A NUMERICAL STUDY ON THE INTERANNUAL TIME-SCALE LOW-FREQUENCY OSCILLATION

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ABSTRACT

Low-frequency oscillation (LFO) of a large-scale flow pattern is an important observational characteristic feature. In this paper, under the forcing of annual periodic variation a two-layer quasi-geostrophic low-spectrum model is used for carrying out a prolonged numerical integration of more than 30 model years. In the model atmosphere, the interannual time-scale LFO is implicitly reproduced. The result is quite agreeable with the observational evidence.

I. INTRODUCTION

The flow pattern of the large-scale atmospheric motion and the change of regional weather elements with time not only have quasi-three-week LFO but also show obvious interannual variation, i.e., the interannual time-scale LFO . Quite a few statistical rules of the latter are now widely used in long-range weather forecasting and great importance has been attached to its formation mechanism. This will certainly provide a theoretical basis of dynamics for the corresponding forecasting techniques.

The interannual variation of a weather element, for example, the pressure over the earth's surface, is often characterized by the standard deviation of its secular time series, which varies with place, thus causing different geographical distributions of its interannual variation. These distributions formed have fixed patterns, reflecting the observational features of its interannual variation. Manabe and Hahn (1981) integrated 18 model years by using a global low-resolution spectrum model, which involved, given the sea surface temperature, only the strict heat source forcing of annual periodic variation other than any interannual variation outside the source. They not only simulated the distribution of the pressure over the earth's surface, but also successfully duplicated the logical spatial distribution of its interannual variability, i.e., the standard deviation. Another observational feature of the interannual variation is that in some years a characteristic flow pattern, such as the winter blocking pattern, is similar to the average state of climate whereas in other years a flow pattern may develop abnormally, causing considerable difference between years. Similarly, Lau (see Hoskins and Pearce, 1983) integrated 17 3/4 model years for the GFDL global model only using the seasonal forcing of annual variation without introducing the forcing of any other time components. The result shows that the winter blocking pattern develops abnormally in certain model years.

This study holds that for the interannual variation in the real atmosphere, from the viewpoint of observation, there are two important observational facts which are noteworthy in addition to the geographical distribution of the standard deviation and the abnormal development of the flow pattern in certain years. One is that both the large-scale flow pattern and the change of weather elements with time are often featured by the quasi-periodicity measured in year.The other is that the persistence of the abnormal flow pattern often shows interannual variation.

In view of the fact that the two observational features are closely related to operational forecasting, either to the extrapolated forecasting or to the searching of the forerunner in the early stage of abnormality, a numerical study will be made of their formation. First observational evidence of periodicity and persistence will be given and then a comparison will be made between the numerical integration and the observational evidence.

II. OBSERVATIONAL EVIDENCE OF PERIODICITY AND PERSISTENCE

Using the data of the spherical coefficients A_n^m and B_n^m of the 500 hPa monthly mean height field (Shi et al., 1985), we obtain

$$D_{ij}=\sum_{n=m}^{m+b}\sum_{m=0}^{4}[(A_{n,i,j}^m-A_{n,0,j}^m)^2+(B_{n,i,j}^m-B_{n,0,j}^m)^2], \tag{1}$$

where $i=56, 57,\ldots, 66, 68,\ldots,74$, $j=1,2,\ldots,12$, $i=0$ represents the spherical coefficient in 1967, D_{ij} represents the simularity of the monthly mean height field(January through December) in the years of 1956—1966 and 1968—1974 to that in 1967 (when D_{ij} reached its minimum, the two flow patterns are most similar), m is the number of waves spread zonally, and $(n—m)/2$ is the number of waves spread meridionally. It is generally believed that most of the secular variation of the atmospheric motion is due to the planetary-scale action of extra-long waves, etc. (See Brun,1985). Hence here we take zonal wavenumber only up to $m=4$.

