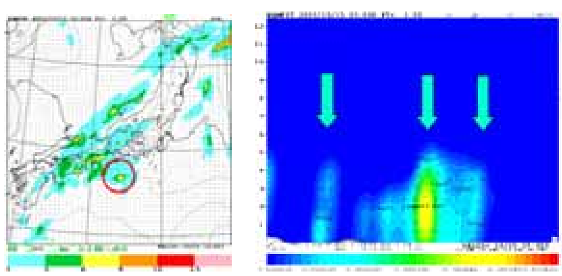

Fig.9 The same to Fig.8 except the analysis assimilated radar reflectivity and the R/A data by JNoVA_CLD.

analysis becomes finer at the next mesoscale analysis and the appropriate treatment of the observation error need to be required. Otherwise, the analyzed atmosphere can be sometimes stabilized too much.

The assimilation of the radar reflectivity has been also attempted with the JNoVA using 2-ice bulk microphysics. It becomes apparent that the radar reflectivity is useful to reproduce the convection even over the sea where there is no explicit forcing like orography when it is assimilated together with the R/A data. However, we also find there are some problems to be solved. One is the redundancy of the R/A data and radar reflectivity. The other is the length of the assimilation window or the nonlinearity of the JMA-NHM using 2-ice bulk microphysics scheme. It seems that it is too strong so that the minimization of the cost function is failed in the case of 3 hour assimilation window.

There are many researches so far that report the success of the assimilation of the radar reflectivity by the 4D-Var using the cloud microphysics. But they are the storm scale data assimilation. Under the conditions of the resolution is about ten kilometers and the assimilation window is from 3 to 6 hours, it seems quite difficult to get the same kind of results by the 4D-Var using cloud microphysics.

The effective assimilation of radar reflectivity still remains as one of future issues because this data has information related to 3-dimensional structure of moisture / precipitation.

Acknowledgment

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