A STUDY ON PHYSICAL MECHANISM OF INTERANNUAL VARIATIONS OF LARGE–SCALE FLOW PATTERNS *

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ABSTRACT

The thermal forcings of annual and interannual periodic variations are introduced into the barotropic vorticity equation, by using low order spectral model of the equation, more than 40 numerical experiments whose integration time is larger than 100 model years are performed in order to investigate variations of large–scale flow patterns arising from both external interannual thermal forcing and internal dynamical processes. In certain parametric range, when the frequency of the forcing term with interannual period equals to the frequency which is created by the internal dynamical processes alone, the amplitude of interannual variations of flow patterns increases obviously, and the period becomes double. In other parametric range, the amplitude of interannual variations of flow patterns shows abrupt changes and other nonlinear behavior, along with gradual changes of interannual forcing parameters.

Key words: large–scale flow pattern, interannual variation, abrupt change, numerical experiments

I. INTRODUCTION

There has been a series of observational studies in the interannual variation of large–scale atmospheric flow patterns. The physical mechanism of interannual variations of flow patterns can generally be attributed to two types of processes, i.e. the internal dynamical process (Manabe and Hahn 1981) and nonseasonal variation of external forcing (Lau 1981). Manabe and Hahn (1981), Lau (1981) and Ma (1990) reproduced interannual variations of large–scale flow patterns and their characteristic quantities in the model atmosphere. Because the thermal forcing had a strict annual period without any interannual variation component and the constant boundary condition was used in the above papers, it can be inferred that those reproduced interannual variations were triggered by internal dynamical processes of the atmosphere. The above papers studied the effect of the first type possible mechanism on the interannual variation of flow patterns.

Up till now no paper about the interannual variation of flow patterns, under the joint influence of the atmospheric interannual dynamic process and nonseasonal external forcing, has been seen yet. This paper is going to initially analyze the problem. We at first analyze the interannual variation of flow patterns triggered by the atmospheric internal dynamical process only; then introduce the external periodic forcing of different interannual scales and investigate the feature of interannual variations of flow patterns under the joint effect of possible mechanism of the two types of processes; at last discuss the results, especially the phenomena in relation to nonlinear behavior.

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II. MODEL

The barotropical equation

$$\frac{\partial}{\partial t}\left(\nabla^2\psi-\frac{\psi}{\lambda^2}\right)+J\left(\psi,\nabla^2\psi-\frac{\psi}{\lambda^2}+f_0\frac{h}{H}+\beta y\right)=f_0\frac{D_E}{2H}\nabla^2(\psi^*-\psi) \tag{1}$$

is adopted in a truncated spectral form (Charney and Devore 1979)

$$\dot{\psi}_A=-k_{01}(\psi_A-\psi_A^*)+h_{01}\psi_L, \tag{2}$$

$$\dot{\psi}_K=-(\alpha_{n1}\psi_A-\beta_{n1})\psi_L-\delta_{n1}\psi_C\psi_N-k_{n1}(\psi_K-\psi_K^*), \tag{3}$$

$$\dot{\psi}_L=(\alpha_{n1}\psi_A-\beta_{n1})\psi_K+\delta_{n1}\psi_C\psi_M-k_{n1}(\psi_L-\psi_L^*)-h_{n1}\psi_A, \tag{4}$$

$$\dot{\psi}_C=\varepsilon_n(\psi_K\psi_N-\psi_L\psi_M)-k_{02}(\psi_C-\psi_C^*)+h_{02}\psi_N, \tag{5}$$

$$\dot{\psi}_M=-(\alpha_{n2}\psi_A-\beta_{n2})\psi_N-\delta_{n2}\psi_C\psi_L-k_{n2}(\psi_M-\psi_M^*), \tag{6}$$

$$\dot{\psi}_N=(\alpha_{n2}\psi_A-\beta_{n2})\psi_M+\delta_{n2}\psi_C\psi_K-k_{n2}(\psi_N-\psi_N^*)+h_{n2}\psi_C. \tag{7}$$

The derivation of the above equations and values of relevant parameters refer to Charney and Devore's paper (1979).

