BLOCKING FORMATIONS BY THE TURBULENT UP-SCALE CASCADE

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1. Introduction

Amplification of low-frequency planetary waves in the troposphere is often coupled with a blocking formation. The importance of transient eddy forcing by synoptic disturbances to maintain low-frequency planetary waves has been a focus of interest in recent years. Many blocking episodes appear to be related to the transient eddy forcing. However, there are exceptions where enhanced transient eddy forcing failed to create blockings, or blockings occurred without significant transient eddy forcing (see Wiin-Nielsen 1986; Shilling 1986). There is as yet no universally accepted theory of blockings, and the causal relationship of the amplification and blockings remains unclear.

Amplification of planetary waves in the troposphere implies an increase of the wave energy. If total atmospheric energy is partitioned in three energy boxes (zonal, planetary waves, and synoptic to short waves), there are only three paths by which planetary wave energy can increase (see Saltzman 1957): (i) down-scale energy cascade from zonal to planetary wave energy; (ii) up-scale energy cascade from synoptic and short wave to planetary wave energy; (iii) energy supply from external forcing. Every theory describes a unique energy flow to excite the planetary waves, and we can classify a number of theories using these three paths.

According to Shilling's (1986) comprehensive analysis, blocking occurrence shows highest coherence with baroclinic instability of planetary waves down-scale energy cascade. However, there are cases in which barotropic instability plays an important role, and cases in which the up-scale energy cascade from synoptic disturbances dominates the other energy supplies. This suggests that the blocking system is excited by various energy sources from case to case, but reveals the same characteristic structures and behaviors.

In the light of Shilling's puzzling results, Tanaka and Kung (1989) discussed a possibility that blockings can be understood as atmospheric eigenmodes excited by different energy sources from case to case. We intuitively understand the common persistent features as a low-frequency eigenmode. The characteristic structure may be understood such that the eigenvector has the dipole configuration. The eigenmode may be excited by various energy or vorticity supplies because it is a free mode. The positive and negative anomalies should have similar structures (see Dole 1986). We examined eigenmodes of low-frequency, unstable planetary waves in the zonally varying basic state, using spectral primitive equations on a sphere. Two different types of slow-moving Charney modes are found in planetary waves, showing different meridional structures. One of the Charney modes, $M_1$, is stationary at a preferred geographical location, indicating nearly barotropic structure. It resembles so-called O blockings in the atmosphere. The other Charney mode, $M_2$ indicates a dipole structure in the zonally varying basic state. The structures and behaviors of the dipole Charney mode markedly resemble dipole blockings in the atmosphere. We proposed that dipole Charney modes of wavenumber 1, which is modulated by the steady wavenumber 2, is responsible for large-scale dipole blocking, supported, for example, by the up-scale energy cascade from synoptic disturbances. Yet, it is necessary to confirm the hypothesis using a fully nonlinear time-dependent model, because our previous results are based on a linear model under a restriction of small amplitudes.

The purpose of this study is to simulate the amplification of low-frequency planetary waves and concurrent blocking formations as realistically as possible, using a fully nonlinear spectral primitive equation model which is as simple as possible. The hypothesis of the blocking formation due to the up-scale energy cascade from synoptic disturbances under the persistent wavenumber 2 is examined. The energy flows among different waves during blocking events are investigated.

2. A description of the spectral primitive equation model

A system of primitive equations in a spherical coordinate of longitude $\lambda$, latitude $\theta$, normalized pressure $\sigma = p/p_0$, and normalized time $t = 20t$ may be reduced to three prognostic equations of horizontal motions and thermodynamics. The three dependent variables are horizontal wind speeds, $V = (u, v)$, and potential deviation $\phi$ from the global mean reference state. Using a three-dimensional spectral representation, these equations may be written as:

$$\frac{du_i}{dt} + \sigma \partial_r u_i = -i \sum_{j=1}^{M} \sum_{k=1}^{N} r_{jk} u_j u_k + f_i, \quad i = 1, 2, ..., M. \quad (1)$$

where $u_i$ and $f_i$ are the Fourier expansion coefficients of dependent variables and barotropic processes, $r_{jk}$ are Laplace's tidal frequencies, and $M$ is the total number of the series expansion for the 3-D atmospheric variables. Refer to Tanaka and Sun (1990) for the details. Any choice of expansion basis functions will result in the representation of (1) after a proper diagonalization of the linear terms. The resulting expansion basis functions will consist of vertical normal modes andough harmonics. The vertical normal modes comprise barotropic and baroclinic components.

We demonstrated that observed features of blockings can be represented sufficiently by their barotropic components. Based on this observed fact, we collect only the barotropic components of the expansion coefficients. The rest of the baroclinic-barotropic interaction terms and barotropic terms are combined in a single term designated as $s_i$, which describes the formal source-sink term of the barotropic model:

$$\frac{du_i}{dt} + \sigma \partial_r u_i = -i \sum_{j=1}^{N} \sum_{k=1}^{M} r_{jk} u_j u_k + s_i, \quad i = 1, 2, ..., N. \quad (2)$$

where

$$s_i = (B_i^I) + (D_i^F) + (T_i^F), \quad (Z_i). \quad (3)$$

Here, $N$ is the total number of the series expansion for the baroclinic model, and $(B_i^I), (D_i^F), (T_i^F), (Z_i)$, are respectively the formal source-sink terms derived from baroclinic instability, diffusion, topographic forcing, and nondivergent surface stress. Topography is considered only at the wavenumber 2. Refer to Tanaka (1991) for the details. Given the formal source-sink term $s_i$, the nonlinear equation (2) becomes a closed system of the prognostic equation.

