A Study of Predictability for the Barotropic Component of the Atmosphere

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1. Introduction

The predictability might be extended to some extent by predicting averaged quantities. For instance, the spatial averaging results in increasing predictability in planetary waves than in boundary layer turbulence. One may construct a one month prediction model which predicts 5-day or 10-day mean field by separating slowly moving low-frequency variability from unpredictable high-frequency eddies.

One of the viable approaches which has not been pursued yet to extend the predictability is to predict the vertical mean of the state variables. In general, the low-frequency variabilities, such as blocking phenomenon and PNA-like teleconnections, are characterized by their barotropic structures. The barotropic-baroclinic interaction appears to be the key issue.

The purpose of this study is to examine the predictability of the barotropic component of the atmosphere by conducting perfect-twin model experiments. The model sensitivity to the initial error is examined for certain blocking events in the real and model atmospheres using the barotropic model.

We note that any random observational error contained in the state variables can be substantially reduced for the vertical mean in proportion to the square root of the number of data samples. Hence, predicting the vertical mean states can be a viable approach to the medium-range weather prediction.

2. Model description

The model description is detailed in Tanaka (1998). A system of primitive equations with a spherical coordinate may be represented in terms of the 3-D spectral expansion coefficients:

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

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. 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, the external forcing f_i is evaluated as the residual of (1) using the operational global analysis data provided by the Japan Meteorological Agency (GANAL/JMA) for January to March, 1997. Given the external forcing, the model equation (1) is integrated starting from initial states of w_i on certain days during the analysis period. Since the perfect value of f_i is provided when τ and w_i are given, the run is referred to as a controlled-perfect model run for the real atmosphere. We then superimpose an initial error for the controlled-perfect model run (see Tanaka and Nohara, 1997) to conduct a controlled perfect-twin model experiment for the real atmosphere.

3. Result

The barotropic component of geopotential height in the Northern Hemisphere was presented for 1200Z on 7 March, 11 March, and 14 March in 1997. It is found that the overall features of westerly jet, planetary waves, blocking, and synoptic waves in the general circulation are contained in the barotropic component. Since the barotropic component contains overall features of the low-frequency variability, predicting this component alone is still meaningful for the medium range weather forecasting.

Given the time series of the external forcing evaluated from observations, the model equation (1) is integrated from the initial data at 1200Z 7 March 1997. According to the result of the controlled perfect model run, the life-cycle of the pronounced blocking in the real atmosphere is perfectly reproduced by this model. In fact, we demonstrated that the time behavior of the real atmosphere can be reproduced even for the entire three months of the analysis period starting from the initial value on 1 January 1997. The model atmosphere behaves almost exactly as the real atmosphere for three months when the perfect external forcing is provided.

In order to examine the growth of initial error in the controlled perfect model run, we integrate the same identical twin model giving a noise on the initial data. The run is referred to as a controlled perfect-twin model experiment. Superimposed the white noise on the initial data, the model equation (1) is integrated again from the initial date on 1200Z 7 March, 1997. The energy level of the white noise is comparable to that of short waves at zonal wavenumber 15. The noise is referred to as 10% noise since the total error energy is about 10% of the total eddy energy of the barotropic atmosphere. The result of the geopotential height is presented for the controlled perfect-twin model experiment. As in the real atmosphere, zonal flow is replaced by meridional flow on 11 March and the pronounced blocking appears on 14 March. The result demonstrates that the blocking may be predictable one week in advance even if the initial data contain 100% error for the short waves as long as the model error is sufficiently small.

The model sensitivity to the initial noise is further examined for various amount of initial white noise superimposed on 1 January 1997. The experiments are conducted (a) for 10% white noise as mentioned above, (b) for 1%, (c) for 0.1%, and (d) for 0.01%, respectively. The result shows an important message on the relation between the model predictability and the initial noise. It is found that the predictability increases 10 days when the initial error energy decreases to 1/10. Namely, the predictability limit is inversely proportional to the logarithm of the error energy level. As mentioned before, the predictability limit exceeds three month when no error is superimposed in the controlled perfect-twin model.

4. Conclusion

It has long been stated that the deterministic atmospheric predictability may be of the order of two weeks due to chaotic nature of nonlinear fluid systems. Even if we can have a perfect prediction model, a deterministic medium-range weather forecasting has been pessimistic beyond the chaotic barrier of two weeks (see Chen, 1989). However, we demonstrated this is not the case for predicting vertical averaged quantities.

Given the barotropic-baroclinic interactions obtained from the data analysis of the real atmosphere, the model is integrated as an initial value problem. It is shown that the model correctly simulates the entire life-cycle of the blocking event in the real atmosphere. We found in fact that the present model accurately follows the trajectory of the real atmosphere not just for a week but for three months after the initial date as long as the correct external forcing is provided. The result may be non-trivial in reference to our current understanding of chaos. Since the model should contain some noise which is bigger than the butterfly effect discussed by Lorenz, the noise ought to amplify rapidly to abandon the forecast according to the theory of chaos. However, what we have found from this experiment is that the initial value problem perfectly follows the real atmosphere for three months as long as the correct external forcing is provided.

Based on the result of this controlled perfect model, the perfect-twin model experiments are then conducted to examine how the initial error grows. The result shows that the predictability limit is inversely proportional to the logarithm of the error energy level. Specifically, the predictability increases 10 days when the initial error energy is reduced to 1/10. This implies in theory that the predictability is unbounded when the initial error approached to zero. Since the model predicts the vertical mean quantities, the local observational error may be reduced in proportion to the square root of the total number of the data samples. Hence, the result suggests that the vertical mean state may be predictable beyond two weeks if we have a perfect model and sufficient number of observations in the vertical. Hence, the result suggests that predicting vertical mean of the atmosphere can be one of the viable approach to the medium-range weather prediction, provided that the barotropic-baroclinic interactions are accurately parameterized.

References

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