E-4. Initial perturbation methods

E-4-1. WEP method

As in the WEP method in the 2006 and 2007 experiments, perturbations from the JMA operational one week global EPS were tested in the 2008 experiment as well for reference. Since the method to create initial perturbations changed from a global BGM method (F-1) to a global SV method (F-2), structures of the initial perturbation also changed.

In the 2006 and 2007 experiments, the amplitude of the specific humidity was adjusted so that the super-saturation should not occur at an initial time. For this purpose, a reference temperature of the atmosphere was used. In the 2008 experiment, the saturation water vapors were computed in each perturbed temperature field of ensemble members properly using the hybrid coordinates.

E-4-2. Global singular vector method

In this section, the global singular vector (GSV) method used by the 2008 B08RDP experiment is summarized.

The verification results for the 2007 preliminary experiment showed that the ensemble spread of the GSV ensemble prediction system (EPS) was smaller than the RMSE of the fore-casts (see section D-7-2). To improve the ensemble spreads in the 2008 experiment, MRI/JMA added perturbations of the lateral boundaries of the model domain.

a GSV EPS Specifications

The GSV EPS specifications are summarized in Table E-4-1. The main difference from those of the 2007 experiment is the introduction of perturbations of the lateral boundaries. In addition, the weighting of specific humidity in the total energy norm and the target area were slightly changed in the singular vector (SV) calculations.

| Categories | Specifications | Details |
|-----------------------|---------------------|---|
| Forecast model | JMA-NHM | $232 \times 200, \Delta = 15 \text{ km}, 40 \text{ levels(hybrid)}$ |
| EPS members | 11 | |
| Initial perturbation | Targeted global SVs | First five SVs (GSM-T63L40) |
| Target area | Beijing area | $27-42^{\circ}N$, $110-130^{\circ}E$ |
| Energy norm | Moist TE norm | $w_q = 0.3$ |
| Optimization time | 24 hours | |
| Lateral perturbation | GSM-T63L40 EPS | Consistent with the initial perturbation |
| Physical perturbation | None | |
| | | |

Table. E-4-1. Specifications of the GSV EPS for the 2008 B08RDP experiment

Figure E-4-1 depicts the model topography of the GSV EPS forecast domain. The target area of the GSV is southeast of the common verification area. In the 2007 GSV EPS, the initial SVs tended to capture the growth of the mid-latitude air pressure trough which usually passed through the northern part of the model domain (or the target area). Thus, the amplitudes of the initial perturbations were lower in the southern part of the model domain. We shifted the target area southward to capture the northward water vapor flux below 850 hPa in the southern part of the model domain. The introduction of lateral boundary perturbations with the same targeted GSVs makes it possible to move the target area eastward as well to improve the ensemble spreads in the early stage of time integration. In the later stage of time integration, consistently perturbed disturbances are supplied via the lateral boundaries.

In the 2007 experiment, the ensemble spread was insufficient, especially in the lower troposphere. The SVs had relatively large amplitudes in the upper troposphere. The damping factors were determined so that the initial energy of the specific humidity would be mainly below 700 hPa and the initial energies of other variables below 500 hPa. In addition, the weighting of the specific humidity in the total energy norm was changed from $w_q = 0.6$ to $w_q =$ 0.3 to increase the net initial energy of the specific humidity. Although $w_q = 0.1$ was a suitable



0 300 600 900 1200 1500 2100 3000

Fig. E-4-1. Computational domain of the GSV EPS along with the model orography (m) for a 15-km grid spacing. The common verification area is enclosed by a solid rectangle and the target area of the GSV is enclosed by a dashed rectangle.

value in experiment modeling of the 2007 Kyushu heavy rainfall event, the preliminary test results obtained by using $w_q = 0.1$ for the rainfall event of May 2008 in the Beijing area was not as good as that obtained with $w_q = 0.3$. The test result was evaluated by its RMSE and spread, because we could not acquire the precipitation observation data for May 2008 event, although use of the observed precipitation data for the evaluation would be preferable.

To perturb both the initial and lateral boundary conditions, the first five SVs were added to the initial of the global spectral model (GSM-T63L40). The SV amplitudes were adjusted so that any of the maximum values of the five variables did not exceed the typical forecast error of GSM estimated by the statistics in 2007. Those variables were temperature, specific humidity, x and y components of the horizontal velocity and surface pressure. Initial fields with positive perturbations were prepared for both the initial and lateral boundary perturbations of the NHM (the forecast model used for the GSV EPS). In each member, the specific humidity was calibrated so that supersaturation would not occur because these initial fields were used for the lateral boundary perturbations. Time integration of the GSM-T63L40 was performed for up to 36 hours for the control and each of the five members (only for positive perturbations). Forecasted three-hourly model planes, including initials, were interpolated into the NHM model planes, based on a 15-km horizontal grid and 40 vertical levels. Both the initial and lateral boundary perturbations for the GSV EPS were extracted from the difference between the control run and each perturbed run. The extracted initial perturbations were added to (subtracted from) the control initial fields produced by the JMA mesoscale 4D-Var analysis system (see section E-3-1) to prepare the positive (negative) incremental fields for the initials. The extracted lateral boundary perturbations were added to (subtracted from) the control NHM boundary fields produced by the JMA's operational GSM (TL959L60) forecast (see section E-3-5). Any supersaturation was removed from these incremental fields. Finally,

we obtained initial and boundary conditions for 11 members for executing the GSV EPS. The major advantage of this method is the consistency between the initial and boundary conditions, which use the same SVs.

b Impact of the 2008 improvement

The introduction of the lateral boundary perturbations improved the ensemble spread by about 20%. The results of the 2007 preliminary experiment were compared with those of the 2008 B08RDP experiment (Fig. E-4-2). The ensemble spread of all surface elements increased



Fig. E-4-2. Time evolution of the ensemble spread of all surface variables within the common verification area. (a) The 2007 GSV EPS experiment results (7–23 August 2007). (b) GSV EPS results during the Beijing Olympics (7–23 August 2008).

substantially in the 2008 experiment, especially after a forecast time (FT) of 18 hours. To investigate the direct influence of the lateral boundary perturbations, the GSV EPS without lateral boundary perturbations was tested at an initial time of 12 UTC on 7 to 9 August 2008. The lateral boundary perturbations produced by the GSV method were very effective in improving the spread after FT = 18 (Fig. E-4-3).

