Blocking Formation by the Accumulation of Barotropic Energy at the Spherical Rhines Speed

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1. INTRODUCTION

The spectral characteristics of the synoptic to planetary waves are described by Tanaka (1985) by means of the 3D normal mode decomposition, including the vertical spectrum. The analysis scheme is referred to as normal mode energetics. In their analysis, the scale of the 3D normal mode is represented by the eigen frequency of Laplace's tidal equation σ instead of the wavenumber k. The modal frequency is related to the scale by the wave dispersion relation.

As discussed by Tanaka and Terasaki (2004), the spectral peak over the phase speed domain (i.e., c domain) is clearly explained by the Rhines scale which separates the distinct slopes of turbulence and wave regimes (see Fig. 1).

The spectral slope in the phase speed domain is theoretically deduced by Tanaka et al. (2004) to establish the power law of c^2 based on Garcia's criterion of Rossby wave breaking $\partial q/\partial y < 0$. According to this Rossby wave saturation theory, the energy spectrum is found to obey $E = mc^2$, where m is a total mass of the atmosphere for unit area. When the Rossby waves saturates in the turbulence regime, the excessive energy accumulated at the synoptic eddies cascades up toward the spherical Rhines speed c_R.

Once the origin of the spectral peak and the power law is understood by the Rossby wave saturation theory, it is easily speculated that the barotropic energy would ultimately be accumulated at the spherical Rhines speed c_R. The excessively accumulated energy at c_R would stay for long time because there is no way to break down the amplified Rossby wave by the triad wave-wave interactions of turbulence. In this study, we propose a hypothesis such that the atmospheric blocking is a realization of accumulated energy at the spherical Rhines speed c_R exceeding the Rossby wave saturation theory.

The purpose of this study is first to confirm the up-scale energy cascade from the synoptic eddies to the spherical Rhines speed c_R in the phase speed domain. Second, we confirm our speculation such that the blocking phenomenon is characterized as the excessive accumulation of barotropic energy at the spherical Rhines speed c_R. Finally, we confirm the intensification of the up-scale energy cascade from the synoptic eddies to c_R in the phase speed domain during typical blocking events in winter by the composite analysis.

2. EQUATION AND DATA

By expanding the state variable in 3D normal mode functions, we obtain a system of 3D spectral primitive equations in terms of the spectral expansion coefficients w_i, (see Tanaka and Terasaki 2004):

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

where τ is a dimensionless time, σ_i is the eigen-frequency of the Laplace's tidal equation, f_i is the expansion coefficient of the external forcing of viscosity and diabatic heating rate, and r_{ijk}

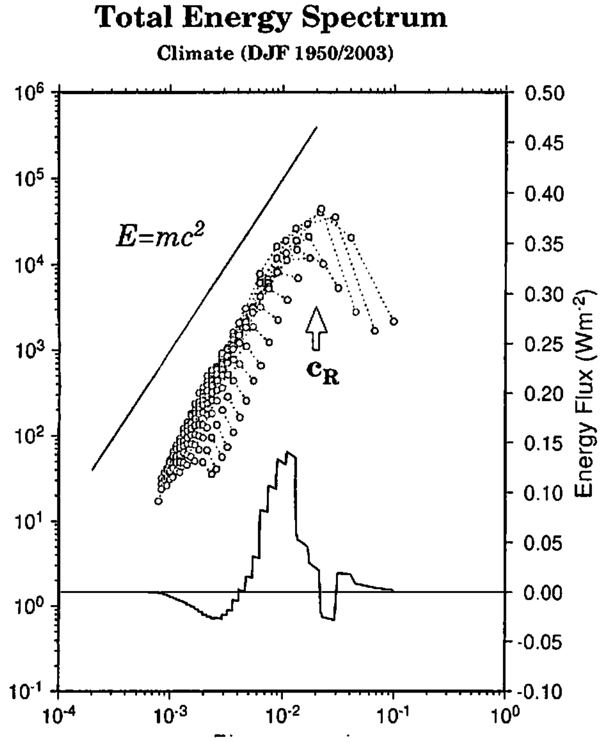

Figure 1: Barotropic energy spectrum E_i and the energy flux F_i as a function of the dimensionless phase speed of Rossby waves $|c_i|$. The spherical Rhines speed c_R is marked by an arrow.

is the interaction coefficients for nonlinear wave-wave interactions calculated by the triple products of the 3D normal mode functions.

Total energy E of the atmosphere (sum of kinetic energy and available potential energy) is simply the sum of the energy elements E_i defined by:

$$E_i = \frac{1}{2} p_s h_m |w_i|^2, \tag{2}$$

where p_s is the mean surface pressure and h_m is the equivalent height. The energy spectrum E_i is plotted as a function of the dimensionless phase speed of the Rossby mode $c_i = \sigma_i/n$ in a resting atmosphere, where n is the zonal wavenumber. The phase speed c_i represents the horizontal scale of a mode by the wave dispersion relation. The westward phase speed is small (large) when the horizontal scale of the Rossby mode is small (large).