For the purpose of reducing the influence of the annual variation of D_{ij} on the analysis result after D_{ij} has been determined, we have calculated the secular mean value $\bar{D}_j$ of D_{ij} (January through December) in the 1956—1974 period and let $D'_{ij}=D_{ij}/\bar{D}_j$, obtaining $D'_i=\left[\sum_{j=1}^{12} D'_{ij}\right]/12$. D'_i reflects the degree of the general simularity of the 500 hPa height field in the ith year ($i=$ 56, 57,..., 66, 68,...,74) to that in 1967. The maximum (minimum) of D'_i indicates the least (most) similarity of the flow pattern in the ith year to that in 1967. It is found that in 1960,1963, 1966, 1969, 1972 and 1974,D'_i reached its maximum and in 1961, 1964, 1967, 1970 and 1973 (at a, b, c, d and e in Fig. 1), D'_i reached its minimum. This suggests that the 500 hPa height fields in 1961, 1964, 1967, 1970 and 1973 are relatively rather similar to each other, in other words, a similar flow pattern would occur once in about three years, indicating that the flow pattern has a three-year oscillation.

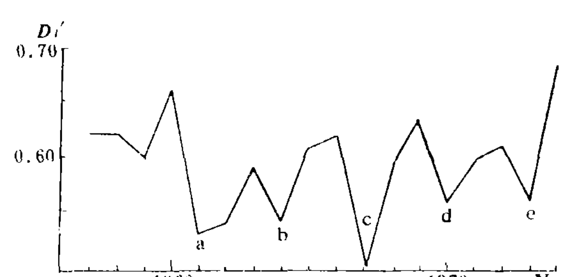

Fig. 1. Variation D_i' with time.

The periodicity of the flow pattern variation may influence the change of regional rainfall with time. Twelve representative stations (Zhangye, Xining, wuwei, Lanzhou, Yinchuan, Tongxin, Tianshui, Yan'an, Xi'an, Yuncheng, Taiyuan and Datong) have been chosen from the semi-arid areas of China for calculating the percentages of the annual precipitation anomalies from 1951 through 1980. After averaging the values in the records from the twelve stations, we obtain the percentages of the regional mean yearly rainfall anomalies R_i ($i=51, 52,\dots,80$). As shown in Fig. 2, the change of R_i with time indicates that there was excessive rain in 1958, 1961, 1964 and 1967 (at a,b,c and d in Fig. 2a). Evidently, in the period of 1958—1967, a rainy year was experienced every three years. This also quite agrees with the three-year oscillation of the 500 hPa flow pattern variation in the Northern Hemisphere (Fig. 1). It is seen from the seasonal distribution of the three-year oscillation that precipitation in May and June showed most noticeable three-year oscillation (Xu et al., 1982). Moreover, the three-year oscillation is also found in the drought-flood grade series during the past 400 years (Luo et al., 1982). Thus, it can be believed in the large-scale flow pattern and the change of rainfall with time in some semi-arid areas, the quasi-three-year oscillation is most probably the characteristic statistical evidence. In this study, emphasis will be laid on the analysis of whether the flow pattern variation in the model atmosphere has a three-year oscillation.

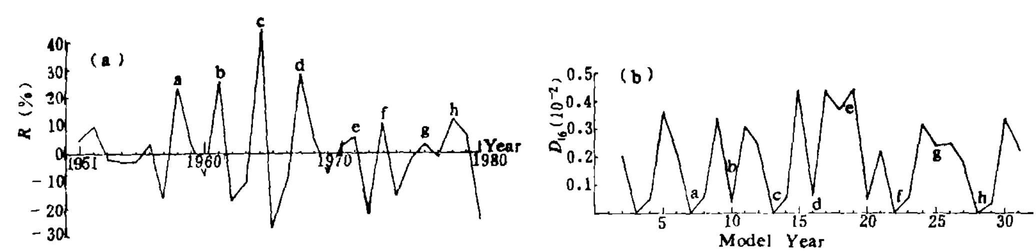

Fig. 2. Variation of R and D_{i6} with time. (a) Mean value of the annual precipitation anomaly percentage R. (b) The 250 hPa monthly distance function of the model atmosphere in June D_{i6}. The parameters $\theta^*_{A0}=0.05$, $\theta^*_{A1}=0.02$, $\theta^*_{K_0}=0$, $\theta^*_{K1}=-0.025$, $\theta^*_{C0}=-0.015$ and $\theta^*_{C1}=0.0301$.