In Charney and Devore (1979), the thermal forcing parameters ψ_i^* $(i=L, C, M, N)$ were set to be zero and ψ_A^*, ψ_K^* to be constant. In this paper we let ψ_j^* $(j=A, K, C)$ be nonzero values and divide ψ_j^* into two parts of constant and transient forcing, with the latter including the annual and nonseasonal periodic forcing. Namely, let

$$\psi_j^*(t)=\psi_{j0}^*+\psi_{j1}^*(t)+\psi_{jn}^*(t),$$

where

$$\psi_{j1}^*(t)=S_{j1}^*\cos\omega_1 t,\quad \psi_{jn}^*(t)=S_{jn}^*\cos\omega_n t,$$

S_{j1}^*, ω_1 are the amplitude and angular frequency of the annual periodic forcing term, and S_{jn}^*, ω_n the amplitude and angular frequency of a nonseasonal or interannual time scale periodic forcing term ($n>2$) respectively. When S_{jn}^* equals zero, it corresponds to the circumstance of strict annual periodic forcing without any interannual scale external forcing. In the following, we at first let S_{jn}^* be zero, and discuss the problem of interannual variations of flow patterns triggered by internal dynamical processes of the atmosphere alone.

III. INTERANNUAL VARIATIONS OF FLOW PATTERNS TRIGGERED BY INTERNAL DYNAMICAL PROCESSES IN THE ATMOSPHERE

Letting $S_{jn}^*=0$ $(j=A, K, L)$, angular frequency of the annual forcing $\omega_1=2\pi/365\text{d}$, and initial values $(\psi_{A0}, \psi_{K0}, \psi_{L0}, \psi_{C0}, \psi_{M0}, \psi_{N0})=(0.080, 0.0001, 0.0001, 0.0001, 0.0001, 0.0001)$, we integrate Eqs. (2)—(7) for more than 100 model years by using the filtering-central difference scheme (Asselin 1972) with the time step being 3 hours. The monthly (January to December) and annual mean spectral coefficients ψ_i $(i=A, K, L, C, M, N)$ in the second model year are taken as the standard values, and then the distance function F_k for each month and year from model year three to one hundred is calculated. Here, F_k is defined as

$$F_k = 100 \times \sqrt{\sum_{i=A,K,L,C,M,N} (\psi_{ik} - \psi_{i2})^2}, \qquad (k = 3,4,5,...,100)$$

If the distance function, F_k, does not change with the sequence number, k, of a model year, it indicates that there is no interannual variation of flow patterns; if F_k changes periodically with k, it indicates that the interannual variation of flow patterns is periodic. The interannual variation of distance function is hereafter used to represent the interannual change of flow patterns.

The computation results show that the interannual variation of F_k in winter is more evident than in summer, which is similar to the circumstance in the atmosphere. Therefore, we discuss the results of the winter month hereafter.

When the value range of annual forcing parameter, S^*_{j1} ($j = A, K, C$), is different, the evolution of flow patterns shows different characteristics. In some parameter ranges, the evolution of flow patterns has same oscillation period as the external forcing, only showing the annual variation without any interannual changes. Correspondingly, F_k is a straight line parallel to the abscissa in F_k–k diagram.

However, in other parameter ranges, the evolution of flow patterns contains both the annual and interannual variation components. F_k is a broken line of periodic variations in F_k–k diagram (Figs. 1c and 1e). It is common knowledge that in the nonlinear dissipative system of constant forcing, with gradual variations of forcing parameters, the periodic state of the system evolution may often change from a period to a doubled period, i.e. a multiplication phenomenon of period, and a triplicate period window may frequently appear in the chaotic area. In this paper, the period–doubling (comparing Fig. 1a with Fig. 1e) and triplicate period (Figs. 1c—1d) phenomena similarly occur in the nonlinear dissipative system of an annual periodic forcing, and they correspond to interannual low frequency variations of 2–year and 3–year periods of large–scale flow patterns.

