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LOW FREQUENCY VARIABILITY OF INTERANNUAL CHANGE PATTERNS FOR GLOBAL MEAN TEMPERATURE DURING THE RECENT 100 YEARS

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ABSTRACT: The TEEOF method that expands temporally is used to conduct a diagnostic study of the variation patterns of 1, 3, 6 and 10 years with regard to mean air temperature over the globe and Southern and Northern Hemispheres over the course of 100 years. The results show that the first mode of TEEOF takes up more than 50% in the total variance, with each of the first mode in the interannual oscillations generally standing for annually varying patterns which are related with climate and reflecting long-term tendency of change in air temperature. It is particularly true for the first mode on the 10-year scale, which shows an obvious ascending trend concerning the temperature in winter and consistently the primary component of time goes in a way that is very close to the sequence of actual temperature. Apart from the first mode of all time sections of TEEOF for the globe and the two hemispheres and the second mode of the 1-year TEEOF, interannual variation described by other characteristic vectors are showing various patterns, with corresponding primary components having relation with long-term variability of specific interannual quasi-periodic oscillation structures. A T^2 test applied to the annual variation pattern shows that the abrupt changes for the Southern Hemisphere and the globe come closer to the result of a uni-element t test for mean temperature than those for the Northern Hemisphere do. It indicates that the T^2 test, when carried out with patterns of multiple variables, seems more reasonable than the *t* test with single elements.

Key words: global mean temperature; patterns of interannual variation; abrupt change of climate; T^2 test

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1 INTRODUCTION

Being an important indication for climatic change, the interannual variation patterns of global mean temperature has been studied mostly focusing on its long-term tendency[1-2] while leaving the short-term (interannual) oscillation modes and their evolution with time a subject very much intact. It is well known that one of the aims in the CLIVER program is to identify and describe the climatic variability and predictability on the seasonal and interannual scales and to conduct climatic prediction on these scales, through observational study[4]. It is then obvious that it is insufficient just to study the tendency, abrupt change and quasi-periodicity in the global climate and the work has to be supplemented by having comprehensive knowledge of global interannual oscillation modes. For instance, a time-varying predictive model that is more realistic can be established if we know how the phase and amplitude are varying on longer-than-interannual scales in the interannual oscillation of climate and diagnose the cause and effect on the basis of it.

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Biography: LIU Jing-miao (1956 –), male, native from Liaoning Province, professor, mainly involving with the study of climatology, diagnoses and prediction of climatic land surface processes, author of more than 30 academic papers.

The abrupt change of climate is mainly shown in that of global mean temperature. Documents [5-8] have done much on mean air temperature over the entire globe or hemispheres and suggested the presence of three major events of abrupt warming over the recent 100 years across the globe. With his results in studying temperature anomalies on the Northern Hemisphere, Gordon (1992) shows that there is significant seasonal change in global warming trends — being maximum in winter but minimum in summer[9]. He argues that the anomalous fluctuation of temperature could vary over time. If the abrupt change of mean temperature is singled out in the study, one cannot fully grasp the nature of temperature change. It necessities more study on the abrupt change of seasonal anomalous pattern of temperature and its relation with the one on the annual scale. In addition, as also shown in the present work with the methods of SSA and SCSA to address the quasi-periodicity (including QBO) and long-term evolution of global temperature fluctuation, a pair of primary components can have quasi-periods that are similar to each other but oscillatory modes that differ significantly. Much discrepancy does exist between the global mean temperature and the long-term evolution of variation modes of seasonal and interannual variation over the Southern and Northern Hemisphere[10-11].

On the basis of the analysis above, attempts are made here to verify the time when annual global and hemispheric temperature changes abruptly (oscillates seasonably) as well as studying the intraannual and interannual variation patterns and the low-frequency variability in terms of monthly mean temperature across the globe and Southern and Northern Hemispheres.

