Medium-range Numerical Weather Prediction by a Simple Barotropic Model with Parameterized Baroclinic Instability

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1. Introduction

The extended-range numerical weather prediction has been hampered by the predictability barrier caused by the chaotic nature of large-scale turbulent flow. The initial error tends to grow rapidly due to the instability included within the model. If we can construct a new type of prediction model which is simple enough to exclude the major dynamical instability within the model, can we expect to extend the prediction limit beyond the prediction barrier of chaos?

The purpose of this study is to attempt a medium-range numerical weather prediction, using a fully-nonlinear primitive equation model which is constructed as simple as possible. This study is an extension of the work by Tanaka et al. (1996) to the study of atmospheric predictability. It is demonstrated by our former studies that this model can simulate realistic atmospheric blocking which often persists more than two weeks.

2. Model description

The model description is detailed in Tanaka (1996). A system of primitive equations with a spherical coordinate may be represented in terms of the 3-D spectral expansion coefficients:

$$\frac{dw_i}{d\tau} + i\sigma_i w_i = -i\sum_{jk} r_{ijk} w_j w_k + f_i, \quad i = 1,2,3,\ldots \quad (1)$$

where τ is a dimensionless time, the symbol σ_i denotes the eigenfrequency of the normal mode at a resting atmosphere, and r_{ijk} is the interaction coefficient for nonlinear wave-wave interactions. In this study, we attempt to construct a spectral barotropic model, using only the barotropic components of w_i retaining only the low-frequency Rossby mode basis. The spectral truncation of the model corresponds to R20. In this study, we consider the following physical processes:

$$f_i = (BC)_i + (TF)_i + (DF)_i + (DZ)_i + (DE)_i, \quad (2)$$

where $(BC)_i$ represents the baroclinic instability, $(TF)_i$ the topographic forcing,$(DF)_i$ the biharmonic diffusion, $(DZ)_i$ the zonal surface stress, and $(DE)_i$ the Ekman pumping for eddies.

3. Result

The model is first integrated as a control run for 1000 days with the standard parameter set. The initial axisymmetric flow is soon saturated by disturbances after about 20 days of time integration. Next, a separated experiment run is performed by superimposing a small error on the day 101. The error energy has a uniform spectral distribution with a random phase in complex Fourier expansion coefficients. The total amount of the imposed error is 0.25×10^5 J/m^2. Since the total energy of the barotropic atmosphere is about the order of 15.0×10^5J/m^2, the error energy is approximately 2% of the total energy.

Figure 1 illustrates the geopotential height error superimposed on day 101. The magnitude of the height error reaches 30 m. The experiment run, containing a small initial error, is integrated for 100 days from 101 to 200 days. The prediction error is measured by the global error energy defined by the difference of the spectral coefficients of the control run $\bar{w}_i$ and the experiment run w_i:

$$E_i = \frac{1}{2} p_s h_0 |w_i - \bar{w}_i|^2 \quad (3)$$

where, p_s and h_0 denote surface pressure and equivalent depth of the reference state. The total error energy is evaluated as the sum of E_i over all waves.

