2. Outline of the MRI-EPS

The MRI-EPS includes BGM cycle system running on the MRI supercomputer system, which is developed by using the operational one-month forecasting system by the Climate Prediction Division (CPD) of the JMA (Kyoda, 2000, 2006), hereafter referred to as the JMA-BGM, as reference. Although the basic specifications of the BGM cycle in the MRI-EPS and JMA-BGM are almost the same, the MRI-EPS is able to generate perturbations in the southern hemisphere (SH), which is not represented in the JMA-BGM. This capability facilitates predictability studies for SH atmospheric motions, such as the SH SSW that occurred in 2002. The following is an outline of the MRI-EPS.

2.1 NH BGM cycle

Figure 1 illustrates the BGM cycle of the MRI-EPS for the northern hemisphere (north of 20°N, hereafter referred to as NH). The cycle time interval is 12 hours, and the adopted norm of the perturbation is the area-averaged variance of the 500-hPa height (Z500) in the NH. At the start of the BGM cycle (00 or 12 UTC), two different initial fields are prepared: one is the control initial condition provided by the analysis field (black circle in Figure 1), and the other is a perturbed initial condition produced by the superposition of a perturbation on the analysis field (colored circle). Then the NWP model is integrated for 12 hours, starting from both initial conditions. These runs are called the control run and perturbed run; they are indicated by the black and blue arrows, respectively, in Figure 1. The difference field *D* between the two forecasts after 12 hours (denoted by the thick dotted arrows) is regarded as a mature perturbation over the course of the BGM cycle. When the perturbation is determined by the difference of the perturbation run, but not from the

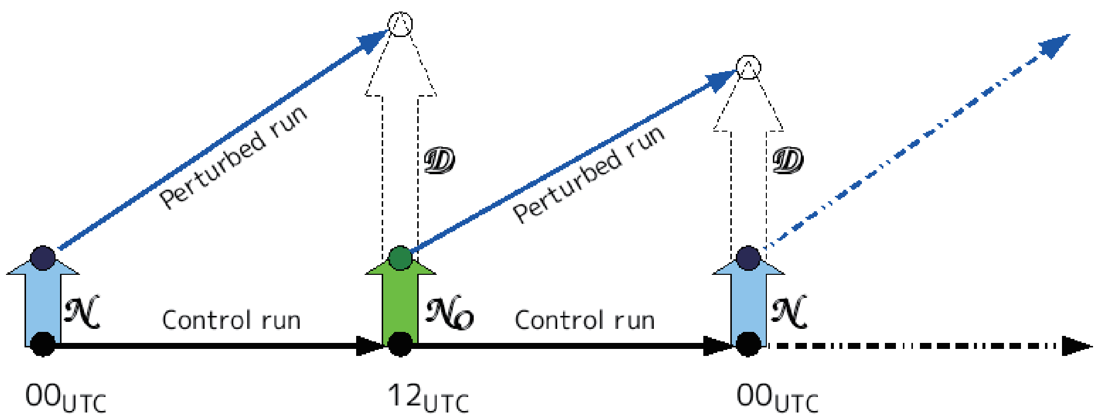

Figure 1: Conceptual diagram of the BGM cycle in the MRI-EPS.

analysis, such a BGM method is called a self-breeding. This type of BGM cycle is adopted in the MRI-EPS and has the desirable characteristic of removing the influence of model bias, which is included in both the perturbed and control runs, on the evaluation of the instability mode of the model.

The difference field D is normalized ("scaled down") so that the norm of D_{Z500} (Z500 difference field) becomes specified value and is subsequently used for an initial perturbation in the next BGM cycle (the normalized perturbation, denoted as N, is shown by the thick colored arrows in Figure 1). Here, the rescaling is carried out so that the area-averaged variance of D_{Z500} in the NH has a magnitude equal to 14.5% of the climatological variance of Z500, which depends on the seasonal cycle. Although the norm is evaluated by the Z500 field, there is rescaling of other forecast variables, such as the height field, horizontal winds, temperature, specific humidity at 23 pressure levels, and surface pressure. The perturbation is normalized by multiplying by the same rescaling factor used to rescale the Z500 field[1]. Furthermore, in the region south of 20°N, the magnitude of the normalized perturbation N is reduced exponentially as follows:

$$N(\varphi) = N_{ext}(\varphi)\ \exp(-(\varphi - 20)^2/50) \qquad (1)$$

where φ is the latitude in degrees and $N_{ext}(\varphi)$ is a normalized perturbation in the extra-NH region ($-90 < \varphi < 20$). The perturbed run in the next BGM cycle then starts from an initial condition consisting of the perturbation N, tapered in the extra-NH region by Eq. (1), and the analysis field.

