Analysis on Spatio-temporal Characteristics of Wintertime Planetary Wave in the Northern Hemisphere Based on 2D FFT

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Abstract. To describe spatial and temporal characteristics of the activities of wintertime planetary waves in the northern hemisphere, their numbers and periods were precisely calculated, based on NCAR/NCEP reanalysis data. The objective variables include sea level pressure (SLP) and anomaly stream function at 850 hPa, 500 hPa and 200 hPa. 2D FFT and spectral analysis reveal that: (1) The wave numbers 1 and 2 dominate the perturbation pattern at 70º-80 ºN zonal belt. (2) The wave numbers 1, 2 and 3 dominate at 60º-70ºN zonal belt. (3) The wave numbers 1-4 dominate at 50º-60ºN zonal belt. The results accord fairly well with Rossby's classical trough formula and are of potential use for understanding the northern hemisphere large-scale oscillations.

Keywords: Planetary wave, Large-scale oscillations, Northern hemisphere, Wave number.

1 Introduction

According to Rossby's [1] previous work on the relationship between variations in the intensity of the zonal circulation of the atmosphere and the displacements of the semi-permanent centers of action, it is well known that the planetary waves have significant impact on the troposphere circulation. Based on the trough formula, as is often called, Rossby roughly calculated the number of the long stationary waves and their wavelength.

Recent studies reveal that the northern hemisphere climate takes on some kinds of oscillations, including the North Atlantic Oscillation (NAO), the Arctic Oscillation (AO) [2] and the Pacific North American pattern (PNA). These features have close relationship with the planetary wave activities. Cavalieri and Häkkinen [3] reported the variability of SLP planetary waves and related these planetary-scale variations with some changes of climate observed in the Arctic over the last fifty years. Yu [4] proposed a stationary wave-2 frame to relate the NAO, AO and NPO on the basis of

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Hoskins' great circle theory. Here the analysis to the higher levels in the troposphere is further extended to demonstrate the planetary wave activities and to show their climate impact.

2 Analysis and Results

The monthly SLP and wind data at 850hPa, 500hPa and 200hPa levels from the NCAR/NCEP Reanalysis Data [5] are used here. Their anomalies are deduced by extracting the corresponding climatologies. The time covers from 1948 to 2003. To examine the characteristics of the planetary-scale wave, only the rotational part of the wind field is kept. It is conducted by decomposing the wind field into non-divergent part $\vec{V}_\psi$ plus an irrotational part $\vec{V}_\phi$ according to the Helmholtz theorem [6]. Thus the stream function ψ is introduced as:

$$\varsigma = \nabla^2 \psi \tag{1}$$

where the ς is the vorticity. The global stream function corresponding to the rotational part of the wind anomaly is acquired through Eq.(1) with the aid of the Fishpack program package [7]. Then the following analysis is conducted on the basis of SLP and the stream functions at 850 hPa, 500 hPa and 200 hPa levels.