By differentiating (2) with respect to time and substituting (1), we obtain the energy balance equation:

$$\frac{dE_i}{dt} = N_i + S_i, \tag{3}$$

where N_i and S_i designated the nonlinear interactions and the energy sources, respectively. The nonlinear interactions are further decomposed in contributions from zonal-wave interactions N_{Zi} and wave-wave interactions N_{Wi}. We then define energy flux in the phase speed domain F_i by the summation of the wave-wave interactions N_{Wi} with respect to c_i in descending order of magnitude:

$$F_i = \sum_{k=1}^{i} N_{Wk}. \tag{4}$$

The data used in this study are four-times daily NCEP/NCAR reanalysis for 51 years from 1950 to 2000 (see Kalnay et al. 1996). The data contain horizontal winds (u, v) and geopotential ϕ, defined at every 2.5° longitude by 2.5° latitude grid point over 17 mandatory vertical levels from 1000 to 10 hPa.

3. ENERGY SPECTRUM

Figure 1 illustrates the result of the barotropic energy spectrum E_i and the energy flux F_i as a function of c_i. Energy levels are connected by dotted lines for the same zonal wavenumber n with different meridional mode numbers l. According to the result, the spectrum indicates two distinct regimes with different slopes for small c_i and large c_i. The energy injected at the synoptic scale (small c_i) cascades up to the larger scale (larger c_i) obeying a specific power law. The spectral peak at c_i=0.02 is clearly explained by the spherical Rhines speed c_R which separates the turbulence regime and wave regime. The spherical Rhines speed is also the speed where the westward phase speed of the Rossby wave balances with the eastward flow speed by the zonal motion. As a result, the Rossby wave at c_R becomes stationary, and appreciable amount of energy supply occurs by the topographic forcing.

The line in the figure denotes the spectral slope of $E = mc^2$ derived by Tanaka et al.

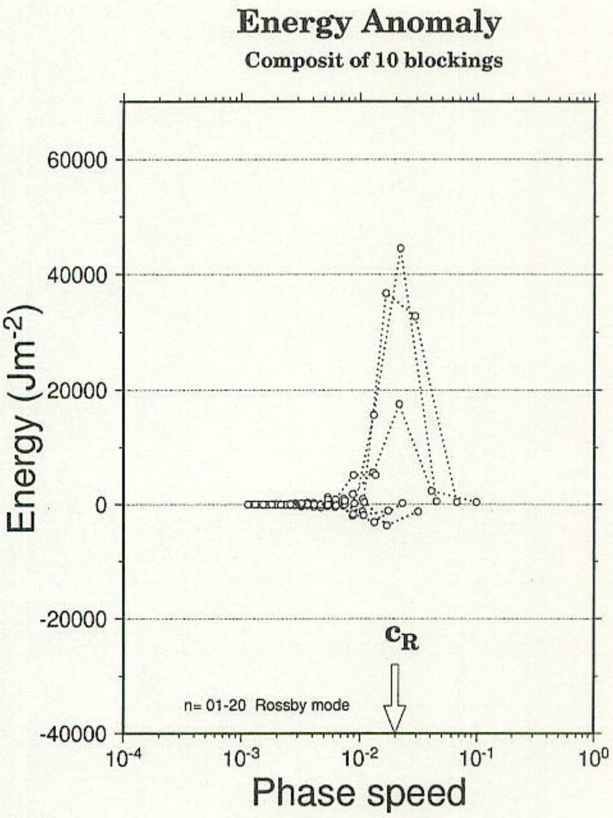

Figure 2: Distribution of barotropic energy anomaly in the phase speed domain for the composite of 10 largest blocking events in the North Pacific.

(2004) from the Rossby wave saturation criterion $\partial q/\partial y < 0$, where $m = p_s/g$ is the atmospheric mass in unit area. The theoretical slope agrees well with the observation.

Figure 1 illustrates also the energy flux F_i in the phase speed domain. According to the result, the energy flux diverges at the synoptic scale around c_i=0.004 and cascades up toward c_R showing the peak value of 0.15 W m^{-2}. The up-scale energy flux converges at c_R as the cascade arrest discussed by Rhines (1975). We notice also that a part of the energy injected at synoptic eddies cascades down to short waves as seen from the negative value of the flux at smallest c_i.

4. BLOCKING

Figure 2 illustrates the barotropic energy anomaly over the phase speed domain for the composite of the largest 10 blockings in the North Pacific. We can confirm that blocking events are characterized by the excessive energy accumulation just over c_R. The peak anomaly reaches 4.0×10^4 J m^{-2} for both regions.