In the MRI-EPS, the initial NH perturbation is obtained every 12 hours with the foregoing BGM cycle. To obtain several initial perturbations to carry out ensemble forecasts with multiple members, similar BGM cycles that start from several initial perturbed fields are conducted simultaneously. In the MRI-EPS, normalized perturbations are (quasi-)orthogonalized with each other at 12UTC by using a method similar to Gram-Schmidt[2], in accord with the JMA-BGM. The obtained orthonormalized perturbations No are shown by thick green arrows in Figure 1. Obtained modes are numbered according to the order of the BGM cycle series. That is, the first mode (also referred to as mode #1) corresponds to the first BGM cycle series and is free from the orthogonalization. In contrast, perturbation of mode #n ($n \geqq 2$) is derived from the n-th BGM cycle series and is orthogonal to perturbations of mode #1, #2, . . . , and #n–1.

To obtain a converged bred mode at the initial time of forecast, we have to conduct a very large number of BGM cycles prior to the initial time. The MRI-EPS aims at rapid convergence of the

[1] In the stratosphere (above 100 hPa height), the factor is multiplied by p/100 at pressure p [hPa] to reduce the amplitude of the perturbation. Otherwise, the stratospheric perturbation has a much larger amplitude compared to the estimated analysis error.

[2] A quasi-orthogonal vector y, obtained from the vector x, to the other vectors $\{x_i\}$ is expressed by $y = x - a\ \Sigma_i < x_i\ , x > x_i$, where a is called the orthogonalization ratio (0 < a < 1, set to 0.75 in the MRI-BGM).

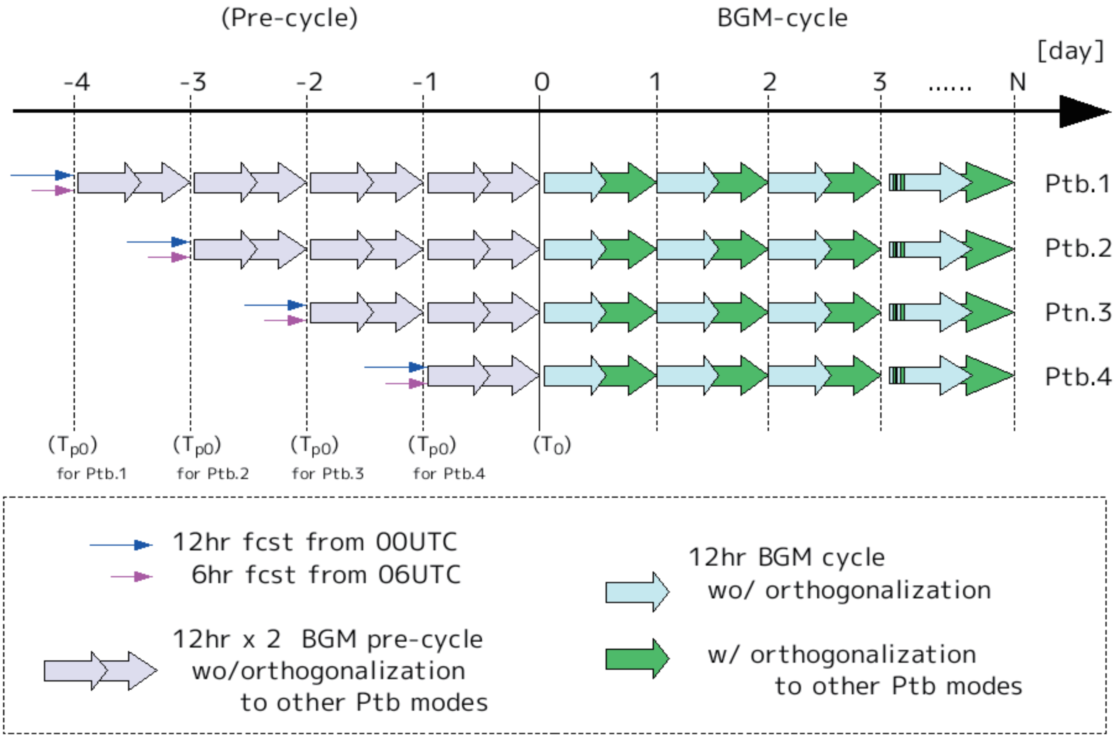

Figure 2: Flow image of pre-cycle and the following BGM cycle

bred vector, and a simple additional pre-cycle is devised by using the concept of the LAF method, as shown in Figure 2. For example, the initial perturbation necessary to initiate a pre-cycle starting from 12 UTC in one day (denoted by T_{p0} in Figure 2) is given by the difference field obtained from the following two control runs without initial perturbations: one control run starts at an initial time 6 hours prior to T_{p0} (i.e., 06 UTC); the other starts 12 hours prior to T_{p0} (i.e., 00 UTC). These two runs are denoted by purple and blue arrows, respectively, in Figure 2. The normalized difference field between the two runs at T_{p0} is then regarded as the first perturbation for the pre-cycle. We subsequently repeat the pre-cycle, including the rescaling procedure every 12 hours, as in the BGM cycle, until the starting time of the BGM cycle (T_0), shown by thick gray arrows in Figure 2.

