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Low-Frequency Variability of Polar Atmosphere due to Blocking Formations: A Numerical Experiment of Blocking

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ABSTRACT

Arctic climate in winter depends on occurrence of large-scale atmospheric blocking and amplification of planetary waves. Understanding the development of blocking formations is an important research subject in polar regions as well as in middle latitudes for time scales of a month to a season.

In this study, we carried out nonlinear numerical simulations of amplification of low-frequency planetary waves and the concurrent development of blocking. The simulations were conducted using a barotropic spectral model derived from three-dimensional spectral primitive equations with a basis of vertical structure functions and Hough harmonics. The model is truncated to include only barotropic Rossby components of the atmosphere with simple physics including biharmonic diffusion, topographic forcing, baroclinic instability, and zonal surface stress. We find that these four physical processes are sufficient to produce a realistic and persistent dipole blocking with a sharp transition from zonal to meridional flows on a sphere.

The simulations confirmed an amplification of the meridional dipole mode due to the up-scale energy cascade from synoptic disturbances under an environment of persistent wavenumber 2. The energy supply from synoptic disturbances contributes to the sharp transition from zonal to meridional flows.

INTRODUCTION

The Arctic is one of the more sensitive regions of the globe in terms of anticipated climate change as well as natural climate variability. Abnormal global-scale anomalies tend to propagate toward high latitudes by the nature of the meridional dispersion of quasi-stationary planetary waves [Hoskins and Karoly, 1981]. Concentration of the wave energy in high latitudes seems to cause the large variability observed in the polar atmosphere.

A separation of a natural climate variability from a human-induced climate change due to anthropogenic greenhouse gases is an urgent problem in global change research. However, our present understanding of natural low-frequency variability with time scales of a month to a season is still insufficient. Atmospheric blocking, which has typical time scales of a week to a month, has long been one of the unsolved central problems in medium-range forecasting. We have neither physical understanding of nor prediction skills for blocking systems. Since the arctic climate depends strongly on the occurrence of large-scale blockings [e.g., Tanaka and Milkovich, 1990], understanding of the atmospheric natural variability associated with the blocking may be one of the the first steps for global change research.

There is as yet no universally accepted theory to explain the blocking, despite a number of proposed theories. Every theory describes a unique energy flow to excite the blocking system. However, there are various blocking cases in which baroclinic or barotropic instability plays an important role, and cases in which the up-scale energy cascade from synoptic disturbances dominates energy supplies. The implication is that the energy source for blocking systems varies from case to case, but reveals the same characteristic structures and behaviors.

In light of this result, Tanaka and Kung [1989] discussed a possibility that blockings can be understood as atmospheric eigenmodes excited by energy sources which vary from case to case. The common persistent features are intuitively understood as the system is a low-frequency eigenmode. The characteristic structure may be understood as the eigenvector has a 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]. The possible mechanisms are focused on barotropic and baroclinic instabilities [Frederiksen, 1982], since the system should be explained by homogeneous equations without a specific forcing term.

We conducted a study of low-frequency, unstable planetary waves in the zonally varying basic state, along the line of studies by Frederiksen [1982] and Frederiksen and Bell [1987], using spectral primitive equations on a sphere. We found two different types of slow-moving Charney modes in planetary waves, showing different meridional structures. One of the Charney modes, M_1, becomes stationary, indicating nearly barotropic structure at a preferred geographical location. It resembles so-called Ω blockings in the atmosphere. The other Charney mode, M_2, shows a meridional dipole structure in the zonally varying basic state. The structures and behaviors of the dipole Charney mode markedly resemble dipole blockings in the atmosphere (see Figure 1). We proposed that dipole Charney modes of wavenumber 1, which is modulated by the steady wavenumber 2, is responsible for large-scale, dipole-blocking formations. The model suggested that the amplification was supported 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 blocking formations as realistically as possible, using a fully nonlinear primitive equation model which is as simple as possible. The hypothesis that blocking results from up-scale energy cascade from synoptic disturbances under a persistent wavenumber 2 is examined.