Figure 3 shows the energy flux in the phase speed domain for the composite of the same 10 blocking events in the North Pacific (solid lines) compared with the clime (dashed lines). The up-scale energy flux from the synoptic-scale source range to c_R is enhanced during blocking events by more than 0.05 W m^{-2} compared with the climate. The energy flux convergence increases evidently at c_R where the energy anomaly shows the peak. The anomaly of 0.05 W m^{-2} has a potential to produce energy anomaly of 2.0×10^4 J m^{-2} for 5 days, which is quantitatively sufficient to explain the energy anomaly during the blocking events. It is confirmed that the up-scale energy flux is clearly instrumental for the blocking formation in both regions.

5. CONCLUSION

In this study, energy spectrum of the large-scale atmospheric motions is examined in the framework of the 3D normal mode decomposition. Attention is concentrated to the barotropic component of the atmosphere where the low-frequency variabilities dominate.

According to the result of the observational analysis, we obtain a characteristic energy spectrum with its peak at the spherical Rhines speed c_R. Based on the criterion of Rossby wave breaking, $\partial q/\partial y < 0$, discussed by Garcia (1991), Tanaka et al. (2004) derived that the energy spectrum in the turbulence regime can be described as $E = mc^2$.

The spherical Rhines speed c_R is the ultimate end point of the up-scale energy cascade by the triad wave-wave interactions. The accumulated excessive energy just over c_R results in a unique behavior, which may be recognized as blocking. The energy level at c_R can exceed the saturation criterion of $E = mc^2$ because it no longer breaks down by the triad wave-wave interactions. Therefore, the accumulated excessive energy at c_R persists sufficiently longer time

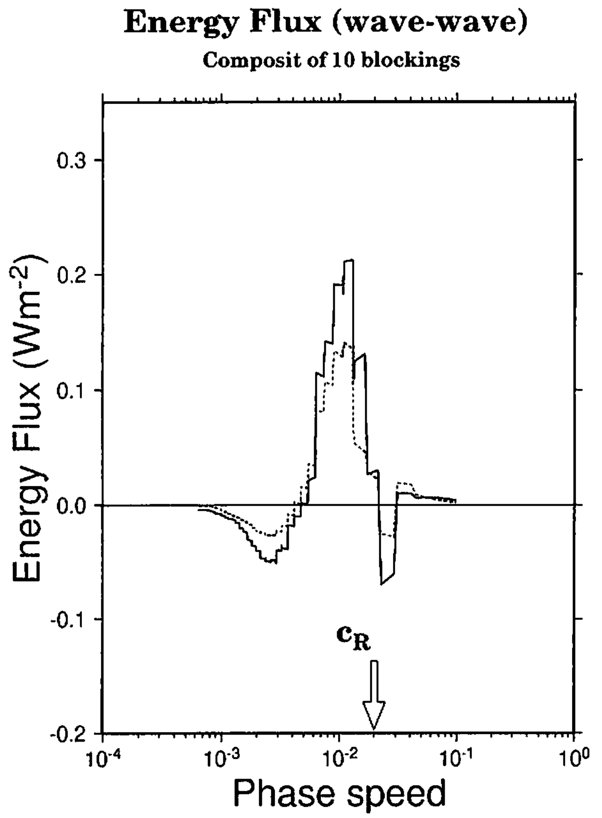

Figure 3: Energy flux in the phase speed domain associated with the nonlinear wave-wave interactions evaluated for the composite of the same blocking events in the North Pacific (solid line) as in Fig. 2, compared with the DJF clime (dashed line).

showing the specific structure with $\partial q/\partial y < 0$ which is characteristic to blocking. The amplified nonlinear Rossby wave at c_R stays at the same location for long time because c_R coincides with the scale of stationary Rossby waves.

Although the up-scale energy cascade may be the principal mechanism for the accumulation of energy at c_R, other mechanisms such as the resonant Rossby wave with topographic forcing (Tung and Lindzen 1979), baroclinic instability of planetary waves (Tanaka and Kung 1989), or accumulation of wave activity density flux by the quasi-stationary Rossby wave train (Nakamura et al. 1997) may act as the excitation mechanism for the stationary Rossby wave at c_R. Those are recognized as different processes to produce the common large-scale configuration as blocking.

In conclusion, the essential feature of a blocking can be understood as the excessive accumulation of barotropic energy at the spherical Rhines speed c_R, where an amplified nonlinear Rossby wave persists long time at the same location showing the breaking criterion $\partial q/\partial y < 0$. The conclusion of this study is derived from the Rossby wave saturation theory in the spectral domain. A further description may be desirable in the spatial domain to achieve more concrete understanding of blocking.

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