Studies have been made by Wang(1963), Li(1963)and Chen (1980) on the persistence of the large-scale flow pattern. In some years, for example, in 1960, circulation of high index lasted as long as six months, whereas in other years, for example, in 1959, it only lasted one month, as shown in Table 2 of the paper by Wang (1963). This suggests that the flow pattern also shows interannual variation in persistence. As for the seasonal variation in persistence, the subtropical high became weakened or intensified eight times in the period of 1954—1975, six times in October or November, indicating that the subtropical high tends to change from strong to weak or vice versa most probably in autumn (Chen, 1980), and the change in the west wind index persistence also often occurs in the transitional season (Wang, 1963).

In the next section, prolonged numerical integration will be performed for the 2-layer quasi-geostrophic spectrum model, and the periodicity and persistence of the flow pattern variation in the model atmosphere will be analyzed.

III. PERIODICITY AND PERSISTENCE OF THE LARGE-SCALE FLOW PATTERN IN THE MODEL ATMOSPHERE

By way of a low spectrum the 2-layer quasi-geostrophic model in the β-plane is transformed to an equation set having the coefficient of spectral evolution as an unknown function. The governing equation for the 2-layer quasi-geostrophic model in the β-plane is

$$\frac{\partial}{\partial t}\nabla^2\psi_1, = -J(\psi_1, \nabla^2\psi_1 + \beta^* y) + f_0\frac{\omega_2}{\Delta p} - K'_b(\psi_1 - \psi_3), \tag{2}$$

$$\frac{\partial}{\partial t}\nabla^2\psi_3 = -J(\psi_3, \nabla^2\psi_3 + \beta^* y) - f_0\frac{\omega_2}{\Delta p} - K'_b(\psi_3 - \psi_1) - Kd\nabla^2\psi_3$$

$$-\frac{f_0}{H}J(\psi_1, h), \tag{3}$$

$$\frac{\partial}{\partial t}(\psi_1 - \psi_3) = -J(\psi_2, \psi_1 - \psi_3) - \frac{f_0}{\Delta p}\lambda^2\omega_2 + \lambda^2 h'_d[(\psi_1 - \psi_3)^* - (\psi_1 - \psi_3)], \tag{4}$$

where all symbols are conventional and the subscripts 1, 2 and 3 stand for the 250, 500 and 750 hPa levels respectively.

After the non-dimensionalization of Eqs. (2)—(4), let

$$\psi_1 = \psi + \theta, \quad \psi_3 = \psi - \theta, \quad \psi_2 = \psi,$$

$$(\psi, \theta) = \sum_{i=A,K,L,C,M,N} (\psi_i, \theta_i) F_i,$$

$$h = h_K F_K,$$

$$\theta^* = \sum_{i=A,K,C} \theta_i^* F_i.$$

Substituting Eqs. (2)—(4) yields the equation set having ψ_i and θ_i as the unknown functions. For the form of the equations, see papers (Luo, 1987; Ma et al., 1987).

The physical process contained in the 2-layer quasi-geostrophic model has a zonal asymmetric heat source, idealized large topography, nonlinear advection, dissipation effect, etc. The spectral evolution coefficient in the heat source term $\theta_i^* = \theta_{i0}^* + \theta_{i1}^* \cos\omega t$ ($i =$ A, K,C), where the term involving $\cos\omega t$ is the term of the thermal forcing of the annual periodic variation and the circular frequency of the annual periodic variation,is used to describe approximately the annual variation of the solar radiation. $\omega t = 0, \pi/2, \pi$, and $3\pi/2$ represent winter solstice, vernal equinox, summer solstice and autumnal equinox respectively. Thus, the time limitation to all the model months can be set. For example, $2.78199 \leqslant \omega t < 3.29386$ is June in the first model year. In addition to the periodicity of annual variation, there is no interannual change in the heat source and no process of artificial interannual variation is introduced into the model. What needs to be studied is whether the model atmosphere as a nonlinear system of forced dissipation can show interannual variation when excited by the thermal forcing source of the strict annual periodic variation.