2 DATA AND METHODS

(1) The original data are selected from the IPCC's monthly sequences of mean temperature for the Southern and Northern Hemispheres and the globe over the course of 142 years from 1856 to 1997 and pre-treated in monthly standardization.

(2) The EEOFs procedure is used to investigate the annual, 3-year, 6-year and 10-year variation patterns constituted by temporal points on the monthly and interannual scales. The EEOFs analysis, proposed by Weare (1982), is capable of presenting detailed, dynamic description of temporal morphology of continuous evolution, by studying characteristic abstract quantity in the spatial field through expanded EOFs[12]. When it is used in the temporal domain, the description of characteristic abstract quantity in the temporal "field" can be expanded with EEOFs so that patterns of continuous evolution can be obtained. To differentiate from the spatial EEOFs, we call it EOFs (or abbreviat it as TEEOFs) by ways that are stated in details as follows:

Set m the number of monthly sequences and n the number of annual sequences. The matrix of original data (of anomalies) can be expressed in the form of

$$X_{(k=3)} = \begin{pmatrix} x_{11} & x_{12} & \cdots & x_{1,n-2} \\ \cdots & \cdots & \cdots & \cdots \\ x_{m1} & x_{m2} & \cdots & x_{m,n-2} \\ x_{12} & x_{13} & \cdots & x_{1,n-1} \\ \cdots & \cdots & \cdots & \cdots \\ x_{m2} & x_{m3} & \cdots & x_{m,n-1} \\ x_{13} & x_{14} & \cdots & x_{1,n} \\ & & \cdots & \\ \cdots & \cdots & \cdots & \cdots \\ x_{m3} & x_{m4} & \cdots & x_{m,n} \end{pmatrix} \quad (1)$$

where k=3 and m=12, X is the expanded matrix for the temporal domain over consecutive three years (Line 3m, Column n-2). Application of EOFs to it results in TEEOFs. If k=1, we can then have an expanded matrix of temporal domain of 1 year. Other matrixes can be determined in the same way. Just as the characteristic vector obtained with EEOFs is a typical distribution of the expanded spatial field, the one derived here actually represents the typical distribution of the expanded field of time domain that has been achieved, i.e. the typical distribution of wave patterns for the particular temporal domain (field). With their time coefficients representing weight coefficients in individual years for corresponding typical distribution of wave patterns, the evolution with time can be depicted by the distribution. It is thus possible to know how long-term (interdecadal-scale, for example) evolution is going on in the annual and interannual oscillatory patterns.

(3) T^2 testing

The abrupt change of climate can be generally summed up in four groups of, namely, mean value, variability, transition and tilting[13]. Present methods for testing abrupt changes include low-pass filter, moving t-test, Cramer's method, Yamamot's method and Mann-Kendall's method, etc. They are generally useful for the abrupt change in statistically averaged mean climatic values with unitary climatic variables considered in the concept and categorization of the abrupt change. As a matter of fact, the climate system involves itself with multiple variables and usually evolves spatially in the form of "field". It can then, strictly speaking, be stated that abrupt climatic change should be defined with all constituting members in the climate system. It requires analysis of the abrupt change in the element field of climate[14, 15]. Apart from it, for any two stages of the climate change, sometimes mean values may be close to each other but the wave structure (temporal domain) or the pattern of climate field (spatial domain) can be different. It is what is known the issue of abrupt change in internal wave structure (or the distribution pattern / vector).

The T^2 statistic can be used to test the significance of difference between two randomized overall mean values[16]. When it is applied in the significance test of oscillatory modes for two climatic periods, $\overline{X_1}$ and $\overline{X_2}$ are made to represent the sample mean vector of primary oscillatory modes in the periods (such as the annual variation mode), with N_1 and N_2 being corresponding sample size respectively.