We constructed a three-dimensional spectral primitive equation model with a basis of three-dimensional normal mode functions for the motionless atmosphere [see Tanaka and Kung, 1989]. The model was then truncated to include only the barotropic component of the atmosphere. The contributions from the baroclinic components were parameterized as baroclinic-barotropic interactions. The model physics include biharmonic diffusion, topographic forcing, baroclinic instability, and zonal surface stress. The up-scale energy cascade from synoptic disturbances to planetary waves is achieved by nonlinear wave–wave interactions. It will be shown that these combinations of physical processes are sufficient to produce a realistic and persistent dipole blocking with a sharp transition from zonal to meridional flow.

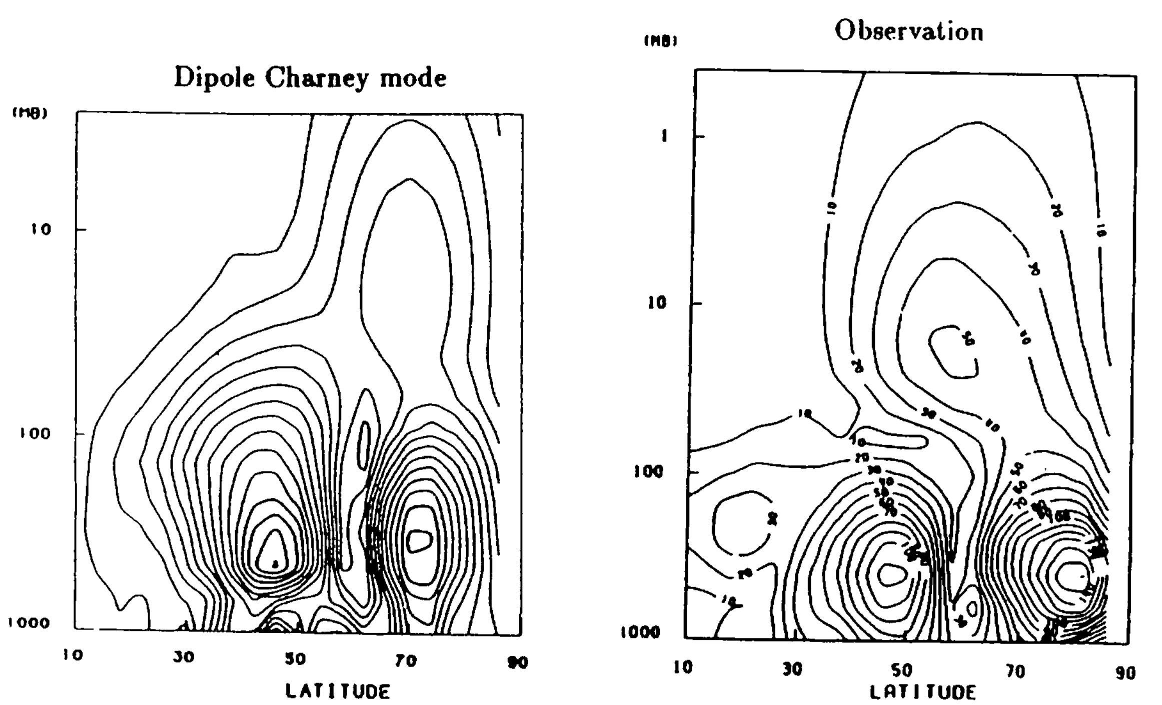

Figure 1. Meridional-height section of the dipole Charney mode M_2 of n=1 in the baroclinic atmosphere [see Tanaka and Kung, 1989], compared with the observed dipole structure of n=1 during the Pacific blocking in January, 1979 [see Tanaka et al., 1989]. Amplitudes of the geopotential height are multiplied by $\sigma^{1/2}$ to remove a density stratification effect.

A DESCRIPTION OF THE SPECTRAL PRIMITIVE EQUATION MODEL

A system of primitive equations in a spherical coordinate system with longitude λ, latitude θ, normalized pressure $\sigma = p/p_b$, and normalized time $\tau = 2\Omega t$ may be reduced to three prognostic equations of horizontal motions and thermodynamics. The three dependent variables are horizontal wind speeds, $V = (u,v)$, and perturbation geopotential ϕ from the reference state of the global mean. Using a three-dimensional spectral representation, these equations may be written as:

$$\frac{dw_i}{d\tau} + i\sigma_i w_i = -i \sum_{j=1}^{M} \sum_{k=1}^{M} r_{ijk} w_j w_k + f_i, \; i = 1,2,\ldots, M, \quad (1)$$

where w_i and f_i are the Fourier expansion coefficients of dependent variables and diabatic processes, σ_i are Laplace's tidal frequencies, r_{ijk} are interaction coefficients, and M is the total number of the series expansion for the 3-D atmospheric variables. 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 and Hough harmonics. Refer to Tanaka and Sun [1990] for details. The vertical normal modes comprise barotropic and baroclinic components.