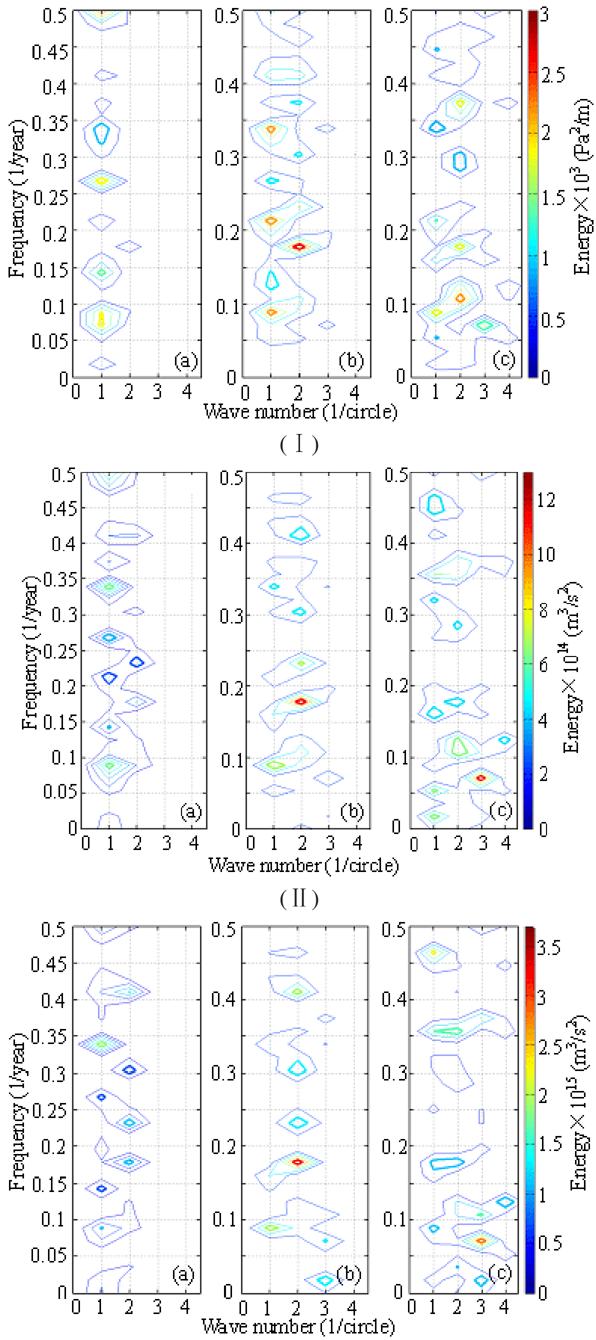
Table 1. Fraction of variance (in percentage) accounted by different wave structures

Field	Latitude	Wave 1	Wave 2	Wave 3	Wave 4	Wave 5
SLP	70°-80°N	71.086	19.787	5.0084	2.0065	0.53583
	60°-70°N	44.529	34.572	9.8977	6.943	1.8271
	50°-60°N	26.601	37.112	16.061	11.722	4.3615
850hPa stream function	70°-80°N	62.705	29.641	5.047	2.0109	0.30322
	60°-70°N	34.058	40.701	15.4	7.3467	1.3215
	50°-60°N	29.592	29.31	20.663	14.185	3.7139
500hPa stream function	70°-80°N	52.222	38.733	6.0772	2.4429	0.33537
	60°-70°N	26.551	42.736	21.062	7.364	1.44
	50°-60°N	25.804	25.823	25.778	16.562	3.8251
200hPa stream function	70°-80°N	60.842	33.641	4.5788	0.79062	0.10893
	60°-70°N	32.834	44.366	17.247	4.6042	0.65593
	50°-60°N	25.658	30.039	25.198	14.434	3.2481

Furthermore, the analysis focuses on three ten-degree latitude bands from 50° N to 80° N latitude, with the January being used as the representative of the wintertime.

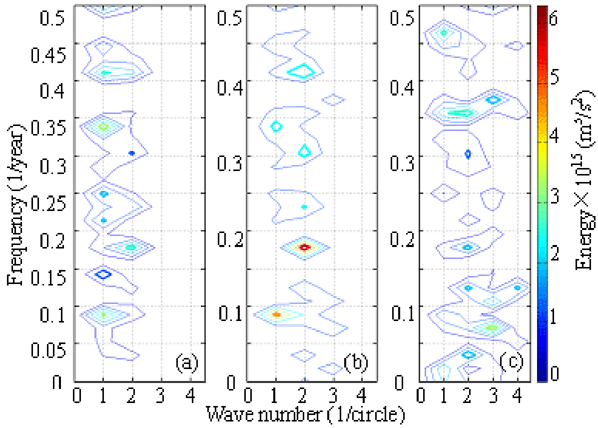
We chose 200 hPa, 500 hPa and 850 hPa layers as the representatives of the upper, middle and lower troposphere. The temporal and spatial structure of the planetary-scale wave revealed by the 2D FFT is shown in Fig.1 respectively for the anomalous SLP and the stream functions at upper, middle and lower troposphere. Also the fraction of variance accounted by different waves is shown in Table 1. As for the case of SLP, the wave structure shows different characteristics in three bands. For the 70°-80°N band, the significant fraction of the variance in SLP is carried by wave 1, which accounts for over 71% of the total variance. The energy in shorter waves increases significantly with the decrease of the latitude. The wave 2 in 60°-70°N band and the wave 3 in 50°-60°N band vary significantly, and they account for over 19 % and 5% of the total variance respectively. This tendency also exists in the stream functions, which has the generally similar energy distribution in the wave number space with the intensity of variation increasing from 850 hPa to 200 hPa level. As for the stream functions, the structures of waves 1-2 in70°-80°N band, waves 1-3 in 60°-70°N band and waves 1-4 in 50°-60°N band dominate the variance and explain over 90% of the total variance. From the lower level to the upper level of the troposphere, the perturbation has the similar pattern in the three bands. The result accords well with the qualitative estimate of the stationary wave length given by Rossby's trough formula.