Figure E-4-4 compares the RMSE and ensemble spread between the 2008 GSV EPS and the 2007 version. The forecast error of the control run (white column in Fig. E-4-4) was considerably improved with respect to both temperature and humidity, though little change was seen in the wind fields. This improvement coincides with an improvement in the mean error of the control run (Fig. E-4-5). In the 2007 experiment, there were large negative biases in temperature and large positive biases in humidity, whereas in the 2008 experiment, the bias errors were substantially suppressed by revision of the predicting soil wetness, which reduce the bias error in the surface temperature (see section E-2-2).

The forecast error of all surface variables in the ensemble mean (RMSE, gray columns in Fig. E-4-4) relative to the control run was moderately improved in the 2008 experiment. It is notable that the performance of the 2008 experiment with respect to both the temperature



Fig. E-4-3. Same as Fig. E-4-2, but for 7–9 August 2008. (a) GSV EPS result with no lateral boundary perturbation. (b) GSV EPS result with lateral boundary perturbations consistent with the initial perturbations of the GSV.



Fig. E-4-4. RMSE at FT = 24 of the control run (white bars), RMSE of the GSV EPS (gray bars) and the ensemble spread (black bars). The(a, e) 2 m temperature, (b, f) 2 m humidity, (c, g) 10 m eastward velocity component, and (d, h) 10 m northward velocity component during 7–23 August 2007 and 7–23 August 2008, respectively.



Fig. E-4-5. Mean error at FT = 24 in relation to initial conditions. (a) 2 m temperature during 7–23 August in 2007 and 2008, and (b) 2 m humidity during 7–23 August in 2007 and 2008.

and moisture fields was good, unlike the 2007 experiment. The ensemble spread of the 24 hour forecast in 2008 increased by about 20% (black column in Fig. E-4-4). The difference between the RMSE and the spread became much smaller in 2008. The relationship between the RMSE and the spread was compared among participants and MRI/JMA obtained the best score (see section E-7-2).

Another improvement was found by examining the receiver-operating characteristic (ROC) curves of the ensemble forecasts (Fig. E-4-6). The hit rate for 3 mm/6 hours and for 5 mm/6 hours was improved by more than 10% without any increase in the false positive rate, but little improvement was observed for 10 mm/6 hours. To improve the detection rate of intense rainfall, the use of physical perturbations might be required.

c Case study

In this subsection, two convective rainfall events affecting the Olympic games are briefly reviewed. The first case is a thunderstorm event at 12 UTC on 10 August 2008. Six-hourly cumulative precipitation observed at weather stations in China is plotted in Fig. E-4-7a and the probabilistic prediction of rainfall with a threshold value greater than 20 mm/6 hours by MRI/JMA is presented in Fig. E-4-7 b. Heavy rainfall was observed near Beijing in the evening (Fig. E-4-7a). An upper-level cold trough approached the Beijing area from the northwest. The GSV EPS (MRI/JMA), as well as those of both the MSC and NMC participants (not shown), predicted a 20% probability of intense rainfall. The false positive area north of Beijing was relatively small in the GSV EPS prediction compared with that of the other participants (not shown). It is informative that the GSV EPS predicted the heavy rainfall area near Beijing with a lead time of 24 hours.

The second case is another difficult-to-forecast convective rainfall event that occurred near Beijing in the evening on 14 August 2008 (Fig. E-4-8a). Only two participants, MRI/JMA and MSC (not shown), predicted possible intense rainfall near Beijing (Fig. E-4-8b). The GSV EPS (Fig. E-4-8b) predicted a 5% probability of precipitation with a threshold value greater than 20 mm/6 hours. This means that one member (P02) of the GSV EPS was able to predict



Fig. E-4-6. ROCs for weak to moderate rainfall intensity. The abscissa denotes the false positive rate (the probability of false detection). The ordinate indicates the hit rate (the probability of detection). The dashed and solid lines denote the scores for 7–23 August in 2007 and 2008, respectively. (a) 1 mm/6 hours, (b) 3 mm/6 hours, (c) 5 mm/6 hours, and (d) 10 mm/6 hours.



Fig. E-4-7. Observed 6-hourly cumulative precipitation and the probabilistic prediction for a threshold greater than 20 mm/6 hours ending at 12 UTC on 10 August 2008 (FT = 24). Contours indicate the mean sea-level pressure. (a) Observed rainfall at weather stations in China (mm/ 6hours). (b) Predicted probability (%) of 20 mm/6 hours by MRI/JMA (GSV EPS).



Fig. E-4-8. Same as Fig. E-4-7 but at 12 UTC on 14 August 2008 (FT = 24). (a) Observed rainfall at weather stations in China (mm/6 hours). (b) Predicted probability (%) of 20 mm/6 hours by MRI/JMA (GSV EPS).

the heavy rainfall area near Beijing. Figure E-4-9 shows the 6-hourly cumulative precipitation predicted by the control (a) and P02 (b). The control run predicted intense rainfall south of



Fig. E-4-9. Predicted 6-hourly cumulative precipitation ending at 12 UTC on 14 August 2008 (FT = 24) (mm/6 hours). (a) Control; (b) P02. The mean sea-level pressure (contours; hPa) and the surface wind field (arrows) are also plotted.

Beijing, whereas P02 predicted that intense precipitation would occur where the heavy rainfall was actually observed. The wind field in the vicinity of the convection was different between them as well. In P02, a southerly wind was dominant at the southern edge of the line of convection, and a northeasterly wind at the northern edge of the convergence produced the upward motion necessary to maintain the convective activity.