To obtain several initial perturbations, we have to proceed through several series of pre-cycles, starting every 12 UTC several days prior to T_0. For instance, if we need four perturbations, we proceed through four different series of pre-cycles, starting from 12 UTC on each of the four days prior to T_0. In the pre-cycle, orthogonalization of perturbations is not conducted. Thus, the perturbations obtained from each pre-cycle series are independent of each other. After obtaining the required number of perturbations with the pre-cycles, the main BGM cycle (denoted by the light and dark green arrows in Figure 2) starts at time T_0. From our experience, perturbations generated in the BGM cycle of the MRI-EPS, after the above-mentioned pre-cycles have been conducted, acquire a well-defined spatial structure, similar to synoptic-scale disturbances over a bred cycle of several weeks. We can therefore use the MRI-EPS to proceed with subsequent ensemble prediction experiments.

2.2 Tropical BGM cycle

In the extra-tropical atmosphere, the perturbations that grow and become dominant are related to the baroclinic instability of westerly jets in the troposphere. Such unstable baroclinic modes are basically characterized by geostrophic modes, the temporal evolution of which is well represented by geopotential height variations in the troposphere. Hence, we have used the area-averaged variance of Z500 to define the norm used to evaluate the amplitude of growing perturbations in the NH BGM cycle. In contrast, in the tropical region, atmospheric modes with divergent motions dominate over geostrophic modes (Rossby mode). Hence, another type of norm should be used to generate growing perturbations appropriate for ensemble predictions of the tropical atmosphere. According to Chikamoto *et al*. (2007), an area-averaged variance of the 200 hPa velocity potential (hereafter χ200) over the tropics from 20°S to 20°N is appropriate for the norm of the perturbations of the BGM cycle in the tropics (TR BGM cycle). Moreover, the normalized perturbation during such a tropical BGM cycle is exponentially damped poleward in the extra-tropics, as is the case for the NH perturbation described by Eq. (1).

According to Chikamoto *et al.* (2007), the time interval of each TR BGM cycle is set to 24 hours to extract slowly growing, large-scale modes of the tropical atmosphere (whereas the time interval of the NH BGM cycle is 12 hours). Both normalization and orthogonalization of the mature perturbation are done at the end of every TR BGM cycle. The rescaling factor is specified, as in the TR BGM cycle of the JMA-BGM system, such that the norm of the perturbation becomes 20% of the climatological variance of χ200.

We have confirmed that initial perturbations in the tropics obtained by these parameter settings of the TR BGM cycle grow continuously over a forecast period of more than five days in the MRI-EPS forecast experiments. We therefore think that the obtained tropical bred modes are suitable for use as initial perturbations in ensemble forecast experiments for the tropical atmosphere.

The developed TR BGM cycle in the MRI-EPS does not include a pre-cycle like the pre-cycle used in the NH BGM cycle; instead, it starts from initial perturbations given by the previously obtained NH bred modes[3]. Although the amplitude of the NH bred mode is rather small in the tropical region because of the artificial damping by Eq. (1), we have confirmed that these tapered perturbations also grow with an e-folding time of about 10 days. Hence, the computed tropical bred modes have converged enough over BGM cycles of several weeks to comprise the initial perturbation for the ensemble forecast experiment in the tropical atmosphere. There are only two tropical bred modes available in the MRI-EPS because the higher bred modes in the tropics have

[3] Or by TR bred modes previously calculated by another TR BGM cycle experiment, if they exist.

spatio-temporal characteristics similar to these two bred modes.

2.3 SH BGM cycle

One of the important merits of the newly developed MRI-EPS is the inclusion of initial perturbations in the southern hemisphere (SH); such perturbations are not used in the operational monthly and seasonal EPSs of the JMA. The exclusion of SH perturbations in these JMA operational EPSs is, of course, due to the practical consideration that the primary target region for the JMA weather forecasts is the NH, including Japan, but not the SH. However, in order to conduct ensemble forecast experiments for the global atmosphere (including the SH atmosphere), we have to prepare initial perturbations in the SH. In particular, these perturbations are indispensable for exploring the predictability of the predominant atmospheric motions in the SH, such as the SH SSW and the southern annular mode (SAM).