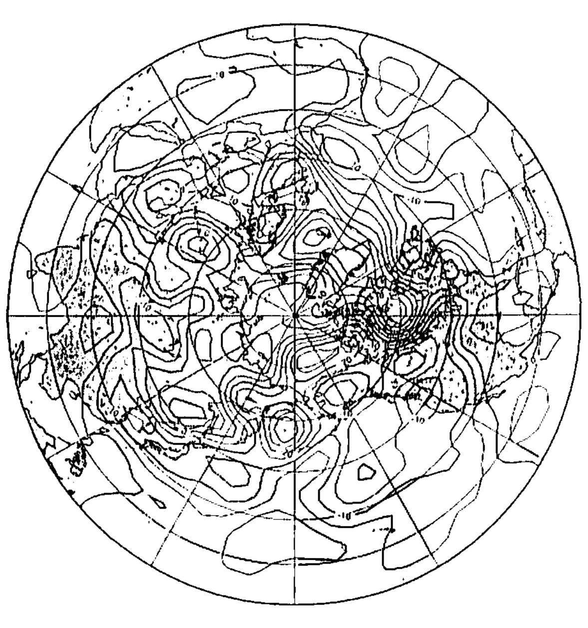
Figure 2 illustrates the error growth with respect to time. The initial error superimposed on the day 101 grows very slowly during the first 30 days and grows rapidly after the day 130. For comparison, a forecast error by persistency is plotted with dashed line started from the day 101. The error energy reaches to the first maximum after 2 days and then oscillates with its period about 3 days. The detailed investigation shows that the high-frequency oscillation in the error energy is associated with synoptic disturbances over the zonal wavenumbers 5 to 10. The predictability by the persistency forecast may be regarded as about 2 days, reaching the error energy at 3.0× $10^5 J/m^2$. Using this value as the criterion for the predictability limit, we may assess that the predictability of our barotropic model reaches more than 30 days. The error energy does not grow for the first 10 days. The e-folding time of the error growth is somewhere around 20 days. The result indeed is astonishing in reference to our knowledge of the ordinary numerical weather prediction.

Figure 3 illustrates the geopotential height difference between the control and the experiment runs on day 111. The contour interval is 5 m for the difference. The maximum error is of the order 60 m; just double of the initial state even 10 days after the beginning of the time integration.

4. Discussion

It has long been said that the deterministic atmospheric predictability may be of the order of two weeks. The deterministic medium-range weather forecasting is believed to be impossible beyond the prediction barrier established by the theory of chaos. The present study, however, made an important break through in the study of the predictability limit. Since the major source of the prediction error is brought by the baroclinic instability of synoptic disturbances, a model which has parameterized the baroclinic instability contains no relevant source of error energy. The result of this study demonstrates that the error growth is controlled by the dynamical instability within the model. Since our barotropic model contains at most a week barotropic instability, the initial error grows only weekly so that the meaningful prediction can be extended even for 30 days after the initial state. Since the high sensitivity to the initial error in prediction has been removed in this model, we may expect a meaningful deterministic medium-range forecast by a further improvement of the model accuracy.

Fig. 1 Geopotential height error (5 m interval) superimposed on day 101.



References

Tanaka, H.L., K. Kimura, and T. Yasunari, 1996: Time spectral analysis for the natural variability of the barotropic model atmosphere with annual cycle. *J. Meteor. Soc. Japan.*, **74**, (in press).

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Fig. 2 Time series of error energy for the experiment run (solid line) and presistency forecast (dashed line).

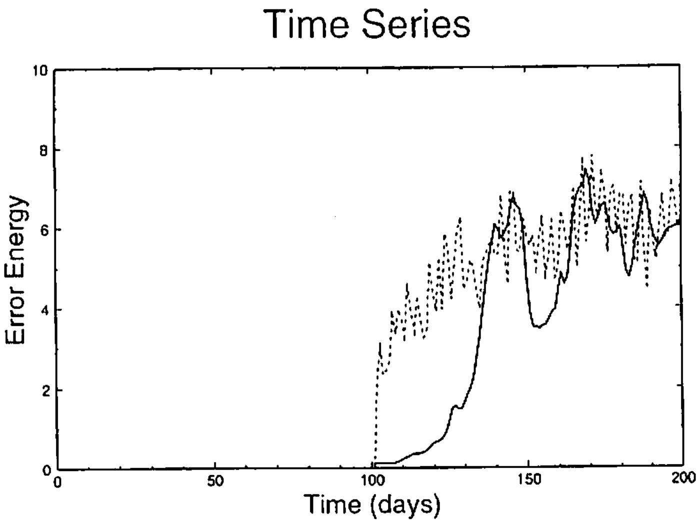

Fig. 3 Geopotential height difference between the control and experiment runs on day 111.