Figure E-4-10a shows the initial perturbation field of equivalent potential temperature at 700 m in P02. The positive perturbed area is spread out over the area south and southeast of Beijing. In P02, the northward component of the initial water vapor flux is calculated in the layer below 1.5 km (Fig. E-4-10b). The northward water vapor flux reaches the Beijing area from the southwest boundary. The transport of air with a high equivalent potential temperature near the surface from the south caused heavy rainfall after 18 hours from the initial time. Figure E-4-11 shows the predicted convective instability (= $\theta_e(700m) - \theta_e(5km)$) at FT = 21. In P02, the air mass with convective instability approaches the Beijing area, producing a linear rainband at the northern edge of the unstable air flow at FT = 24 (Fig. E-4-9b).

Yamasaki (2007), who carried out a numerical study of the Niigata-Fukushima heavy rainfall event, emphasized that latent instability (positive buoyancy of rising air) is important for explaining convective activity and heavy rainfall. The effect of the acquired buoyancy (latent instability; $= \theta_e(700m) - \theta_e^*(3km)$) between 700 m and 3 km are shown in Figs E-4-12a and E-4-12b for the control run and P02, respectively. In the control run, the latent instability is weak south of Beijing (Fig. E-4-12a) at FT = 6 and results in a weak rainband at FT = 12 (Fig. E-4-12c). The initial positive perturbation of equivalent potential temperature at low



Fig. E-4-10. (a) Initial perturbation field of equivalent potential temperature at 700 m in P02 at 12 UTC on 13 August 2008. (b) The northward component of the vertically integrated horizontal flux vector of water vapor at the initial in P02, calculated below 1.5 km (mm m/s).



Fig. E-4-11. Predicted convective instability between 700 m and 5 km at 09 UTC on 14 August 2008 (FT = 21). (a) Control run; (b) P02.



Fig. E-4-12. Latent instability (buoyancy) between 700 m and 3 km at FT = 6 in (a) the control run and in (b) P02, and predicted 6-hourly cumulative rainfall ending at FT = 12 in (c) the control run and in (d) P02.

levels in P02 intensifies the latent instability south of Beijing at FT = 6, where a northward water vapor flux has appeared (Fig. E-4-12b). The strong buoyancy results in strong upward motion, causing the heavy rainfall six hours later (Fig. E-4-12d).

The performance of the GSV EPS was relatively good for the convective rainfall events occurring near Beijing during the Olympic games. The low-level northward air flow may have acquired excess warmth and moisture as a result of the initial P02 perturbations. But its performance in the southern boundary region was not good (Fig. E-4-8). High convective instability was present in the southern boundary region (Fig. E-4-11), but the EPS did not predict convective rains. Perturbations of equivalent potential temperature at the low levels were small at the southern boundary (Fig. E-4-10a). Further improvement of the low-level perturbations, including at the lateral boundaries, might be required to improve the performance.

d Appendix

Figure E-4-13a shows the ROC Area Skill Score (ROCASS) of the GSV EPS in the 2008 B08RDP experiment. ROCASS was derived from the area under the ROC (AUC) as follows.

$$ROCASS = 2(AUC - 0.5)$$

The GSV EPS performance in the Beijing area, where the Olympic games were held, was fairly good according to all criteria, but ROCASS for the common verification area was insufficient. The GSV EPS prediction of intense precipitation in the southern area was not accurate (Fig. E-4-7 and E-4-8). Insufficient perturbation of the GSV EPS in the southern area may account for its failure to predict convective precipitation there.

The GSV EPS was modified in 2009 for predicting intense rainfall during the Baiu season in Japan, and the modified EPS was able to predict some heavy rainfall events in July 2009. Modifications were made to the norm calculations, such as [wq = 0.1] and a damping factor of the energy of water vapor below 500 hPa, to increase both the convective and latent instabilities. The main effect of this modification was to enlarge the area of the initial perturbation of water vapor below the altitude of 1 km. The scheme to make initial perturbations was also changed to reduce the noise due to the downscaling procedure. The GSM-T63L40's model plane was first interpolated into the model plane of the NHM with 180-km spacing, and then into that of the NHM with 15-km spacing. The modified EPS was then used to redo the probabilistic forecasts for the period of the Beijing Olympic games. Figure E-4-13b shows the difference between the ROCASS obtained in the 2008 B08RDP experiments and that obtained with the modified GSV EPS in 2009. Below the rainfall intensity of 35 mm/6 hours, the latter ROCASS is moderately improved.



Fig. E-4-13. (a) ROCASS for 25 July to 23 August 2008. The dashed line denotes the score for the common verification area (30–45°N, 105–125°E) and the thick line the score for the Beijing area (35–45°N, 105–125°E). (b) ROCASS for 7–23 August 2008 for the common verification area (30–45°N, 105–125°E) in the 2008 B08RDP experiment. The thick gray line shows the score of the GSV EPS modified in 2009.

E-4-3. MSV method

In preliminary experiments conducted at MRI in 2007, some shortcomings of the mesoscale singular vector method were addressed (see D-4-3). In the 2008 B08RDP experiment, the method was further improved to make the MSVs computationally stable and to develop suitable initial perturbations for ensemble forecasting.

First, TLM and ADM were replaced with new, computationally more stable versions of these models, including a simplification of turbulent processes and a revision of the large-scale condensation process. These changes allowed a longer optimization time to be used than before without unrealistic growth of perturbations being caused by the breakdown of the linearity approximation. Second, a coarser horizontal resolution of 40 km was used in the singular vector calculations and an 18-hour optimization time was adopted, compared with the 6-hour optimization time adopted in the 2007 experiment, enabling the ensemble spreads to grow consistently until the end of the forecast period. Even when this longer optimization time was applied, the validity of the tangent linear approximation was confirmed. Third, the amplitudes of the initial perturbations were adjusted to be similar to the analysis error. In addition, since MSVs sometimes had an unnatural "peak" value of a particular parameter, the maximum peak size limit was set to three times the analysis error. In other words, if the absolute value of the initial perturbation exceeded three times the standard deviation of the analysis error, the amplitude of the initial perturbation was reduced to equal three times the analysis error. Strictly speaking, this procedure could deform the structure of each singular vector, causing the initial perturbations to grow less. However, without this procedure, the estimated amplitudes of the initial perturbations can be unreasonably small owing to an excessively high peak value in the MSVs. Hence, this criterion for adjusting the amplitudes was introduced, and it was confirmed that the modified initial perturbations could grow in the nonlinear model as steadily as in the linear model. Furthermore, additional modifications, including the adjustment of supersaturation of individual initial fields, the correspondence with the hybrid vertical coordinate used in the forecast model, and the utilization of the variance minimum method (Yamaguchi et al. 2009) for reorganizing initial perturbations, were made. The specifications of the MSVs used for the 2008 B08RDP experiment are listed in Table E-4-2.

