1. Introduction

Numerical weather prediction (NWP) models as well as climate prediction models are constructed on the basis of deterministic governing equations that describe dynamical and physical processes that take place in the real atmosphere. Because the strong nonlinearity that exists in the governing equations produces chaotic motions, Lorenz (1963) remarked that numerical prediction of atmospheric motions eventually loses its skill after a certain forecasting period because of the inevitable growth of initial observational errors. Such non-deterministic behavior is the most important characteristic of chaotic motion. The inability of a NWP model to represent real atmospheric motions perfectly also reduces the predictive skill of numerical weather forecasts. In fact, the predictable period for synoptic-scale disturbances, such as mid-latitude low-pressure systems, is limited to several days, even in a state-of-the-art NWP system, and it is very hard to extend the predictable limit longer than two weeks with a deterministic prediction starting from a single initial condition.

Use of an ensemble prediction has been proposed as a way to extend the predictable limit of two weeks associated with deterministic prediction. The tactics of an ensemble prediction can be summarized as follows: generate slightly different initial conditions, the variability of which reflects the estimated observational errors; perform a model integration for each ensemble member, starting from the corresponding initial condition; and construct ensemble statistics from the predictions of all members. These statistics can provide valuable additional information for the prediction of atmospheric motions. The first statistic of the ensemble prediction is the ensemble mean, which characterizes the average scenario of the prediction. The second statistic is the ensemble spread, which indicates the uncertainty of the prediction and is a measure of the chaotic behavior of atmospheric motions. Finally, the probability distribution function (PDF) of the predicted variables, constructed from all ensemble members, sometimes provides further information: if the PDF has a bimodal distribution, for example, the ensemble prediction implies the possibility of dual prediction scenarios.

In an ensemble prediction, the most important issue is how to generate slightly different perturbations at the initial time. Although an infinite number of initial perturbations would be needed for the ensemble prediction to fully represent the distribution of an initial observational error, for practical reasons the ensemble size is limited to on the order of 100 because of computational resource limitations. Since the 1980’s, NWP centers around the world, including the Japan Meteorological Agency (JMA), have started addressing a technical problem: establishing an operational long-range forecasting system by development of a practical ensemble prediction method that represents the distribution of observational errors with an affordable number of initial perturbations.

During an earlier period of development, an attempt was made to use a Monte Carlo method to add randomly generated perturbations to the analysis field. However, this attempt was found to be in vain because most of these perturbations have large projections on gravity wave modes, and the contribution to modes related to synoptic eddies is very limited. Thus, an infeasibly large number of initial perturbations would be required for the Monte Carlo method to obtain an appropriate ensemble spread.

Another convenient ensemble forecasting method is the so-called LAF (lagged average forecast) method. In this method, the ensemble is composed of deterministic forecasts that start at different initial times. Here, the addition of perturbations to the initialized fields is not required, and a single model run from each initial time suffices for constructing a LAF ensemble. However, a concern with the LAF method is that ensemble members that start from earlier initial times always degrade the quality of the prediction. This issue is crucial for a prediction with a lead time shorter than a few weeks, because the interval of the neighboring initial times is not so short (commonly 6 hours); the interval is determined by the period of the operational global analysis cycle of NWP centers. Moreover, it is not assured that the observational error field at the initial time is suitably represented by the forecasts of LAF ensemble members starting from earlier initial times.

To efficiently represent the initial observational error with a finite number of initial perturbations, the following two approaches for generating initial perturbations based on dynamical considerations have been suggested in recent years: the singular vectors (SV) method and the breeding of growing mode (BGM) method. For these methods, it is expected that the initial spread among ensemble prediction members will be large enough to represent observational errors. The SV method and the BGM method were designed and have been used for operational extended-range (up to about two weeks) forecasts since 1992 by the European Center for Medium-Range Forecasts (ECMWF) and the National Meteorological Center in the United States (NMC, now known as National Centers for Environmental Prediction: NCEP), respectively.