It is important to notice that the barotropic component of the diabatic heating term becomes zero under a minor assumption, since the heating may be assumed to be zero under the ground. Every heat-related energy source in the atmosphere goes to the baroclinic components, and the energy is then transformed into the barotropic component through the baroclinic-barotropic interaction. This is one of the major attractions of constructing the barotropic primitive equation model from the 3-D spectral model. The complicated heating fields produced by numerous physical processes are concentrated to the single concept of the baroclinic-barotropic interaction.

3. Results of the simulation

Figure 1 illustrates daily barotropic geopotential fields during days 54-60. Illustrated is the period when the wavenumber 1 amplifies persistently, indicating a meridional dipole structure. The barotropic geopotential field roughly corresponds to the 500 mb height field.
Fig. 1. Daily barotropic geopotential fields during days 54-60 when a blocking occurred in the model atmosphere. The contour interval is 100 m.

blocking system developed near 45°W, indicating a progression. A dipole blocking emerged with its high pressure center at 60°N. The geopotential height of the high-pressure cell is about 300 m higher than surrounding area. Clearly, the dipole wavenumber 1 is superimposed on the amplified wavenumber 2 with its troughs along 90°E and 90°W.

The results described above reasonably resemble observed blocking evolution. A sharp transition from zonal to meridional flow is clear at the up-stream of the blocking system. The persistence of the system is more than two weeks. Our simple nonlinear barotropic model seems to capture the essential mechanism of the blocking system. It is concluded, at least, that the blocking can be simulated using a barotropic model with four physical processes of diffusion, topographic forcing, baroclinic instability, and zonal surface stress.

The mean energy spectrum and energy transformations for days 30-200 are summarized in the Table. The symbols designate total energy $E_n$, nonlinear interaction $N_{n0}$, diffusion $D_{n0}$, topographic forcing $T_{n0}$, baroclinic instability $B_{n0}$, and zonal surface stress $2S_n$. The units are $10^9 J m^{-1}$ for energy and $10^{-3} W m^{-1}$ for energy transformations. The important role of the nonlinear interaction is evident in energy transfer from the source to the sink in this model.

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<th>$N_{n0}$</th>
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<th>$T_{n0}$</th>
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The amplification of the meridional dipole structure of $n=1$ is important for the development of the large scale dipole blocking. The amplification of $n=2$ is also required. We demonstrated that a model run without topography fails to simulate the large-scale blocking because the planetary waves were not amplified. To analyze the cause of the amplification of $n=1$ and $2$, an energy budget analysis is conducted for low-frequency variations during the blocking period. The

Fig. 2. A schematic diagram of the up-scale self-interaction of wavenumber 1 under the environment of steady wavenumber 2. Suppose that a small disturbance of wavenumber 1, $u_1$, interacts with steady wavenumber 2, $\phi_2$. The nonlinear interaction between $n=1$ and 2 causes amplification of $\phi_1$ and $\phi_2$. Then the $\phi_1$ causes the amplification of $u_1$ by a gravest growth requirement. This closed loop of positive feedback between $n=1$ and 2 amplifies the wavenumber 1 drawing energy of the wavenumber 2.

Fig. 3. A schematic diagram of the trajectory of $w_1$ in multidimensional phase space. Suppose that triad wave-wave interactions among $n=0$, 1, and 2 dominate the rest of wave-wave interactions in (1) and that $n=0$ and 2 are in quasi-equilibrium. A condition for dominant up-scale interaction with $n=2$ (i.e., vanishing down-scale interaction) is satisfied when a low-frequency unstable mode of $n=1$ becomes stationary under a weak dissipation. The growing direction describes the unstable manifold and the decaying direction, the stable manifold. The trajectory tends to approach the unstable manifold and grow exponentially. This implies that the low-frequency Charney mode of $n=1$ is captured by $n=2$. 

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4. Concluding remarks

In this study, we carried out nonlinear numerical simulations of amplification of low-frequency planetary waves and concurrent blocking formations. Analysing energetics of blocking formations in the model, we confirmed an amplification of the meridional dipole mode by means of the up-scale energy cascade from synoptic disturbances. We find that the persistent wavenumber 2 plays a catalytic role in drawing synoptic wave energy and feeding wavenumber 1 and that without it a realistic blocking was not simulated.

The results of our numerical simulation are summarized as follows:
(i) the wavenumber 2 is amplified by the prescribed topographic forcing;
(ii) synoptic disturbances are excited by parameterized baroclinic instability;
(iii) under the quasi-stationary wavenumber 2, a meridional dipole mode of wavenumber 1 is amplified by the up-scale energy cascade from synoptic disturbances;
(iv) basic futures of the blocking are created by the superposition of the amplified wavenumbers 1 and 2, and the synoptic disturbances contribute to the sharp diffuent structure of the zonal jet.

Recent studies of a critical layer solution for breaking Rossby waves show a blocking-like solution (e.g., McIntyre and Palmer 1985). The solution provides us a clear insight of convection and turbulence. We note however that the critical layer solution is associated with a down-scale energy cascade, whereas the blocking is mostly related with the up-scale cascade as demonstrated by this study. Based on this fact, it is inferred that turbulence creates disorder (e.g., chaos) when the energy cascades down scale, whereas it creates order (e.g., zonal jets and blockings) when the energy cascades up scale.

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References