Two prolonged integrations are performed for the spectral evolution, the time for integrations being 31 and 61 model years respectively. The initial condition is $\varphi = \varphi_{01} =$ (0.06760, 0.00001, 0.00000, -0.02000, 0.00000, 0.00000, 0.06760, 0.00001, 0.00000, -0.02000, 0.00000, 0.00000), where $\varphi = (\psi_A, \psi_K, \psi_L, \psi_C, \psi_M, \psi_N, \theta_A, \theta_K, \theta_L, \theta_C, \theta_M, \theta_N)$.From the result of the integration we obtain the 250 hPa monthly mean stream function field (January through December) and using the monthly mean field for all the months in the third model year as the fiducial field we have the distance function between the monthly mean field for the corresponding months in the fourth, fifth,..., thirty-first or sixth-first years and the fiducial field D_{ij} ($i = 4, 5, \ldots, 31$

or 61, $j=1,2,\ldots, 12$). The features of the interannual change of the large-scale flow pattern in the model atmosphere can be analyzed from the change of the distance function D_{ij} with time. Fig. 2b shows the change of the distance function D_{ij} with time in the monthly mean stream function field of June. It can be seen from Fig. 2b:

(1) The valley value of D_{i6} occurs in the 7th , 10th, 13th and 16th model years (at a, b, c and d), indicating that the 250 hPa stream function fields in June of the 7th, 10th, 13th and 16th model years are similar to that in June of the 3rd model year, and the intervals between the four valley values are all three years. That is to say, in 7—16 model years a similar monthly mean stream function field would occur every three years. This suggests that the large-scale flow pattern has a three-year periodicity in variation.

(2) In the 17th—31st model years, the three-year oscillation is not obvious, showing that the periodicity has changed in the time series. This is similar to the observational evidence shown in Fig. 2a, where the three-year periodicity was dirupted at the beginning and end of the 1970s.

(3) It is known from the experience in forecasting that in a period when the three-year periodicity in rainfall is disrupted, evidence of the three-year oscillation can still be seen. Take Fig. 2a for example. The year of 1967 was the peak year of precipitation. According to the three-year periodicity, 1970 would also be the peak year. But it was not. This means that the three-year periodicity was disrupted. However, 1973, the following peak year, was observed inspite of the disruption of the three-year periodicity. We know that windows of the three-year or six-year periodicity often occur in a chaotic area, similar in appearance to the situation here. This needs further studies. From the results of numerical integration in this paper, in three years after 16 model years, the valley value does not occur in the 19th model year. In appearance, the three-year periodicity is disrupted, but three years after the 19th model year (at e), i.e., in the 22nd model year (at f), a new valley value occurs. It is also true for the case of the valley value in the 28th model year. This agrees with the curve of the precipitation evolution shown in Fig. 2a and the experience in forecasting.

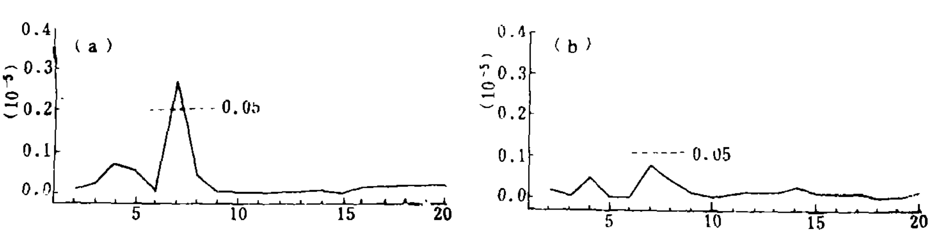

Fig. 3. Periodogram of the distance function D_{i7}: (a) In the 4th−43rd model years, and (b) in the 4th−61st model years.The parameters $\theta^*_{A_0}=0.05$, $\theta^*_{A_1}=0.02$, $\theta^*_{K_0}=0$, $\theta^*_{K_1}=-0.025$, $\theta^*_{C0}=-0.015$, $\theta^*_{C1}=0.0300$. The ordinate is the intensity square and the abscissa the period (year).