In the originally set H_0, the two overall mean vectors are equal, i.e. $m_1 = m_2$. The statistic is defined as

$$F_{12} = \frac{(N_1 + N_2 - M - 1)T_{12}^2}{M(N_1 + N_2 - 2)} \tag{2}$$

in which

$$T_{12}^2 = \frac{N_1 N_2 (\overline{X_1} - \overline{X_2}) S_{12}^{-1} (\overline{X_1} - \overline{X_2})}{N_1 + N_2} \tag{3}$$

$$S_{12} = (S_{ij})_{M*M} = \frac{\sum_{a=1}^{N_1} (x_{ia}^{(1)} - x_i^{(1)})(x_{ja}^{(1)} - x_j^{(1)}) + \sum_{a=1}^{N_2} (x_{ia}^{(2)} - x_i^{(2)})(x_{ja}^{(2)} - x_j^{(2)})}{N_1 + N_2 - 2} \tag{4}$$

where the statistic S_{12} is the variance difference between the two overall mean values. It is then possible to prove that F_{12} observes the F distribution with the degree of freedom being $(M_1, N_1 + N_2 - M - 1)$. Given the critical value F_a and with F_{12} calculated, a comparison is made between F_{12} and F_a with the condition of H_0. If $|F_{12}| \geq F_a$, then original assumption H_0 is in the negative, suggesting the presence of significance difference between the two overall mean values; if $|F_{12}| \leq F_a$, then the assumption is accepted. It is apparent that the T^2 test is in effect a generalized t test but more reasonable, because the latter is simply conducted on its own. Concrete steps are very much the same between the two.

3 INTERANNUAL OSCILLATORY MODES

Tab.1 gives the TEEOF results of mean air temperature for the whole globe and the two hemispheres over periods of 1, 3, 6 and 10 years. When the field of domain is 1 or 3 years, it is shown, the first three characteristic vectors take up more than 62% in the total contribution of variance, and especially, more than 72% for the Southern Hemisphere and the globe, with the first three characteristic vectors representing their primary distribution of modes. Take the oscillation for 6 and 10 years for example. The first three characteristic vectors for the globe and Southern Hemisphere account for over 66% of the variance contribution while those for the Northern Hemisphere for about 50%. It is then safe to state that it is generally representative to just study the interannual modes denoted by the first three characteristic vectors, for all short-term oscillations.

As shown in Fig.1a, the first mode reflects the pattern of the intraannual variation with the characteristic value being the minimum in winter but the maximum in summer, all staying in the positive territory. Compared with the seasonal variation of the mean mode, the Northern Hemisphere goes in phase but the Southern Hemisphere out of phase, with the seasonal variation of the mean climatic state. Differences, though, exist between the hemispheres — for the characteristic vector value, the monthly amplitude is the smallest for the Southern Hemisphere where the maximum occurs in the fourth month; the vector is the largest for the globe in the eighth month; the amplitude is the largest for the Northern Hemisphere with irregular fluctuation that

Tab.1 Variance contribution by the first six terms of TEOF for mean temperature across the globe and over Northern and Southern Hemispheres.

	Serial No.	1	2	3	1～3	4	5	6	1～6
globe	1 Yr	78.73	6.72	3.02	85.47	2.95	1.97	1.62	95.01
	3 Yr	68.55	7.21	4.41	80.17	2.72	1.80	1.41	86.09
	6 Yr	62.53	5.43	4.79	72.75	3.31	2.46	1.92	80.43
	10 Yr	58.25	4.30	3.47	66.02	3.41	2.88	2.24	74.54
SH	1 Yr	81.28	6.46	2.88	90.62	2.16	1.43	1.22	95.63
	3 Yr	71.53	7.24	4.79	83.55	2.49	1.46	1.33	88.82
	6 Yr	66.15	4.84	4.29	75.28	4.04	2.79	1.94	84.05
	10 Yr	61.20	4.94	3.08	69.22	2.96	2.71	2.55	77.44
NH	1 Yr	61.22	9.09	7.11	77.42	5.05	4.28	3.73	90.47
	3 Yr	49.07	7.68	5.38	62.13	3.94	3.61	2.97	72.65
	6 Yr	42.52	6.05	5.31	53.88	3.48	3.26	3.04	65.77
	10 Yr	38.90	4.52	3.89	47.31	3.79	3.40	2.21	57.31