A heavy rainfall event that occurred in July 2008 around Beijing was investigated to assess the performance of the ensemble prediction in which MSVs were used for the initial perturbations. Figure E-4-14 shows the observed 6-hour cumulative rainfall on 5 July, whose valid times correspond to FT = 12 (Fig. E-4-14a), FT = 18 (Fig. E-4-14b), and FT = 24 (Fig. E-4-14c) in the forecast model initialized at 12 UTC on the previous day. The singular values, the growth rate in the nonlinear model, and the similarity index between the two for this event are presented in Table E-4-3. Except in the first mode, linear and nonlinear growth rates were in good agreement and highly correlated. Therefore, we inferred from these results that these singular vectors, which were the fastest growing perturbations in the linear model, would also grow in the nonlinear model. Figure E-4-15 shows the horizontal distributions of the vertically integrated energy of the MSVs at both the initial and final times and the forecast result obtained with a nonlinear model, which provided the basic fields for the singular vector calculation. The second and third leading singular vectors had high sensitivity over Beijing, where intense rainfall was observed within 18 hours after the initial time. On the other hand, the sensitivity area of the first singular vector was more localized and did not spread at all over the target region even

at the end of the optimization time. These characteristics of the first singular vector can be attributed to its targeting of comparatively small disturbances associated with convective motions reproduced in the numerical model. Consequently, the first singular vector was more dominated by the moisture term than were the second and third singular vectors.

The ensemble spreads of the subsequent model forecasts evaluated in the common verification area are plotted in Fig. E-4-16. The MSV spreads were improved considerably compared with those in the 2007 experiment, and they were by no means inferior to the WEP results, especially with regard to the amplitude of the ensemble spreads. Figure E-4-17 shows the RMSEs of the control run and the ensemble means obtained by the MSV and WEP methods at FT = 24 for variables at the surface and at 850 hPa against the 4D-Var analysis results. The MSV RMSEs were smaller than both the WEP RMSEs and those of the control forecast for almost all variables. This result also shows the some of the improvements implemented in the 2008 experiment performed effectively.

In consideration of the results of the preliminary experiments (see section E-4-6), the global singular vector (GSV) method was selected as the initial and lateral boundary perturbation method for the B08RDP experiment in 2008. However, the MSV method was useful for mesoscale ensemble forecasting, especially for short-range forecasts of local severe weather.



Fig. E-4-14. 6-hour accumulated rainfall observations valid at (a) 00 UTC, (b) 06 UTC and (c) 12 UTC on 05 July 2008.





Fig. E-4-15. Horizontal distributions of the vertically integrated total energy of MSVs. (a) First SV at the initial time of 12 UTC on 04 July 2008; (b) first SV at the final time of 06 UTC on 05 July 2008; (c) and (e) same as (a) but for the second and third SV, respectively; (d) and (f) same as (b) but for the second and third SV, respectively; (g) sea surface pressure (contours) and windfields (arrows) of the forecast (nonlinear) model at the initial time; (h) same as (g) but at the final time.



Fig. E-4-16. Variation of the ensemble spread evaluated in the common verification region for the experiment using (a) MSVs as the initial perturbations (MSV) and (b) the JMA global EPS perturbations as the initial perturbations (WEP). The initial time was 12 UTC on 04 July 2008.



Fig. E-4-17. RMSEs (FT=24) against analysis fields at (a) the surface and (b) 850 hPa. The initial time was 12 UTC on 04 July 2008.

| | Specification of the Mesoscale SV |
|--------------------------|---|
| Horizontal mesh | $88 \times 76 \ (\Delta x = 40 \ \text{km}, \ \Delta t = 150 \ \text{s}), \ \text{LMN}$ |
| Vertical levels | 40 ($\Delta z = 40 - 1180$ m) |
| Norm | Total Energy Norm (wt = 1.0 , wq = 0.3) |
| Optimization time | 18 hours |
| Moist physics | Large-scale condensation |
| Convection | Moist Convective Adjustment |
| Lanczos iteration | 20 times (using the leading 5 SVs for ensemble prediction) |
| Target area | Common verification area (30.0-45.0°N, 105.0-125.0°E) |
| Others | Adjustment of supersaturation, Variance minimum method |

Table. E-4-2. Specifications of the MSVs for 2008 B08RDP experiment

Table E-4-3. Relationships among singular values (Svals), nonlinear growth (Nlg), and their similarity index (SI) for each MSV. The initial time was 12 UTC on 04 July 2008, and the optimization time was set to 18 hours.

| | Sval | Nlg | SI |
|---|-------|-------|-------|
| 1 | 8.398 | 9.834 | 0.473 |
| 2 | 7.369 | 8.485 | 0.869 |
| 3 | 6.661 | 6.140 | 0.822 |
| 4 | 5.964 | 5.336 | 0.680 |
| 5 | 5.773 | 5.442 | 0.705 |

E-4-4. MBD method

The mesoscale breeding (MBD) method which employs the self-breeding cycle with the JMA nonhydrostatic model using the moist total energy norm by Barkmeijer et al. (2001) was again tested in the 2008 experiment. To ameliorate shortcomings of the MBD method in the 2007 experiment, following modifications were made in 2008.

1) An incremental approach using the low resolution (40 km) breeding cycle was implemented. In the 2007 experiment, self-breeding cycle with a horizontal resolution of 15 km was employed, then bred vectors contained small scale (high wave number) perturbations which may shrink in a short period. We unified horizontal resolutions in the three initial perturbation methods based on the mesoscale model (MSV, MBD and LET) to 40 km. This unification removes small scale perturbations and makes implementation of lateral boundary perturbations easier.