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

$$\frac{dw_i}{d\tau} + i\sigma_i w_i = -i \sum_{j=1}^{N} \sum_{k=1}^{N} r_{ijk} w_j w_k + s_i, \; i = 1,2,\ldots, N, \quad (2)$$

where

$$s_i = (DF)_i + (TF)_i + (BI)_i + (ZS)_i$$

Here, N is the total number of the series expansion for the barotropic model, and $(DF)_i$, $(TF)_i$, $(BI)_i$, $(ZS)_i$ are respectively the formal source–sink terms derived from diffusion, topographic forcing, baroclinic instability, and zonal surface stress to be described later. 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.

Diffusion

In this study, we approximate biharmonic type diffusion based on the 3-D scale index σ_i combined with the Rossby wave dispersion (for wavenumber $n \neq 0$) as:

$$(DF)_i = -K\left(\frac{n}{\sigma_i}\right)^2 w_i \quad (3)$$

where K is a diffusion coefficient and $K(2\Omega a^4) = 2.0 \times 10^{16}$ $m^4 s^{-1}$.

Topographic Forcing

A kinematical uplift of an air column by the surface topography H has been parameterized by a forced upward motion w_0 which is induced by the barotropic flow V_0. We use the topography of

$$H(\lambda, \theta) = -A\sin^2(\pi\mu^2)\cos(2\lambda) \quad (4)$$

where A = 400 m and $\mu = \sin\theta$. The spectral representation of w_0 gives $(TF)_i$.

Baroclinic Instability

When the norm of $w_i(\tau)$ for eddies is small compared with that of the zonal component, we can predict the direction to which $w_i(\tau)$ grows; this direction is the unstable subspace ξ_i due to the atmospheric baroclinic instability. When $w_i(\tau)$ grows along the unstable subspace, both the baroclinic and barotropic components of $w_i(\tau)$ will grow exponentially, maintaining consistent structure. It is in this process that the zonal baroclinic energy is transformed to the eddy barotropic energy. It is suggested by Tanaka and Sun [1990] that this process operates even for finite amplitude planetary waves. Following this concept, we attempted to parameterize the atmospheric baroclinic instability for our barotropic model by

$$(BI)_i = \frac{da(\tau)}{d\tau}\xi_i = -i\nu a(\tau)\xi_i \quad (5)$$

where $a(\tau) = \sum_i w_i(\tau)\xi_i^*$, and ν is the complex eigenvalue of the stability problem associated with ξ_i. The growth rates and phase speeds used in this study are listed in Table 1.

n	1	2	3	4	5	6
Mode	M_2	M_2	M_2	M_2	M_C	M_C
day^{-1}	0.06	0.11	0.15	0.18	0.25	0.35
° day^{-1}	8.9	9.1	9.0	8.6	8.1	8.4

Table 1. Mode name, growth rates (day^{-1}), and phase speeds (°day^{-1}) of the baroclinically unstable modes for wavenumbers n=1-6. M_2 is the dipole Charney mode and M_C the shallow Charney mode.

Zonal Surface Stress

As the baroclinic waves grow, the nonlinear zonal-wave interaction begins to accelerate the zonal motion. A northward shift of the subtropical jet occurs due to the northward eddy momentum transport induced by the baroclinic waves. For the barotropic flow, the important physics that must be considered to balance the northward shift of the jet are the surface stress and mountain torque. We adopt the following parameterization of the zonal surface stress:

$$(ZS)_i = -\alpha(w_i - \bar{w}_i) \quad \text{for} \quad n = 0 \tag{6}$$

where $\bar{w}_i$ is the monthly mean for January 1979, and $\alpha(2\Omega) = 2.32 \times 10^{-6} s^{-1}$ which corresponds to the relaxation time of 5 days.