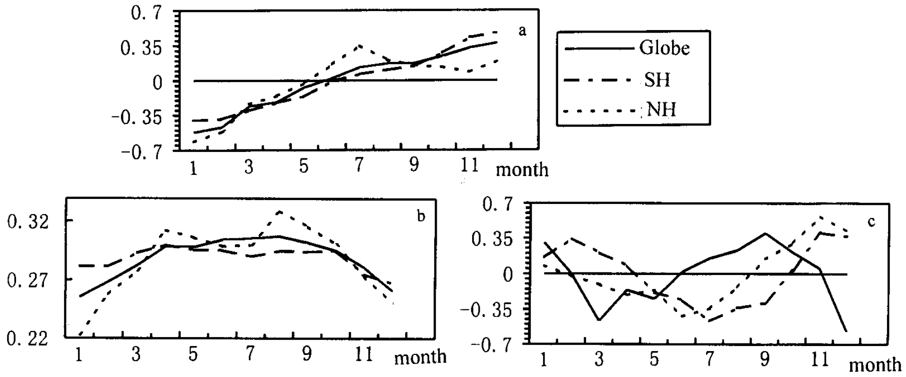

Fig.1 Primary oscillatory modes within 1 year. a. TEEOF1; b. TEEOF2; c.TEEOF3.

results in two maxima, one in the fourth month and the other the eighth month (the largest).

From Fig.1b & 1c, we know that the second mode of the 1-year time domain is relatively consistent with its major features reflecting the tendency all implicit in the annual variation while the third mode is a good indicator of semi-year oscillations. In the figure, the globe changes from positive value in the first month to the first low (negative) value in the third month before rising to the maximum positive value in the ninth month and again, changes to negative in the twelfth month, being equilibrium to a semi-year wave. In contrast, the top of positive territory for both the hemispheres is in the eleventh month while that of negative territory is in the seventh and sixth month respectively, i.e. there is a complete cycle of oscillation within a year in the hemispheres. This characteristic vector depicts the pattern of intraannual oscillation in the two hemispheres.

The distribution pattern shown in Fig.2a for the first mode of the 3-year temporal domain agrees with Fig.1a, which is composed of distribution of three similar annual variation anomalies. The figure shows that the second mode of the field of time domain acts in ways similar to that in Fig.1b by displaying a long-term tendency pattern for the 3-year oscillation. It should be noted, of course, that the distribution pattern is different in the Southern Hemisphere from that in the whole globe and Northern Hemisphere, in that the former varies from positive to negative while the latter does just the opposite, with the transition of sign taking place around the eighteenth month. In contrast, the distribution pattern of the third characteristic vector is relatively consistent for the

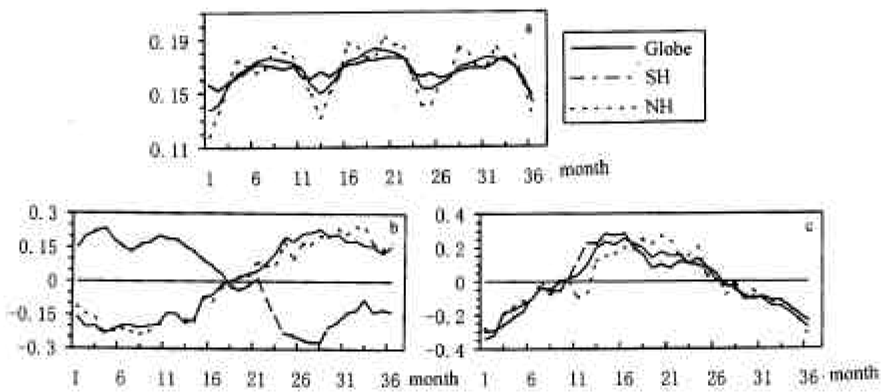

Fig.2 Same as Fig.1 but within 3 years.

globe and the hemispheres, indicating clear presence of patterns oscillating at quasi-36 month periods.