The MRI-EPS system is capable of simulating a SH BGM cycle, a BGM cycle for the SH (south of 20°S). The parameter values and procedures, such as the norm, time interval of each cycle, and the rescaling and orthogonalization method are determined in the way described in Section 2.1 for both the SH and NH BGM cycles. We discuss the effects of the newly obtained SH bred modes on the forecast skill of the ensemble predictions for the SH atmosphere in Chapter 4.

2.4 Forecast model and ensemble forecast experiments

The atmospheric forecast model used in the MRI-EPS is the JMA atmospheric global spectral model (GSM), which has been used in the operational one-month ensemble forecast system as of March 2013. This is a global hydrostatic spectral primitive model with a TL159 reduced Gaussian horizontal grid; the grid size is about 120 km around the equator and becomes coarser toward the poles. The model includes 60 vertical layers arranged up to 0.1 hPa based on the η (σ-p hybrid) coordinate system. A two-time-level, semi-Lagrangian integration scheme has been adopted to carry out the integration over time efficiently.

The model includes several schemes that parameterize processes representing radiative interactions with atmospheric molecules, clouds and aerosol particles, cloud schemes that predict cloud water content and diagnose cloud amount, a mass-flux type cumulus convection scheme, and a planetary boundary layer scheme that evaluates turbulence in the lower tropospheric near the surface. Heat and hydrological balances associated with these processes are calculated every time step during integration of the model (note that the radiation scheme is run every several time steps). Moreover, the model includes processes that generate and break orographic gravity waves, which are not explicitly resolved in the model. To specify the surface boundary condition of the atmospheric model, a SiB type land surface scheme is also included in the model. Observed sea surface temperature (SST) anomalies at the initial time are kept constant over the forecast period; they are added with the climatological SST to specify the surface boundary conditions over the sea. The climatological sea-ice distribution is specified during the forecast period. Refer to the JMA web page[4] for details of the atmospheric and land surface model.

Ensemble forecast experiments with the MRI-EPS are performed using the global atmospheric model described above, with initial perturbations generated by the BGM cycle system of the MRI-EPS according to the following procedure. First, the initial conditions for forecast experiments are specified by obtaining initial perturbations as well as analysis (or climatological) data for the atmosphere, land, and sea surface. The initial time of the model integration is set to 12 UTC on a given day. The MRI-EPS can specify initial perturbations for each region of the NH, TR, and SH, as described in Chapter 2, and for the entire globe as well by using a combination of the three perturbations. For example, if the focus of interest is on the northern hemisphere, it is appropriate to combine the NH and TR perturbations without the SH perturbation (refer also to the last paragraph of Chapter 4). Perturbed initial conditions for the MRI-EPS are created by the analysis with addition (ensemble member is referred to as a name including the symbol "p") or subtraction (member name including the symbol "m") of perturbations generated with the BGM system. Hence, taking account of the control forecast without an initial perturbation, the ensemble size (number of members) of the MRI-EPS becomes 2N + 1, where N is the number of generated bred modes. Table 1 explains the naming rules for the ensemble members of the MRI-EPS. Since NH and SH perturbations are generated by using the same configuration of the BGM cycle system, these perturbations are named on the basis of the number of the bred mode with the symbols "p" or "m"; the names also specify the names of the ensemble members. In contrast, because there are only two generated TR modes, the first and the second TR bred modes are used to construct the initial perturbations for the even- and odd-numbered MRI-EPS ensemble members, respectively, in accord with the JMA operational EPS system.

Table 1: Rules for naming MRI-EPS ensemble members.

Member name	M00	M01p	M01m	M02p	M02m	M03p	M03m	M04p	M04m	.....
Ptb.mode (NH)	—	01p	01m	02p	02m	03p	03m	04p	04m	.....
Ptb.mode (TR)	—	01p	01m	02p	02m	01p	01m	02p	02m	.....
Ptb.mode (SH)	—	01p	01m	02p	02m	03p	03m	04p	04m	.....

4 http://www.jma.go.jp/jma/jma-eng/jma-center/nwp/outline2013-nwp/pdf//outline2013_03.pdf (at the time of writing)

Second, the model integration is carried out starting from the initial conditions specified by the foregoing procedure. During the integration, the land surface conditions are predicted by the land surface model, the SST anomaly is kept constant, and the distribution of sea ice is specified by a daily climatology, as in the BGM cycle. When a standard setting of the MRI-EPS system has been chosen, forecast data such as altitude, temperature, and wind speeds are stored at six-hour intervals on latitude-longitude grids with a 1.25-degree spacing at the specified pressure levels, in a so-called pressure-level file.