In the above computation, the time step is 3 hours. In order to examine the effect of

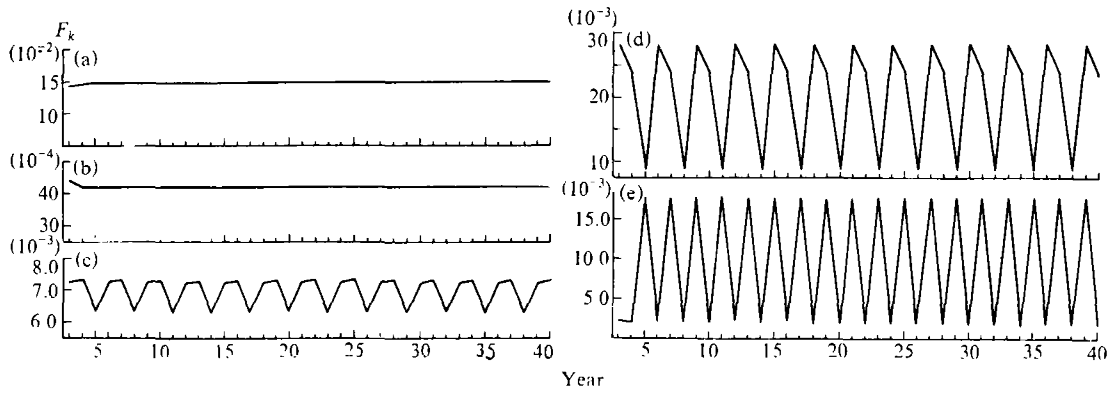

Fig. 1. Interannual variations of February distance function F_k. The abscissa is the sequence number of model year; $S^*_{A0} = 0.50$, $S^*_{A1} = 0.20$, $S^*_{K0} = 0.0$, $S^*_{c0} = -0.15$; (a) $S^*_{k1} = -0.440$, $S^*_{c1} = 0.200$; (b) $S^*_{k1} = -0.450$, $S^*_{c1} = 0.205$; (c) $S^*_{k1} = -0.451$, $S^*_{c1} = 0.200$; (d) $S^*_{k1} = -0.4521$, $S^*_{c1} = 0.200$; (c) $S^*_{k1} = -0.4520$, $S^*_{c1} = 0.200$.

time step, four sets of experiments are performed with the time step of 1.5 hours. The experimental results show that in some ranges of parameter S^*_{K1}, the evolution of flow patterns exhibits only annual variation without any interannual changes; however, in other ranges, the evolution of flow patterns displays the annual as well as interannual variation components (figure omitted). It seems that the phenomenon that the external forcing of annual period can trigger the interannual variation of flow patterns may result from the property of the nonlinear system (2)—(7) instead of the computation.

Because S^*_{K1} approximately depicts the intensity of thermal sea–land difference in the zonal direction, it can be inferred that when the thermal difference of sea–land reaches a certain intensity, it is able to trigger the interannual low–frequency oscillation of motion of the model atmosphere.

In the atmosphere, the evolution of some characteristic quantities of circulations and regional rainfall shows a quasi–three–year periodic characteristic, which is extensively applied in the operational forecasts. We further discuss the interannual variation of flow patterns of three–year period next.

IV. INTERANNUAL VARIATIONS OF THE FLOW PATTERNS ARISING FROM BOTH INTERNAL DYNAMIC PROCESS IN THE ATMOSPHERE AND NON–SEASONAL FORCING

The interannual variation of 3–year period (denoted as T_d) shown in Figs. 1c and 1d is triggered by internal dynamical processes in the atmosphere. We are going to analyze the interannual variation of flow patterns arising from both interannual dynamical processes in the atmosphere and non–seasonal forcing, especially to analyze what kind of characteristic the interannual variation of flow patterns has when the oscillation period of non–seasonal external forcing is the same as or close to T_d.

In order to analyze the interannual variation of flow patterns arising from both internal dynamical processes in the atmosphere and interannual–scale forcing of 2–, 3–, 4–, 5–years periods, we use the values of thermal forcing parameters S^*_{j0}, S^*_{j1} ($j=A, K, C$) in Fig. 1d, let non–seasonal external forcing parameters $S^*_{An}=0.0$, $S^*_{Kn}=0.0$, $S^*_{Cn}\neq 0.0$ ($n=2, 3, 4, 5$), and ω_n be the angular frequencies of 2–, 3–, 4–, 5–years respectively. The computation results are shown in Fig. 2.

Now we interpret the results in Fig. 2.