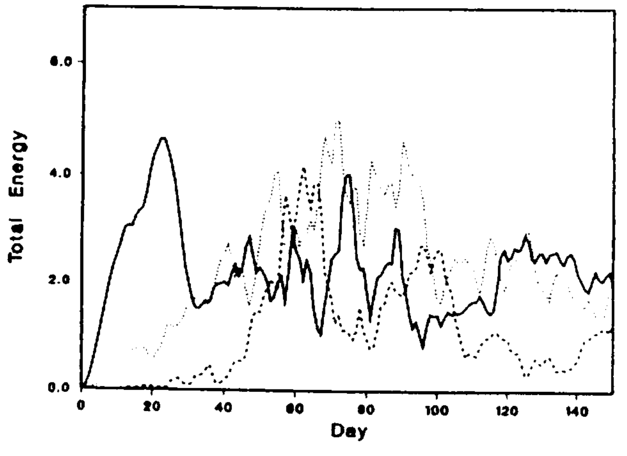

Figure 2. Time series of total energy of zonal wavenumber n=1 (dashed line), n=2 (solid line), and the sum of n=3-6 (dotted line). Units are $10^5\ J\ m^{-2}$.

n	E_n	NL_n	DF_n	TF_n	BI_n	ZS_n
0	1136	258	-11	-44	0	-203
1	131	25	-28	0	11	0
2	204	-185	-54	207	32	0
3	76	4	-35	3	31	0
4	72	-9	-39	9	39	0
5	56	-15	-38	-2	58	0
6	50	-83	-48	-2	138	0

Table 2. Averaged energy variables for wavenumbers n=0-6 during days 30-200. The symbols designate total energy E_n, nonlinear interaction NL_n, diffusion DF_n, topographic forcing TF_n, baroclinic instability BI_n, and zonal surface stress ZS_n. The units are $10^3\ J\ m^{-2}$ for energy and $10^{-3}\ Wm^{-2}$ for energy transformations.

RESULTS OF THE SIMULATION

The results of the numerical integration are shown first in Figure 2 for time series of eddy energies in contributions from n=1, n=2, and the sum of n=3–6. It is clear that the initial growth of eddy energy is caused by topographic forcing of n=2. The energy of n=1 increases after day 40, indicating energy peaks around day 60. During the peak period of n=1, a pronounced blocking occurred in the model atmosphere.

Figure 3a–b illustrates barotropic geopotential fields during the model days 54–61. The barotropic geopotential field roughly corresponds to the 500 mb height field. The coastal line is drawn for reference in the model results. During days 54–69, a blocking high appeared near 0°E along 60°N. The wavenumber 2 amplifies with its troughs along 90°E and 90°W. A dipole structure of wavenumber 1 with its high pressure center at 60°N and low pressure center at 40°N is superimposed on the wavenumber 2. A sharp transition from zonal to meridional flow is clear up-stream of the blocking system. The duration of the blocking is more than two weeks and the results reasonably resemble observed blocking characteristics. Our nonlinear barotropic model seems to capture the essential mechanism of blocking systems. We can conclude, at least, that the blocking can be simulated using a barotropic model with four physical processes, i.e., diffusion, topographic forcing, baroclinic instability, and zonal surface stress.

The results of the energy and energy transformations are summarized in Table 2 for time averages of days 30–200. The eddy energy is largest at n=2, and second largest at n=1. The higher wavenumbers contain less energy. There are two major energy sources; one is the topographic energy source at n=2, and the other is the baroclinic energy source at n=6. The energy is then redistributed by the nonlinear interactions toward n=0. As in observation, n=1 receives energy through the nonlinear interactions. There is a main energy sink at n=0 from the zonal surface stress. Diffusion is evenly distributed over the waves. The important role of the nonlinear triad interactions is evidently to transfer energy from the source at n=2 and 6 to the sink at n=0. The transfer is characterized as the up-scale cascade from small-scale motions to large-scale motions. We confirmed that the up-scale energy cascade into n=1 increased rapidly during the onset of the blocking in the model atmosphere.