In addition to the findings above, Fig.3a shows that the first mode of TEEOF in the 6-year interannual oscillation is similar to that in Fig.2a. It is clearly shown that the annual starting value (of the characteristic vector in January) and ending value (of that in December) all increase over those in the preceding year, due to relatively long domain of time. It is obvious that the characteristic vector in winter tends to have increasing values over time as compared to less dramatic variation in other seasons. The irregularity shown in the distribution within 1 year for the Northern Hemisphere is even stronger than that in Fig.2a. From Fig.3b, we know that a quasi-6-year periodic wave is evident in the second mode of the 6-year TEEOF, with the phase of the Northern Hemisphere just the opposite from that of the whole globe and Southern Hemisphere — the former starts and ends both in the negative while the latter starts and ends both in the positive. For the third mode of the 6-year TEEOF, however, consistency prevails for the Northern Hemisphere and the whole globe, taking the shape of an up-side-down "V", while an upright "V" is present in the Southern Hemisphere. The vector for wave patterns of higher order mainly represents all corresponding quasi-periodic oscillatory patterns and associated mixing features (figure omitted). For instance, the fifth mode for the globe and Southern Hemisphere indicates workings of a 36-month quasi-periodic oscillation; the second wave in that hemisphere is made implicite for 25 months; differences are very large in the distribution of oscillation between the Northern Hemisphere and the globe / Southern Hemisphere, with the characteristic vector experiencing 6 waving events starting from the first month. The value of wave becomes the minimum in June or July in the boreal summer (to be at the top of the oscillation) but is the maximum in December or January (to be at the bottom of the oscillation). It is shown that the fifth mode in the Northern Hemisphere represents the structure of Wave 2 in the anomalies of the annual variation. For the rest, such as the sixth mode, quasi-2-year waves (24-28 months) and other irregularities are shown.

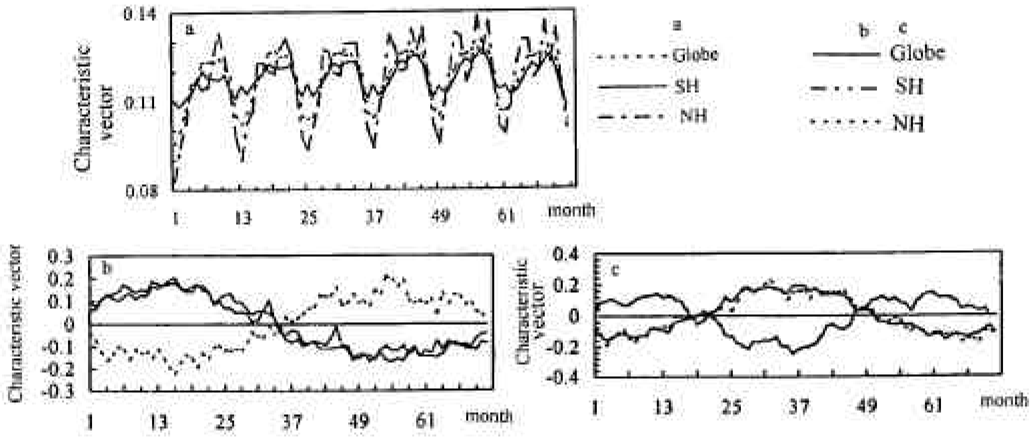

Fig.3 Same as Fig.1 but within 6 years.