The 2D FFT gives further information on the temporal characteristics of the spatial structure mentioned above. Waves of different length scale have different characteristics of the time evolution. [3] pointed out that the phases of waves 1 and 2 in 70°-80°N band have significant peaks at 3.6, 5.6 and 12.5 years for SLP field. The present analysis focuses on the amplitude of the variation but not on the phase. However, the temporal characteristic can also be seen from Fig. 1. The powers of waves 1, 2 and 3 in 50°-80°N band show concentration peaks at 2.9-, 3.6-, 4.4-, 5.6-, 6.9-, 12.5-, near 14-, near 33-, and near 60-year periods both for SLP and for stream functions. The 3.6-year period is likely related to atmospheric circulation changes with El Nino [8]. The 5.6-year period is probably associated with the variability in Arctic sea ice extent [9]. The reason for the decadal and the interdecadal signals is not clear and needs further exploration. It should be noted that the 5.6-year period is most significantly associated with the wave 2 structure in 60°-70°N band, while the decadal signal is most significantly associated with the wave 1 structure in all the three bands and with the wave 3 structure just in 50°-60° N band. Except for the decadal signal, the interannual (here are 2.9-, 3.6- and 6.9-year periods) signal is also very significantly associated with wave 1 structure in high latitude bands. This may cast some light on their physical interpretation. ENSO has its global influence through the Rossby wave propagation and dispersion on the sphere and thus the signal can be detected at all the three bands. The Arctic



(III)

Fig. 1. 2D FFT of the perturbed SLP and stream function



(Ⅳ)

Fig. 1. (*Continued*)

sea ice extent variation can cause the large-scale perturbation, which directly influences the high latitude region because the perturbed long Rossby wave propagates in the zonal and northward direction but not in southward direction according to Hoskins' great circle theory [10].

(Ⅰ) a. SLP in 70º-80ºN band; b. SLP in 60º-70ºN band; c. SLP in 50º-60ºN band;

(Ⅱ) a. 850 hPa stream function in 70º-80ºN band; b. 850 hPa stream function in 60º-70ºN band; c 850 hPa stream function in 50º-60ºN band;

(Ⅲ) a. 500 hPa stream function in 70º-80ºN band; b. 500 hPa stream function in 60º-70ºN band; c. 500 hPa stream function in 50º-60ºN band;

(Ⅳ) a. 200 hPa stream function in 70º-80ºN band; b. 200 hPa stream function in 60º-70ºN band; c. 200 hPa stream function in 50º-60ºN band

The spatial-temporal structure is further explored by power spectrum analysis with the time series (1948-2003) of the variances accounting for waves 1-4, as shown in Fig. 2. The fraction of variance is calculated with the FFT of the anomalous quantity subtracted from the zonal average for each calendar January. The time evolution further supports the above conclusion of the wave structure at three latitude bands. It has been known from Table 1 that waves 1 and 2 dominate the variance for 60º-80ºN band. An interesting point here is that the waves 1 and 2 in 60º-80ºN band vary out of phase, i.e. they alternatively dominate the variance among most of years and only coexist in few years. The out-of-phase evolution of different wave structures exists from the surface to the upper troposphere level. Also the overall wave structures keep well vertically.