2) The optimization time of the breeding cycle was changed from 12 hours in the 2007 experiment to 6 hours.

3) In the 2007 experiment, breeding cycle was done only twice using global ensemble (WEP) perturbations at 12 UTC of one day before. In the 2008 experiment, 6 hour breeding cycles were performed throughout the experimental period sequentially without reinitialization. Sequential breeding cycle without orthogonalization may yield conversion of bred vectors to a single Lyapnov vector, but this concern was solved by inclusion of the lateral boundary perturbation in the breeding cycles (E-5-2).

4) Lateral boundary perturbations are implemented in the breeding cycles (E-5-2).

5) Removals of water vapor super-saturation were performed for each perturbed member at all breeding cycles' initial conditions.

6) Bred vectors for momentum were properly converted to wind components at each breeding cycle and computation of initial perturbations. In the 2007 MBD method, difference between the momentum and wind in the perturbation was ignored for simplicity.

7) To save computational time, forecasts in breeding cycles were performed with the warm rain process.

As shown in Fig. E-4-18, 6 hour self breeding cycles with a horizontal resolution of 40 km were conducted consecutively. The moist total energy norms were computed by the differences between the control runs and perturbed runs, and the bred perturbations of all prognostic variables except soil temperatures were normalized every 6 hour. The normalization coefficients are determined by the square root of the ratios between the total energy norms of perturbed runs and a standard norm, as described in D-4-4.

Five bred vectors were interpolated and added to the initial condition of the control run (Meso 4D-Var analysis for the Beijing area; E-3-1) as the incremental perturbation to make five positive ensemble members. Additionally, the interpolated bred vectors were subtracted from the initial condition of the control run to make five negative ensemble members. These negative members are almost symmetric to positive members but the ensemble mean is slightly modified after the saturation adjustment.



Fig. E-4-18. Schematic chart of the MBD method in the 2008 experiment.

E-4-5. Local ensemble transform Kalman filter (LET) method

Performance of the initial perturbations produced by NHM-LETKF (Miyoshi and Aranami, 2006) was investigated. Outline of procedures of the ensemble forecast in B08 was as follows (Fig. E-4-19):

- (1) Six hour forecast-analysis cycle with NHM (40kmL40) of 20 members was performed. Surface and upper sounding data that passed the operational QC procedures were assimilated by LETKF. Ensemble mean of assimilation results was recentered around the analyzed fields obtained by Meso-4DVar system at every 12 UTC in the forecast-analysis cycles.
- (2) Ten members were selected by a cluster analysis.
- (3) Due to insufficient observation data, only the perturbations produced by LETKF were used in this project. Initial conditions of ensemble members were produced by adding the perturbations of the selected 10 members from their ensemble mean to the analyzed fields that was obtained by the Meso-4DVar system.



Fig. E-4-19. Schematic illustration of the procedure for producing the initial perturbations.

To establish a procedure for producing proper initial perturbations, several sensitivity experiments on the horizontal resolution of models and observation data were conducted using LETKF. In this section, results of these experiments are explained.

Because ensemble forecast requires large computer resources, number of ensemble forecast, horizontal resolution, domain size, and physical processes should be determined properly. Considering the limited computer resources of MRI in the B08 RDP experiment, we adopted 20 as the ensemble size. As for the horizontal resolution of LETKF and observation data, three preliminary experiments were performed. In these experiments, two horizontal resolutions (grid numbers); 50 km (60×60) or 20 km (150×150), and two kinds of observation dataset; MA data or GA data, were used. MA data and GA data were observation dataset that were used in the operational mesoscale and global analyses of JMA after quality control procedures, respectively. The resolution of mesoscale analysis and global analysis are 20 km and 110 km. Accordingly, the biggest difference between MA data and GA data are the thinning distance of the observation data. Combining of the horizontal resolutions and observation

data, three kinds of experiments; 50km-GA, 50km-MA and 20km-MA, were conducted. To reduce the computation time, the warm rain process was adopted in the forecast-analysis cycles.

Figure E-4-20 shows the time series of the analysis increment and the difference between the analysis and observation. The analysis increment was gradually reduced in all experiments. This indicates that the LETKF data assimilation performed properly. In three days from the start of the forecast-analysis cycle, the increment was greatly reduced and the difference from the previous cycle's increment became also small. This variation of the increment indicates that 3-days pre-run is required to converge the forecast-analysis cycles into a stable level.

The horizontal maps of the ensemble mean and spread of rainfall, sea-level pressure and surface wind are shown in Fig. E-4-21. Because the boundary condition was not perturbed, the spread near the boundary was small. Compared with the spread over the sea, the spread over land was relatively small due to more densely distributed observations over land. This contrast of the spread also indicates that the assimilation with the LETKF was performed properly.

A typhoon was reproduced near Kyushu in all experiments. However, the sharp pressure pattern near the center of the typhoon was not reproduced in 50km-GA, while the typhoon developed most in 20km-MA. As for the ensemble spread, the spread near the center of the typhoon was larger when MA



Fig. E-4-20. Time series of the increments (red lines) and the difference between the analyzed value and assimilation data (black lines).



Fig. E-4-21. (a)-(c) Horizontal distributions of ensemble mean on the rainfall (colored), pressure (contours) and surface wind (vectors). (d)-(f) are the same except for the ensemble spread.

data was used, while the spread at the southern part of the typhoon was larger when GA data was used. The large spread at the southern part of the typhoon in 50km-GA was yielded by the flat pressure pattern of the typhoon. These results indicate that 20km-MA is the best combination for the mesoscale ensemble experiment. Even if the resolution of 50 km was used, MA data improved the analyzed fields. Because the domain of the mesoscale analysis of JMA did not cover that of the MRI's B08RDP experiment, GA data and MA data were assimilated after the redundant data were removed Several implementations and

ameliorations were performed before LETKF was applied to the B08 ensemble experiment. Following is the



Fig. E-4-22. Vertical distributions of the differences of temperature and water vapor mixing ratio of member 000 against the ensemble mean. Smooth pattern in the left panels shows the improvement of the analyzed field without local patches.

list of implementations and ameliorations: (1) rigorous treatments of momentum and pressure (e.g., accurate treatment of air density), (2) implementations of vertical hybrid coordinate, (3) saturation adjustment of the initial field, (4) removal of local patches, (5) cluster analysis procedure for choosing 10 members from 20 members, (6) lateral boundary perturbations in EnKF cycles (see E-5-5), and (7) replacement (re-centering) of the ensemble mean with the analysis fields that were obtained by Meso-4DVar analysis at every 12 UTC.