SUMMARY

We have shown that a simple barotropic model with four physical processes of diffusion, topographic forcing, baroclinic instability, and zonal surface stress can simulate a realistic and persistent blocking. The basic structure of large-scale blocking is explained by a superposition of a meridional dipole structure of wavenumber 1 and a monopole structure of wavenumber 2. The problem in large-scale blocking is then reduced to explain why these planetary waves are amplified. A model run without topography failed to simulate the large-scale blocking since the planetary waves were not amplified. The existence of quasi-stationary planetary waves is essential for the blocking. As found by our energy budget, the important amplification of low-frequency wavenumber 1 is caused by the nonlinear wave-wave interactions. We confirmed that the largest portion of the energy supply came from synoptic disturbances. The energy supply from the topographic forcing appears to be of

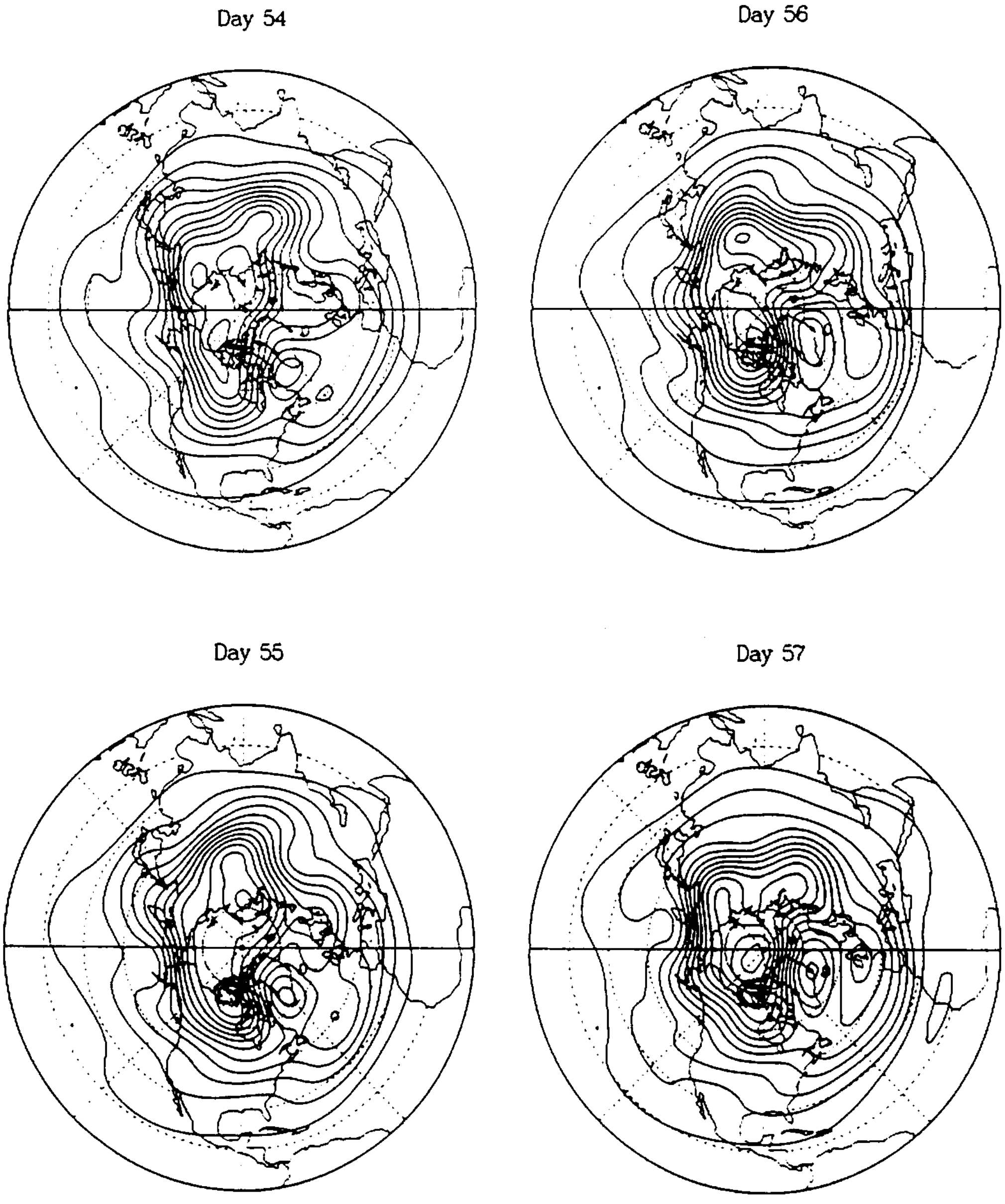

Figure 3a. Geopotential fields during 54-57 days when a blocking occurred in the model atmosphere. The contour interval is 100 m.

secondary importance. Synoptic disturbances contribute to the amplification of wavenumber 1 and to the sharp transition from zonal to meridional flows when the quasi-stationary planetary waves already exist. Therefore, excitations of quasi-stationary planetary waves and synoptic disturbances are both important for blocking formations.