(1) Under the joint influence of non–seasonal periodic external forcing and internal dynamical processes in the atmosphere, characteristics of interannual variation of flow patterns may include the following four categories:

(i) Domination of internal dynamical processes in the atmosphere (Fig. 2a). The time evolution of F_k in Fig. 2a still exhibits a characteristic of 3–year period, the amplitude and phase of the period are close to those of oscillations triggered by internal dynamical processes in the atmosphere (Fig. 1d), indicating that when the intensity of non–seasonal periodic external forcing is small, the characteristics of interannual variation of flow patterns are still determined by internal dynamical processes in the atmosphere.

(ii) Domination of non–seasonal external forcing (Fig. 2b). The time evolution of F_k in Fig. 2b displays a strict 2–year period oscillation, and the original oscillation of 3–year period arising from internal dynamical processes in the atmosphere has disappeared completely.

(iii) Period–doubling phenomenon of non–seasonal external forcing (Figs. 2c and 2d). The interval between peak values a and b in Fig. 2c is 6 years; therefore, the interannual variation of 6–year period (output) of flow patterns is just twice as much as that of the 3–year period (input) of non–seasonal external forcing, resulting in the period multiplication phenomenon between input and output. Meanwhile, the evolution of F_k in Fig. 2c still remains the trace of 3–year period, namely the interval between valley points b′ with a′ and c′ is still 3 years, or a valley value year occurs again every 3 years.

In Fig. 2d, there is a complete cycle between peak values a and b, which is an oscillation of 8–year period (output). The output period is just twice as large as the 4–year period (input) of interannual external forcing.

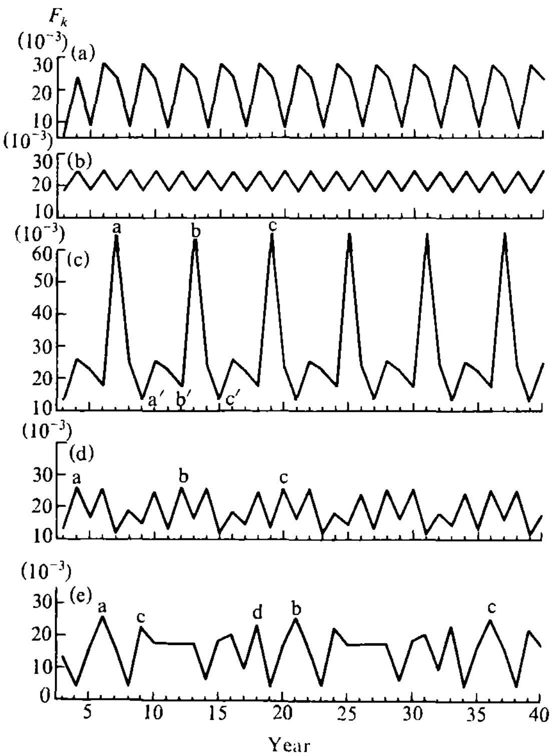

Fig. 2. Interannual variations of February distance function F_k arose from both the non–seasonal forcing of different periods and internal dynamical processes in the atmosphere. The abscissa is the sequence number of model year; $S^*_{A0}=0.50$, $S^*_{A1}=0.20$, $S^*_{K0}=0.0$, $S^*_{K1}=-0.4521$, $S^*_{C0}=-0.15$, $S^*_{C1}=0.20$, $S^*_{An}=0.0$, $S^*_{Kn}=0.0$; (a) $S^*_{Cn}=0.2\times10^{-9}$, $T_n=3$a; (b) $S^*_{Cn}=0.2\times10^{-8}$, $T_n=2$a; (c) $S^*_{Cn}=0.2\times10^{-8}$, $T_n=3$a; (d) $S^*_{Cn}=0.2\times10^{-8}$, $T_n=4$a; (e) $S^*_{Cn}=0.2\times10^{-8}$, $T_n=5$a;