Local patches originated from LEKF (Ott et al., 2004) were removed by Miyoshi et al. (2007), which was implemented for NHM by Fujita et al. (2009). Figure E-4-22 shows the vertical distributions of analysis increment of temperature and mixing ratio of water vapor from the ensemble mean. Without local patches, the discontinuity at 8th layer was removed.

As for the cluster analysis, the variation of normalized energy in lower-atmosphere was obtained by the following equation (Eq. 4-5-1):

$$E = \int_{20m}^{1.46km} \iint \left\{ \frac{u^2 + v^2 - (u^2 + v^2)_{\min}}{(u^2 + v^2)_{\max} - (u^2 + v^2)_{\min}} + \frac{\theta^2 - \theta^2_{\min}}{\theta^2_{\max} - \theta^2_{\min}} + \frac{q_v^2 - q_v^2_{\min}}{q_v^2_{\max} - q_v^2_{\min}} \right\} dSdz \dots (4-5-1)$$

where u, v, θ and q_v are horizontal wind components, potential temperature and mixing ratio of water vapor, respectively. ()_{min} and ()_{max} are the maximum and minimum values among all ensemble members. The integration was performed over the whole domain in the horizontal and from 20 m to 1.46 km in the vertical. Distances between each cluster and the ensemble mean were evaluated in terms of the variation of normalized energy in the cluster analysis. Selection of ensemble members started with one in the largest group that was the farthest from the ensemble mean.

Next, preliminary experiments on lateral boundary perturbations in forecast-analysis cycles and replacement (re-centering) of ensemble mean with the analyzed field of the Meso-4DVar system are explained. The detailed producing procedure of the boundary perturbations and their detailed impacts are explained in the section E-5-5. As for

the replacement of ensemble mean with the analyzed field of the Meso-4DVar system, the analysis using LETKF could be significantly different from that of Meso-4DVar system after many forecast-analysis cycles because the observation data assimilated by LETKF was fewer than those of Meso-4DVar system and because the LETKF system was in the development stage. Thus, the ensemble mean of LETKF analysis was replaced with the analyzed field of the Meso-4DVar system at every 12 UTC. Figure E-4-23 shows the impact of the perturbation of the boundary condition and of the replacement of ensemble mean. Forecast-analysis cycles were performed for 5 days. When lateral boundary perturbations in forecast-analysis cycles were used, the spread not only near the boundary but also inside of the domain were increased. When the ensemble mean was replaced, the shape of the rainfall region was changed though the value of ensemble spread was not affected much.



Fig. E-4-23. Impacts of the boundary perturbations and of the replacements of the ensemble means with Meso-4DVar analysis fields.





Fig. E-4-24. (a) Ensemble spread and (b) RMSE of 24-hour forecast and initial conditions of the day after.

Namely, the rainfall region extended from west to east when the replacement was performed, while it extended northeastward when the replacement was not conducted. To avoid the separation of analyses of LETKF and Meso-4DVar, the replacement (re-centering) procedure was conducted at every 12UTC in the B08 experiment.

Finally, the improvements of the ensemble spread and of analyzed fields by aforementioned implementations and ameliorations are explained. Figure E-4-24 shows the ensemble spread and RSME of 24-hour forecast against the initial condition before and after implementations and ameliorations. To compute RSME, initial conditions of the day after were used as correct fields because they were produced from the analyzed fields. In this experiment, cluster analysis was common and no perturbation was added to the boundary condition. When implementations and ameliorations were performed, the ensemble spread was increased and the analysis fields because closer to the next day's initial condition. Then, the implemented and ameliorated version of LETKF, which shows better performance, was used in the B08 experiments.

E-4-6. Comparison of the 5 methods¹

a) Comparison prior to the 2008 experiment

Prior to the 2008 experiment, the performance of each of five initial perturbation methods (WEP, GSV, MSV, MBD and LET) was verified by checking their ensemble spreads and the root mean square errors (RMSEs) of the ensemble mean. Lateral boundary perturbations described in E-5 were implemented in all initial perturbation methods when they were verified.

Figure E-4-25 shows the time sequence of the ensemble spreads of surface variables for the 2 days from 3 to 4 July 2008. Spreads by GSV are largest after FT=18, whereas in MSV, the spread of surface precipitation grows most rapidly in the first 6 hours. Spreads of LET were relatively small and their growth was slow.

Figure E-4-26 shows the RMSEs of the control run and of the ensemble means obtained with the five methods at FT=24 for surface variables against the 4D-Var analysis described in E-3-1. RMSEs of the ensemble means are smaller than those of the control run except surface pressure by LET and WEP. RMSEs of GSV were the smallest, followed by those of MSV and MBD.

Figure E-4-27 shows each ROC area skill score (ROCASS) for PoP with thresholds of 0.1, 1, 3, 5, 10, 15, 20, and 25 mm per 6 hours. GSV was best for weak rains of less than 3mm, whereas MBD and MSV were more suitable for moderate or intense rain. The likely reason is that GSV tends to perturb synoptic scale disturbances whereas MBD and MSV tend to perturb mesoscale disturbances, which affect local intense rains.

Considering these results, we selected GSV as the initial perturbation method for the 2008 B08RDP experiment. Specifications of the mesoscale ensemble prediction system of MRI/JMA are listed in Table E-2-1.

¹ Contents of this section are submitted as Saito et al. (2010b).