It is known from the discussion above that there is variation from the fourth to the sixth mode of TEEOF of the global and hemispheric mean temperature concerning the 6-year annual oscillation pattern. Specifically, the 2-3-year periodic oscillation is contained in the globe and Southern Hemisphere while the Northern Hemisphere is different in that the fourth mode is a quasi-3-year periodic oscillation, the fifth mode represents the anomaly of the annual oscillation and the sixth mode combines the irregular variation and the quasi-3-year oscillation.

For the 10-year oscillation in TEEOF, similar characteristics are also found, with more significant rising trends in the annual minimum and maximum variation. A rise of 0.02 is recorded in the boreal winter (December or January) while an amplitude of 0.01 is measured in both the globe and the austral winter (bottom) and summer or autumn (top), for the value of characteristic vector. Regarding the distribution, it is similar to Fig.2b, i.e. the change is from negative to positive for the whole globe and Northern Hemisphere and from positive to negative for the Southern Hemisphere, shifting the sign around the sixtieth month. For the Southern Hemisphere, a wave is completed when the characteristic value changes from the first month (negative) to the 88th month, fluctuating in the negative territory from the 89th to 120th month. It roughly reflects a quasi-5-6-year oscillation. The amplitude is relatively large in the Northern Hemisphere, containing a two-wave structure in the 10-year oscillation. Both the initiative value of Wave 1 (negative) and ending value of Wave 2 (negative) are very large absolutely while they are small at the conjunction. For the sixth characteristic vector of the 10-year TEEOF, difference is found in the globe and the hemispheres. For the former, two wave structures are contained from the first month (negative) to the 84th month, with the first wave covers a length of 48 months and the second wave 36 months. For the Southern Hemisphere, one and a half wave structure is contained, spanning from January (positive) to the 72nd month for a complete cycle with the latter half wave covering a length of 36 months that changes from positive to negative for the period from the 73rd to 84th month and from negative to positive for the period from the 109th to 120th month. It is now obvious that relatively short, quasi-4-5-year wave structures are contained in the distribution patterns of the Northern Hemisphere.

It is not difficult to note that the distribution of patterns in the Northern Hemisphere is the most complicated and irregular regardless how long the time domain may be. It is typical of large amplitude of monthly variation, large span of wave structure of annual distribution patterns and small variance contribution taken by each of the distribution patterns. It is just the opposite in the Southern Hemisphere. It may be related with the physical structure of the underlying surface in the hemispheres, with large area of land and wide range of seasonal change of climatic state over the Northern Hemisphere; in the Southern Hemisphere, however, the climatic state is limited in seasonal change due to the maritime nature. In the anomalous state of climate, the amplitude of seasonal change is closely related with that of the climatic state — the latter increases with the former and otherwise is true. In other words, the anomality of climate is associated with the mean state of climate. The onset of ENSO is such an explanatory example — it usually happens in March when the SST rises in the normal cycle of climate change.

4 LOW-FREQUENCY VARIATION OF SHORT-TERM ANNUAL PATTERNS

Fig.4 gives the first primary component (TPC1) of TEEOF with the time domain as long as 1 year. It tends to vary consistently with the annual variation of air temperature for the whole globe and the hemispheres[7]. A decreasing trend is found from the mid-phase of the 19th century to the early stage of the 20th century, followed by an obvious increasing trend till the 1930's ~ 1940's, with the sign changing from negative to positive from the 1930's. When TPC1 is positive, obviously, it is consistent with the first mode (the distribution pattern of temperature in the year); the larger the positive value, the better-defined the distribution pattern of temperature, and otherwise is true; when TPC1 is negative, the distribution pattern is thought to be out of phase with the pattern shown in Fig.1a. In other words, for the period before the 1930's, the first pattern of distribution pattern was in phase with that in Fig.1a — the temperature anomaly was negative, being the largest in winter (deviating the most from the mean) but smallest in spring (April) or summer (August); for the period after the 1930's, the first pattern of distribution was decided by Fig.1a, when the temperature was positive, the seasonal change was small in winter but large in spring or summer and the seasonal change in temperature anomaly was the largest in the Northern Hemisphere but smallest in the Southern Hemisphere. As described above, the first mode represents the intraannual seasonal pattern in which the sign of monthly temperature anomaly is decided by time coefficient. The TPC1 curve in Fig.4a is the long-term variation trend of such a anomalous pattern (before smoothing). Fig.4b and Fig.4c are respectively the TPC2 and TPC3 of Mode 2 and Mode 3 in the 1-year oscillation. The figures show that the modes are mainly positive and negative waves without obvious rising or falling tendency. Such evolution indicates that as the patterns of temperature oscillation shown by the second ad third characteristic vectors are of implicit tendency and semi-year waves (as shown in Fig.1b and 1c), their association with corresponding TPC well reveals a quasi-2-year periodic period, because the distribution patterns they govern are always shifting between "consistent" and "out-of-phase" states of characteristic vectors when the time coefficient is either positive or negative.