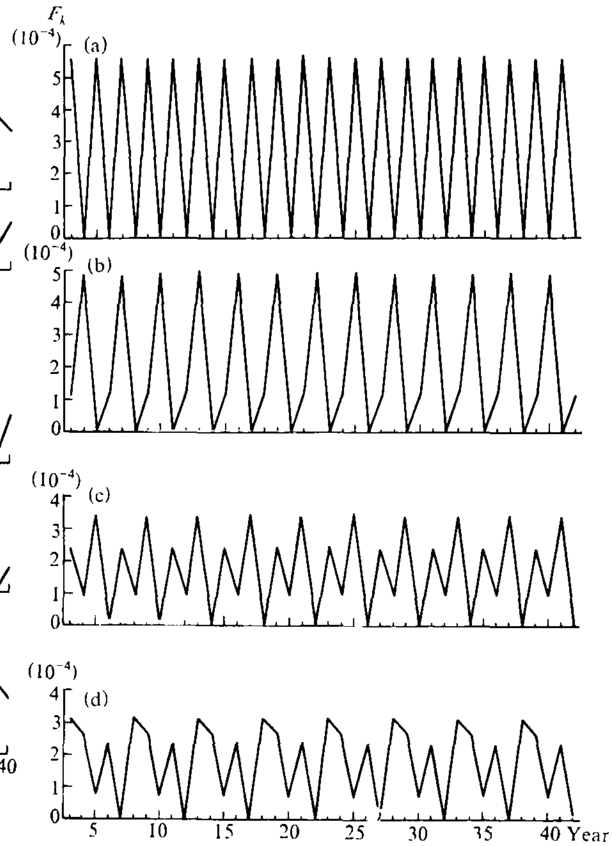

Fig. 3. Interannual variations of February distance function F_k arising from non–seasonal forcing. $S^*_{A3}=0.0$, $S^*_{K3}=0.0$, $S^*_{C3}=0.0045$, other parameters are the same as Fig.1b; (a) $T_n=2a$, (b) $T_n=3a$, (c) $T_n=4a$, (d) $T_n=5a$.

(iv) Joint effect of internal dynamical processes in the atmosphere and non–seasonal external forcing (Fig. 2e). The interval between peak values a and b is 15 years, whereby to consist of an oscillation period. It is just the least common multiple of the period (5–year) of non–seasonal external forcing and the period (3–year) of oscillations triggered by internal dynamical processes.

The period length of non–seasonal forcing is the same, but the intensity is different in Fig. 2a and Fig. 2c. Inversely, the intensity of non–seasonal forcing is the same, but the period length is different in Figs. 2b—2e. The above two kinds of differences result in obvious discrepancy of interannual variations of flow patterns. This shows that under the joint influence of non–seasonal forcing and internal dynamical processes, whether the intensity or period length of external forcing, both may affect the interannual variation of flow patterns.

(2) It is obvious that the amplitude of F_k in Fig. 2c is the largest among those in Figs. 2b—2e. It is 8.74, 3.77 and 2.43 times as large as that of F_k in Fig. 2b, Fig. 2d and Fig. 2e respectively. By comparing Fig. 2c with Fig. 1d, it can be seen that the period length of oscillations in the former is twice as large as that in the latter, indicating that when the oscillation period of non–seasonal external forcing is the same as that triggered by internal dynamical processes alone, the amplitude of interannual variation of flow patterns becomes larger and the period length is doubled.

By comparing the time evolution of F_k in Figs. 2b—2e with that in Fig. 1d, it can be seen that there are obvious differences between the interannual variation of flow patterns (Figs. 2b—2e) arising from both non–seasonal forcing and internal dynamical processes and that (Fig. 1d) triggered by internal dynamical processes of the atmosphere alone.

In the above computation, the time step is set to be 3 hours. Under the circumstance that the time step is 1.5 hours, the similar computational results also suggest that when the oscillation period of non–seasonal external forcing is close to that triggered by internal dynamical processes of the atmosphere, the amplitude of interannual variations of flow patterns is the largest (figure omitted).

In some parameter ranges, the internal dynamical processes of the atmosphere are unable to create the interannual variation of flow patterns (Fig.1b). On the basis of the parameters in Fig. 1b, after incorporating the non–seasonal external forcing the computational results show that the flow pattern also exhibits the interannual oscillation (Fig.3), which is obviously triggered by the non–seasonal external forcing. In order to match with the cases in Fig. 2, the period lengths of non–seasonal external forcing in Fig. 3 are set to be 2, 3, 4 and 5 years respectively.