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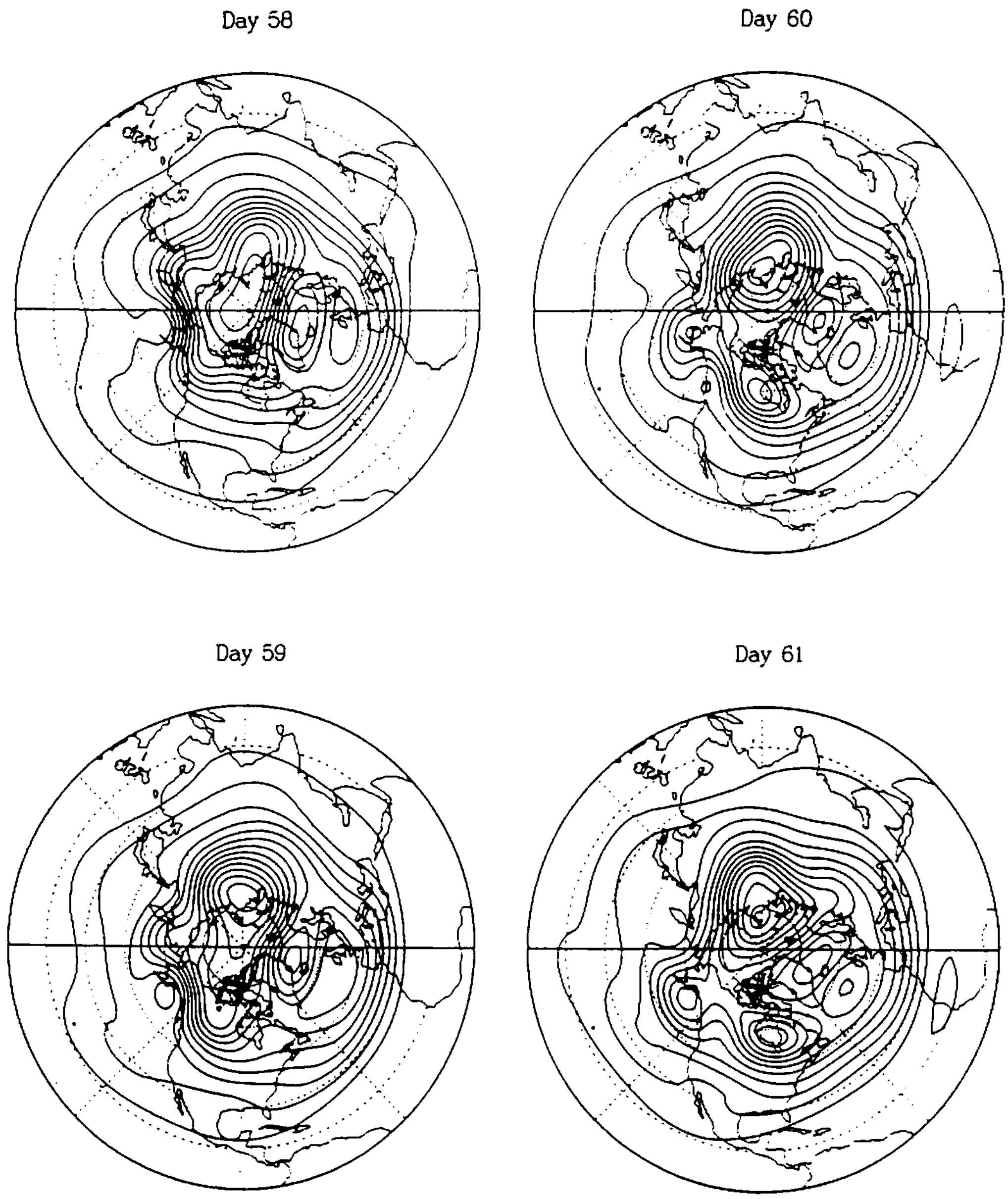

Figure 3b. Geopotential fields during 58-61 days when a blocking occurred in the model atmosphere. The contour interval is 100 m.

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