In the SV method, initial perturbations are composed of the fastest-growing modes over a specified short time interval (which is typically shorter than 48 hours) based on a tangent linear model, which is obtained by locally linearizing the original nonlinear NWP model, and its adjoint model (e.g., Buizza *et al*., 1993). The modes are obtained by singular value decomposition (SVD) of the so-called error matrix describing the linear evolution of initial perturbations over the specified time interval. The associated singular value gives the rate of linear amplification of the singular vector over the specified period.

In the SV method, it should be noted that the initial perturbation specified by the singular vector does not necessarily show the largest growth in the original NWP model during a time interval of several days because of the emergence of nonlinearity of the initial perturbation during its growth. Moreover, because the original NWP model has a huge number of degrees of freedom and includes various dynamical and physical processes that interact with each other, it requires several practical compromises in using the tangent linear model: omission of several physical processes in the model; selection of a limited number of variables to construct the error matrix; and use of a large-scale model that neglects motions on a scale smaller than synoptic eddies by truncating the spatial resolution of the original NWP model, thereby reducing the size of the error matrix.

In spite of these practical issues, the SV method brought about a remarkable improvement compared to the LAF method with respect to the spread-skill relationship, in which a larger ensemble spread corresponds to an ensemble mean forecast with less skill. The SV method has thus been recognized as one of the most promising ensemble techniques for medium-range ensemble forecasts. Today, the SV method is used in medium-range ensemble forecasts at the ECMWF and the JMA, and also in ensemble typhoon forecasts and meso-scale severe weather forecasts (e.g., Yamaguchi *et al*., 2009).

In the BGM method, the perturbations used to construct the ensemble members are given by so-called bred vectors, which are disturbances obtained by integrating the NWP model from small arbitrary initial perturbations over a long time interval before the initial time of forecast. In the course of the long integration, perturbations are rescaled over short cycles, called BGM cycles, whose interval is typically 12 hours, and integrated again. At the end of the BGM cycles, all perturbations are scaled to a desirable amplitude. These scaled perturbations make up the initial perturbations for the ensemble forecasts (Toth and Kalney, 1993; Legras and Vautard, 1995). More specifically, in each BGM cycle, integration of the NWP model over a short period of time is performed from an initial condition consisting of the superposition of a perturbation onto the analysis field (perturbed run). A mature perturbation is then obtained by subtracting the analysis field from the forecast of the perturbed run at the end of the BGM cycle. The magnitude of the mature perturbation is evaluated with respect to a given norm, such as an area-averaged variance at a geopotential height of 500 hPa over a specified region, or the total energy norm of the perturbation. The mature perturbation is rescaled to a specified magnitude based on the norm and is used as the initial perturbation for the next BGM cycle. After many BGM cycles over a long enough time interval, an optimal initial perturbation is obtained. The optimal initial perturbation is called a bred mode; it is the perturbation with the largest growth rate over the previous time interval. The bred modes correspond to the local Lyapunov vectors when a perfect model assumption is adopted by replacing the analysis with the forecast (control run), starting from the initial condition without any perturbation at the end of each BGM cycle. The tangent linear model is used there to evaluate the evolution of the perturbation over time.

Compared with SV methods, the BGM method has the advantage of using the original nonlinear NWP model to evaluate the evolution of perturbations over time. However, the BGM method has an additional computational cost associated with the multiple BGM cycles required to generate the initial perturbations for conducting the ensemble forecast. The NCEP has confirmed that the BGM method has the ability to improve the forecast skill of medium-range predictions (Toth and Kalney, 1997). The NECP and JMA now use the BGM method operationally for medium-range and seasonal ensemble forecasts.

The JMA uses the BGM method for operational one-month and seasonal ensemble forecasts and uses the SV method for operational one-week and typhoon ensemble forecasts.

We have recently constructed a new global atmospheric ensemble forecasting system that uses the BGM method [MRI-EPS (BGM)] on the supercomputing system of the MRI. The MRI-EPS facilitates MRI research activities concerned with climate variation and the predictability of atmospheric motions by conducting medium range or sub-seasonal range ensemble forecast experiments. This report provides an outline of the MRI-EPS, directions for how to use the system, and a description of the characteristics of the bred vectors obtained with the MRI-EPS. This article also presents results of ensemble forecast experiments conducted with the MRI-EPS for the prediction of a stratospheric sudden warming (SSW) event.