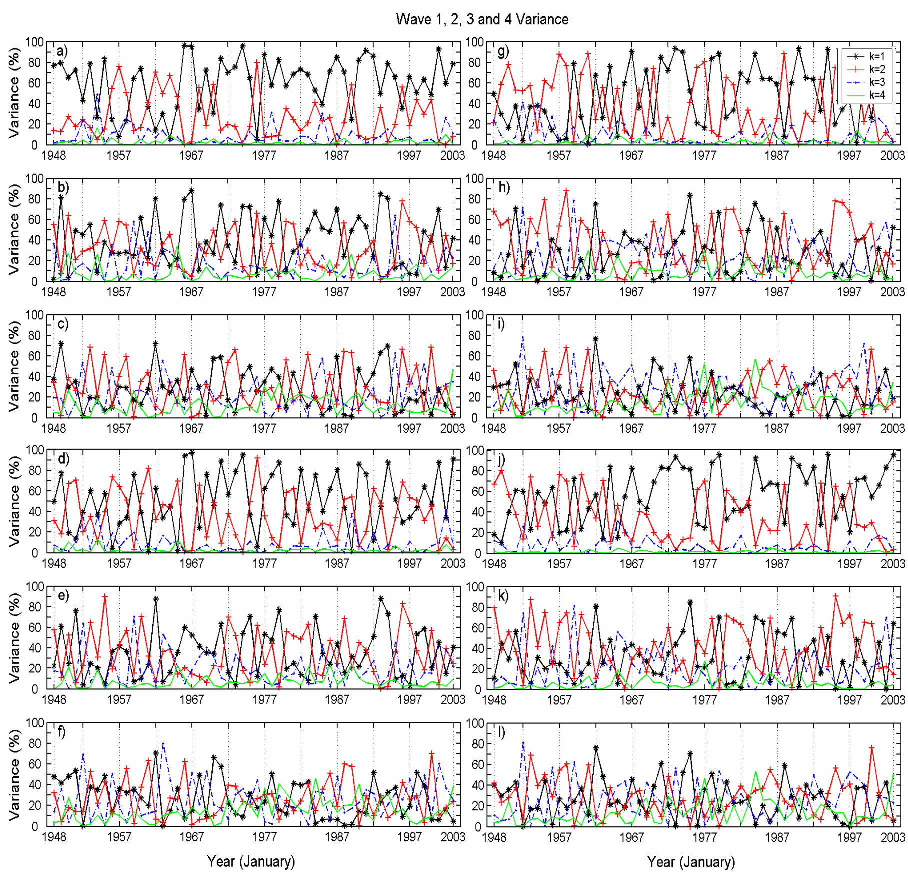


Fig. 2. Time series of the fraction of variance accounted by different wave structure

3 Discussion and Conclusion

It is anticipated from Rossby's pioneering work that the stationary long Rossby wave stands in the northern hemisphere and has close relationship to the intensity of the semi-permanent action center. Based on the NCAR/NCEP reanalysis data, the idea is fully examined and it is shown from the diagnosis that the variation of the perturbed SLP and stream functions from lower to upper troposphere has rather systematic structure. Waves 1-4 dominate the variance pattern at 50°-60°N band, while waves 1-3 and 1-2 dominate it in 60°-70°N band and in 70°-80°N band respectively. The significant wave structure accounts for over 90% of the total variance.

a. SLP in 70°-80°N band; b. SLP in 60°-70°N band; c. SLP in 50°-60°N band;
d. 850 hPa stream function in 70°-80°N band; e. 850 hPa stream function in 60°-70°N band; f. 850 hPa stream function in 50°-60°N band;

g. 500 hPa stream function in 70°-80°N band; h. 500 hPa stream function in 60°-70°N band; i. 500 hPa stream function in 50°-60°N band;
j. 200 hPa stream function in 70°-80°N band; k. 200 hPa stream function in 60°-70°N band; l. 200 hPa stream function in 50°-60°N band

According to Hoskins' great circle theory, an important application of the wave structure is that the large scale climate variability in the northern hemisphere can be understood from the point of view of the teleconnection. Large scale Rossby wave can transfer the perturbation information along the ray path around the sphere. Thus the North Atlantic Oscillation, the Arctic Oscillation and the oscillation in the north Pacific are likely to be connected through the wave process. Given the perturbation source at the north Atlantic, the signal can propagate northeastward as the form of planetary wave and cross through the Arctic region to the north Pacific. However, the assumption should be further explored with the data analysis and model works.

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