There are the following differences in Fig.3 and Fig.2:

(1) In Fig.2 the maximum amplitude (Fig.2c) is 8.75 times as large as the minimum amplitude (Fig.2b) . In Fig.3, when the period of non–seasonal external forcing is 2 years (Fig.3a) , the amplitude of interannual variations of flow patterns is the largest; when the forcing period is 5 years (Fig. 3d), the amplitude is the smallest. The former is only 1.75 times as large as the latter.

(2) The period of interannual variations of flow patterns in Fig. 2 differs mostly from those of non–seasonal forcing, exhibiting 6–, 8– and 15–year periods. However, interannual variations (output) of flow patterns in Fig. 3 have same periods as those of non–seasonal forcing (input).

(3) Let $R = A_f / S^*_{Cn}$, where A_f is the amplitude of interannual variations of F_k and S^*_{Cn} the amplitude of non–seasonal periodic forcing. R is the ratio of the interannual variation amplitude of flow patterns to the intensity of interannual–scale external forcing, and it can be regarded as the ratio of the intensity of oscillations triggered to the source intensity. The order of R in Fig. 2 is 10^2—10^3; while that of R in Fig.3 is 0.1. It seems that in some parameter range and under the joint influence of possible mechanism of two types, the same interannual–scale forcing may trigger more intense interannual variations of flow patterns.

V. ABRUPT CHANGE PHENOMENON OF INTERANNUAL VARIATIONS AMPLITUDE OF FLOW PATTERNS

Letting $(S^*_{A0}, S^*_{A1}, S^*_{K0}, S^*_{K1}, S^*_{C0}, S^*_{C1}, S^*_{A3}, S^*_{K3}) = (0.50, 0.20, 0.00, -0.4521, -0.15, 0.20, 0.00, 0.00)$ and taking 14 values in interval $[5.006, 4.980\,] \times 10^{-8}$ S^*_{C3} with an equal distance, then 14 experiments whose integration time is 100 model years are performed. The results of the first 11 experiments show that the amplitude of interannual variations of distance function, F_k, is all below 0.8×10^{-4}. However, when S^*_{C3} is reduced from 4.986×10^{-8} to 4.984×10^{-8}, the amplitude of interannual variations of distance function, F_k, abruptly increases.The amplitude of interannual variationof F_k after the abrupt change (Fig. 4a) is about 10 times as large as that before the abrupt change (Fig. 4b).

The abrupt increase of the amplitude of interannual variation of F_k reflects the sudden enlargement of the range of interannual variation of flow patterns, implying that the deviation or anomalous extent from the normal of some year circulations increases. It suggests that the gradual variation of the intensity of non–seasonal periodic thermal forcing can trigger the flow pattern of large deviation from the normal.

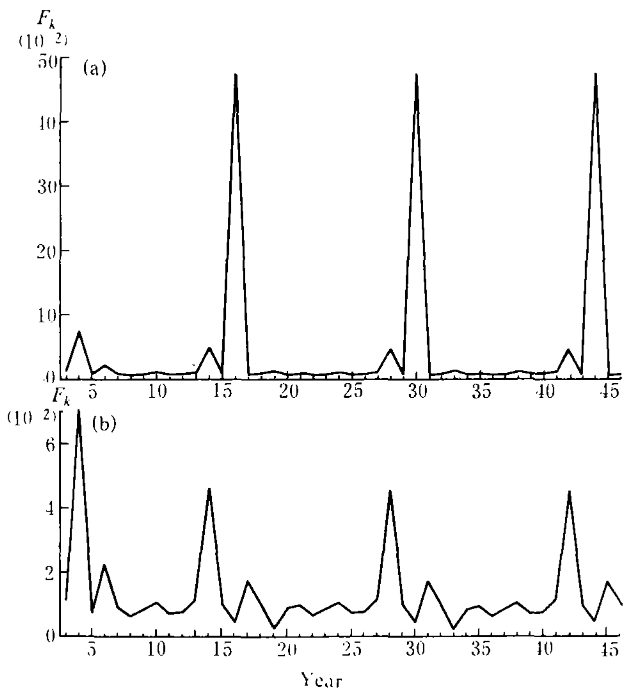

Fig. 4. Interannual variations of February distance function F_K. (a) $S^*_{c3} = 4.984 \times 10^{-8}$; (b) $S^*_{c3} = 4{,}986 \times 10^{-8}$.