The change in periodicity can be more clearly seen from the result of the prolonged numerical integration of 61 years. With the values of the 250 hPa monthly mean stream function field (from January through December) over the years, the distance function between the mean flow field of July and the fiducial flow field D_{i7} ($i=4, 5,\ldots,61$) can be determined. Then two analyses of periodicity are made for the time series of D_{i7} , one in the 4th-43rd model years and the other in the 4th-61st model years. The result is that the seven-year periodicity is obvious in the former (Fig. 3a) but is no longer obvious in the latter (Fig. 3b). This suggests that in the output of 61-year integration, the seven-year periodicity is evident in the change of the monthly mean flow field of June with time during the first 40 years or so but is disrupted later.

Based on the monthly mean flow field from the output of the above 31-year integration and taking the flow field at winter solstice of the first year as the fiducial field, we obtain the distance function between the monthly flow field and the fiducial flow field, and then the secular mean value of the monthly distance function (January through December) and its anomalies. It can be seen from the analysis of the monthly and yearly changes of these anomalies that:

(1) The persistence of the circulation abnormality has interannual variation.

In the 5th model year, for example, the negative anomaly persists from January through October whereas in the 20th model year both positive and negative anomalies last no more than two months in the period.

(2) The persistence of the circulation abnormality is easily disrupted in the transitional season.

The correlation coefficients of these anomalies between the neighboring months can be calculated from the anomalies of the monthly distance function (January through December) of the 31-year integration. These correlation coefficients reflect the persistence in the months of circulation abnormality. It is found that the greater their positive values, the better their persistence, whereas their negative values indicate that the circulation abnormality cannot persist. The results are shown in Table 1. It is seen that the correlation coefficients (r) are

Table 1. Correlation Coefficients (r) of the Distance Function (%)

Months	J–F	F–M	M–A	A–M	M–J	J–J	J–A	A–S	S–O	O–N	N–D	D–J
r	99	38	18	−44	63	74	61	98	56	−29	98	87

negative in April—May and October—November, indicating that generally the circulation abnormality cannot persis in the transitional season. This is quite coincident with the results obtained by Wang (1963) and Chen (1980).

IV. DISCUSSION

The large-scale, flow pattern and the change of weather elements with time in the real atmosphere often show periodicity and persistence. As statistical laws these characteristic features find wide application in long-range and climatic forecasting. Thus, the inherent physical mechanism of these laws has set a question of dynamics of the long-term weather process and is worth thorough studies.

No other forcing source of non-annual periodic variation has been taken into account apart from the heat source of the annual periodic variation. However, the model atmosphere can still show quite clearly the features of the interannual variation. It seems that the dynamics within the atmosphere is able to excite oscillation which is lower than the oscillation frequency of the forcing source. This is one of the reasons for the interannual variation.

The external forcing source of non-annual periodic variation may exert a considerable effect on the model atmosphere. How does the dynamics within the atmosphere behave after the external source is introduced? We will continue our studies of the question.

In this study, the quasi-three-year low-frequency oscillation of the model atmosphere is mainly discussed. In the real atmosphere, however, there exist other time scales. For example, the two-year and five-year oscillations have not been dealt with. Moreover, the β-plane approximately sets a limit to the ability of the descriptive wave action of the model to propagate in the meridional direction. This is not as good as the analysis using the spherical coordinate model.

We will continue to study these question in due time.

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