Fig. E-4-25. Ensemble spreads of surface variables for the 2 days from 3 to 4 July 2008. The units of the left vertical axis are hPa for mean sea level pressure (Psea), m/s for surface (10 m) winds (U and V) and K for 2 m temperature. The units of the right vertical axis are % for surface (2 m) relative humidity (RHs) and mm for the 3 hour precipitation.



Fig. E-4-26. RMSEs of surface variables against the 4D-Var analysis for 3-4 July 2008.



Fig. E-4-27. ROC area skill scores against 6 hour precipitation intensity for 3-4 July 2008.

b) Re-computation of the MBD and LET results

After the 2008 experiment, a bug was found in the MBD experiment. This bug was in the horizontal interpolation from the 40km bred vectors to the 15 km initial perturbation, and it resulted in small horizontal scale noises in the initial conditions (Fig. E-4-28a). The LET method also had a similar bug. In addition, in LET, differences in momentum and wind perturbations had been improperly handled when the initial perturbations were interpolated. Here, we present some results of the re-computation of the two methods after these bugs were fixed.

Figure E-4-29 shows the time evolution of the ensemble spreads of surface variables with MBD and

LET for the 2 days from 3 to 4 July 2008. The MBD spreads are almost the same as in the 2008 experiment (Fig. E-4-25), whereas with LET, the diurnal changes in the spreads of surface relative humidity and temperature became more distinct.

Figure E-4-30 shows the time evolution of the ensemble spreads of the 500 hPa variables for the 2 days from 3 to 4 July 2008. The GSV spreads are largest after FT=18, probably as a result of the lateral boundary perturbation. Figure E-4-31 shows the RMSEs of the control run and of the ensemble means obtained with the five methods at FT=24 for surface variables against the analysis after the bug fix. The RMSEs of MBD are improved compared with those obtained with the MBD and LET methods before the interpolation bug was fixed (Fig. E-4-26). The improvement in LET is clearer and RMSEs of LET are smaller than those of WEP.



Fig. E-4-28. Initial perturbations of sea surface pressure with the MBD method at 12 UTC 4 July. a) Before the bug-fix. b) After bug-fix.



Fig. E-4-29. Ensemble spreads of surface variables for the 2 days from 3 to 4 July 2008 after re-computation. See Fig. E-4-3 for explanation of units.



Fig. E-4-30. Ensemble spreads of variables at 500 hPa level for 3-4 July 2008. Unit of vertical axis is m for height (Z), m/s for meridional wind (V), K for temperature (T) and % for relative humidity (RHs), respectively.



Fig. E-4-31. Same as Fig. E-4-4-but after bug-fix in the MBD and LET methods.

Figure E-4-32 shows the ROC area skill scores (ROCASS) after the bug fix. As seen in Fig. E-4-33, the ROCASS score of MBD improved for intense rains of more than 15 mm/6hours. The improvement in the LET score is more distinct; it improved clearly at all precipitation intensity thresholds.



Fig. E-4-32. Recomputed ROC area skill scores against 6-hour precipitation intensity for 3–4 July 2008 after the bug in the MBD and LET methods was fixed (see Fig. E-4-5).



Fig. E-4-33. ROC area skill scores before and after the bug fix.

c) Comparison of perturbations produced by 4-perturbation methods

In this subsection, the perturbations obtained by 4 perturbation methods are explained.

Before describing the characteristics of each perturbation method, a rainfall band chosen as a target of the comparison is briefly mentioned. Figure E-4-34a shows the horizontal distribution of 6-hour rainfall amount of 'control run' (CNTL) at 00 UTC 5 July 2008. The experiment of CNTL is a prediction from the Meso-4DVar analysis fields without adding any initial perturbation. The initial time of the CNTL was 12 UTC 4 July. When numerical prediction was performed from the initial fields of CNTL, the rainfall band extending from the southwestern China to the Yellow Sea was reproduced by 00 UTC 5 July. A low-pressure system was developed near Beijing in this rainfall band (indicated by a red arrow in Fig. E-4-34a), while the maximum rainfall point of the rainfall band existed at the central part of China (indicated by a blue arrow). Warm and humid southwesterly airflow prevailed on the southern side of the system near the surface (Figs. E-4-34b and E-4-34c). This warm and humid air mass was supplied into the rainfall band while the rainfall band was moving eastward. On the northern side of the system, there was the relatively cold northerly flow that was converged with the southwesterly flow along the band. The low-level convergence of warm humid southwesterly flow and cold northerly flow is an important factor for the development of the rainfall band. At the height of 500 hPa, the northerly airflow of cold and low-equivalent potential temperature (θe) air entered the rainfall band from the north (Figs. E-4-34d and E-4-34e).

In this subsection, we selected one member that brought maximum rainfall amount from each perturbation method, and then examined their characteristics of initial perturbations. Table E-4-4 shows the maximum 6-hour rainfall amount of the following experiments: 'Gsv-gsv', 'Mbd-wep',



Fig. E-4-34. Forecast results of the CNTL at 00 UTC 05 July 2008. (a) Six-hour rainfall distribution, (b) and (c) temperature and equivalent potential temperature near the surface. Panels of (d) and (e) are the same as those of (b) and (c), except for the height of 500 hPa. Contour lines and vectors indicate sea surface pressure and horizontal wind. Red and white contour lines in (b)-(e) indicate 6-hour rainfall region over 1 mm.

'Letkf_wep' and 'Msv-wep'. Here, experiments are referred to as a combination of the names of the perturbation methods used in producing the initial and boundary conditions. For example, the name of 'Msv-wep' means that the initial and boundary perturbations were produced by the Msv method and the Wep method, respectively.