VI. RESULTS AND CONCLUSIONS

There are clear interannual variations of the flow patterns of large–scale motion and the regional drought / flood and cold / warm in the real atmosphere. The understanding of those regular patterns and forming mechanism may offer a physical basis for the scientific prediction of anomalous years in large areas.

Some problems have been studied (Manabe and Hahn 1981; Lau 1981; Ma 1990), and however there are still many problems to be analyzed in the possible mechanism of the interannual variation of large–scale flow patterns. We pay particular attention to the following two problems: (1) the characteristics of interannual variations of flow patterns under the joint influence of non–seasonal periodic thermal forcing and internal dynamical processes of the atmosphere; (2) the abrupt change of interannual variations amplitude of flow patterns. This paper preliminarily studies the two problems.

In a famous paper, under the conservative conditions Charney and Devore (1979) started from the truncated spectrum form of barotropic vorticity equation and got a constraint that the perturbation quantities of spectral coefficients ψ_L must satisfy. It is a linear oscillation equation and its restoring force is related with β effect and so on, thus establishing a connection between the large–scale motion and linear conservative oscillation system. For a nonlinear forcing oscillation system, the periodic external forcing may trigger new patterns of state evolution. The new pattern may be periodic, and its period length is integer times of the period length of external forcing. This result is suggestive. Because the motion of the earth atmosphere is driven by the annual periodic external forcing of solar radiation, if the annual periodic external forcing is able to trigger new periodic evolution, whose period length is integer times of annual period, then it just corresponds the interannual variation of flow patterns. It seems that in some circumstances the interannual variation of flow patterns of atmospheric motion may be a reflection of the general nature of nonlinear forcing oscillation system, and the forming mechanism of interannual variations of flow patterns can at last be included in the nonlinear mechanism of forced dissipative systems. The computation results in this paper show that in the model atmosphere the external forcing of annual period is indeed able to trigger the interannual oscillations of flow patterns of several to fifteen year periods.

Meanwhile, the computational results in this paper also indicate that the characteristics of interannual variations of flow patterns (Fig. 2), arose from both internal dynamical processes in the atmosphere and non–seasonal external forcing, are more complicated than that triggered by the internal dynamical process in the atmosphere (Figs.1c and 1e) or non–seasonal external forcing (Fig.3) alone. When the oscillation period of non–seasonal external forcing is close to or equal to that triggered by internal dynamical processes alone, a new oscillation form of interannual variations of flow patterns appears. The amplitude of the oscillation obviously increases and the period becomes double.

There have been many results, which are relevant to that the gradual variation of thermal forcing parameters may trigger abrupt changes of large–scale flow patterns in the model atmosphere. However, those papers did not incorporate the periodic external forcing of interannual–scale. In this paper, after incorporating the forcing, the gradual variation of thermal forcing parameter triggers the abrupt change of amplitude of interannual variations of flow patterns. Namely the flow pattern suddenly changes from a state with mild interannual variations and small deviations from normals to a state with more violent interannual variations and larger deviations from normals. The sudden increase of the interannual variation amplitude of flow patterns corresponds to the abrupt enhancement of anomalous extent of large–scale flow patterns, which is related with anomalous years. This is a problem worthy to be further investigated.

The interannual variation of large–scale motion of the atmosphere and its forming mechanism are very complicated problems. The preliminary work has been done in this paper and there are many problems not involved here, for example, the truncated spectrum problem. The computational results in this paper indicate that the internal dynamical processes of the atmosphere may trigger the interannual variations of flow patterns with a 3–year period, which is consistent with Ma's paper (Ma 1990). The truncated spectrum model used in this paper has 6 dimensions, while Ma's model has 12 dimensions. Although two truncated spectrum numbers are different but the results are similar. Nevertheless, we still do not know what kind result will appear after more spectral components are introduced into the model. Such problems as the model used include too few physical processes, different computation schemes may affect results and so on, require further study.

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