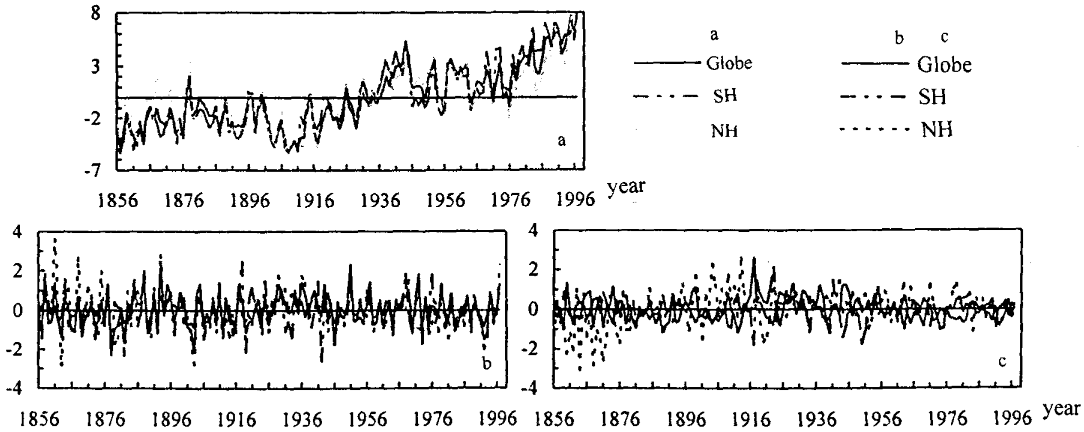

Fig.4 Primary components corresponding to the oscillatory modes within a year. a. TPC1; b. TPC2; c: TPC3.

Fig.5a ~ 5c are the first primary component (TPC1) of 3, 6 and 10 years respectively. It is obvious that all of them agree with those in Fig.4a. It is noted, however, that the longer the time domain of TEEOF, the smoother the curve of the time coefficient will be. It is not hard to understand. In equivalence, the time coefficient is a smoothing one in relation to the time-domain field of TEEOF. The longer the time domain, the smoother the time coefficient will be. The TPC1 in the 10-year TPC1 is similar to the temperature tendency represented by 10-year smoothing of the anomalous sequence of temperature. It indicates that rising trends are usually shown in the long-term variation of each of the intraannual anomalies for every 1-year time domain, which is represented by the first mode of TEEOF over 100 and more years.