Because the maximum 6-hour rainfalls in the chosen members were larger than that of CNTL (Table E-4-4), the perturbations in the chosen members contain the special features that enhanced the rainfall. Figure E-4-35 is the initial ensemble spread distributions of temperature at the height of 700 hPa. When the initial ensemble spread distributions were compared, we found that 4 experiments can be divided into the following two groups: 'Singular vector group' (Gsv and Msv) and 'Breeding group' (Letkf and Mbd). Namely, the regions of large spread were located near Beijing in 'Gsv-gsv' and

'Msv-wep'. On the other hand, the large spread existed at the southwestern China in 'Letkf-wep' and 'Mbd-wep'. As for the spread of the horizontal wind, the spreads in 'Letkf-wep' and 'Mbd-wep' were relatively larger than those in 'Gsv-gsv' and 'Msv-wep'. These differences between 'Singular vector group' and 'Breeding group' were yielded by the difference of the idea of 4 methods. Namely, in the Gsv method and the Msv method, perturbations that were expected to achieve maximum growth in terms of the specific norms are obtained by referring the CNTL's prediction in the evaluation period. On the other hand, perturbation of the Letkf method and the Mbd method are obtained from the past results of the ensemble forecasts.

Horizontal extents of large spread regions are also different among 4 experiments. The large spread region in 'Msv-wep' was localized around Beijing, and the value of spread was larger than those in other methods. When the spread of 'Letkf-wep' was compared with that of 'Mbd-wep',

Table E-4-4. Maximum 6-hour rainfall and their horizontal position (I_max, J_max) and number of the member.

| ALL | Rain_max | I_max | J_max | Member |
|-----------|----------|-------|-------|--------|
| CNTL | (121.29) | (58) | (75) | - |
| Gsv-gsv | 140.85 | 58 | 75 | 5 |
| Msv-wep | 134.79 | 58 | 75 | 5 |
| Mbd-wep | 155.22 | 57 | 76 | 1 |
| Letkf-wep | 142.22 | 58 | 74 | 5 |



Fig. E-4-35. Initial ensemble spreads of temperature and horizontal wind at the height of 700 hPa at 12 UTC 04 July 2008. (a) Gsv-gsv, (b) Msv-wep, (c) Mbd-wep, (d) Letkf-wep. Red contour lines indicate the regions where 6-hour rainfall exceeds 1 mm at 00 UTC 05.

spread over Japan was smaller than that of 'Mbd-wep'. This small spread over Japan in 'Letkf-wep' was yielded by the assimilation of dense observation data over Japan.

Next, the perturbations obtained by 4 experiments are compared. Figure E-4-36 shows the horizontal distributions of perturbation of temperature and θ e. As mentioned before, the horizontal extent of perturbation in 'Msv-wep' was much smaller than those of other methods. Black circles in Fig. E-4-36 indicate the positions of maximum 6-hour rainfall amount in 4 experiments. They were located at the southwestern part of China, though the low-pressure system existed near Beijing. These maximum 6-hour rainfall points existed in the positive perturbation regions of θ e in 'Gsv-gsv', 'Msv-wep' and 'Letkf-wep'. The low-level positive perturbations are favorable for the development of the rainfall band, because warmer and more humid airflow was supplied into the rainfall band. As for 'Letkf-wep' and 'Mbd-wep', the contrasts of the perturbation were seen along the rain band. For example, the perturbation on the southern side of rainfall band was positive and that on the northern side was negative in 'Letkf-wep'. The horizontal pattern of perturbation in 'Mbd-wep' was similar to that of 'Letkf-wep', however, the sign of perturbations was opposite.

Figures E-4-37 and E-4-38 are the vertical cross sections of the ensemble spreads and of perturbations of temperature and θe , which were along y-direction crossing the point of maximum 6-hour rainfall. In 'Gsv-gsv', the regions of large perturbation were seen mainly below the height of 300 hPa. The positive perturbation of temperature and θe at the lower atmosphere was overlaid with the negative perturbation layers. This overlapping structure of perturbations made the atmospheric condition unstable, and then reinforced the rainfall band. In 'Msv-wep', perturbations existed around the rainfall band. The regions of positive perturbation of temperature and θe extended upward at the position of the rainfall band. The regions of large negative perturbations of temperature and θe existed on the northern side of positive perturbations. This distribution is similar to the structure of



Fig. E-4-36. Perturbation distributions of T (a-d) and θe (e-h) at the height of 1000 hPa at 12 UTC 04 July 2008. (a) and (e) Gsv-gsv, (b) and (f) Msv-wep, (c) and (g) Mbd-wep, (d) and (h) Letkf-wep.

well-developed rainfall band; positive and negative perturbations correspond to the updraft region and the middle-level rear inflow region, respectively. These distributions are also favorable for the development of the rainfall band. In 'Letkf-wep', the positive and negative perturbations existed on the southern and northern side of the band, respectively. These low-level perturbations are also favorable for the development of the band, because warmer and more humid air mass on the southern side of the band enhances the convections and the cold airflow on the northern side intensifies the low-level convergence. In 'Mbd-wep', the perturbation pattern is similar to that in 'Letkf-wep'. However, the positive and negative signs of perturbations are opposite. However, the positive perturbations of temperature and θ e at the lower atmosphere on the northern side of rainfall band were overlaid with the negative perturbation layers. This vertical structure of temperature and θ e, not the horizontal distribution of perturbations at the lower atmosphere, might intensify the convections.



Fig. E-4-37. Vertical cross sections of ensemble spreads of T (a-d) and θe (e-h) at 12 UTC 04 July 2008. (a) and (e) Gsv-gsv, (b) and (f) Msv-wep, (c) and (g) Mbd-wep, . (d) and (h) Letkf-wep. Vertical cross sections were along the y-direction crossing the points of maximum 6-hour rainfall of 00 UTC 05. Red circles at the surface indicate the position of maximum rainfall.

Fig. E-4-38. Same as Fig. E-4-37 except for perturbations of T and θe .

These results indicate that the perturbations of 4 experiments have their own characteristics. The perturbations of 'Msv-wep' are easiest to understand because the perturbations correspond to the updraft and rear inflow regions. However, the airflow that was supplied into the rainfall band on the southern side of the rainfall band was not modified in Msv-wep. On the other hand, a method of 'Breeding group' modifies the low-level inflow. Thus, the combination of the Msv method and a method of 'Breeding group' should be investigated because it has a potential to be an effective perturbation for mesoscale ensemble predictions.