The second and third TPC (figure omitted) of mean temperature TEEOF for the whole globe and the hemispheres in time domains of 3, 6 and 10 years come close to those shown in Fig.4a and 4b — being predominant with positive and negative waves and alternating with positive or negative periods of time. Their very existence shows that long-term evolution of other oscillatory patterns (as studied above) in the 3, 6 or 10 years of temperature variation will strengthen or weaken with identical or opposite phase if the value of TPC they correspond to is positive or negative. As the time coefficient fluctuates in positive and negative alternation, the distribution patterns, dependent on the second or third characteristic vector and their time coefficients which have been through TEEOF treatment in all time-domain fields of the global and hemispheric mean temperature, keep changing from being consistent, or out of phase, with the characteristic vectors. Quasi-periodic oscillations and long-term variations are, as a result, formed on varying time scales. Nonetheless, the longer the time domain of TEEOF, the slower the temperature oscillatory patterns will transform over all fields of time domain, due to the factor of smoothing. In some sense, low-frequency variability and its causes/effects can be better revealed for quasi-periodic oscillations of all time scales, owing to the study of TEEOF above.

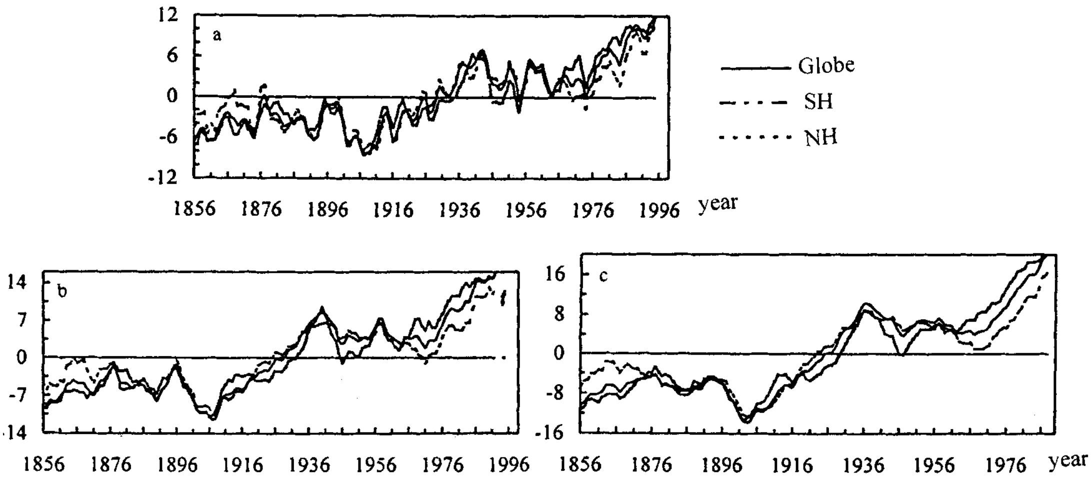

Fig.5 First primary component of inter-annual oscillatory modes within 3 years (a), 6 years (b) and 10 years (c).

What is worth mentioning is the occurrence of explosive growth over the gradual increase in the 100 and more years, as displayed by the long-term variability of TPC1 on all scales of time domain (as shown in Fig.4 & Fig.5). One of them took place from the beginning of the 20^{th} century to the 1930's ~1940's and the other from the 1960's ~ 1970's till the present, a continuous growth. It is not accidental at all. There are three abrupt changes over the period, as discovered in a test of annual variation patterns, which will be discussed later in the work. One of them, which happened from the end of the 19^{th} century to the start of the 20^{th} century, was itself not evident in Fig.4 and Fig.5. It is then clear that it has weaker impact on the short-term patterns of annual oscillation than the other two growth, a finding that agrees in some way with what the author studies in [10, 11].

5 ABRUPT CHANGES OF ANNUAL VARIATION PATTERNS

Fig.6a ~ 6c gives the temporal variation of F value, for which the T^2 test has been applied for the mean annual variation patterns of the globe and hemispheres. The figure shows that all of the three curves have areas of maxima, in which two are consistent in the time of appearance. One was at the end of the 19^{th} century when the F value was the maximum in the Northern Hemisphere but the minimum in the Southern Hemisphere. The other was in the 1920's when there was not much difference between the whole globe and the hemispheres but was the largest for the globe and the Northern Hemisphere. There was another domain of time in which the F value was at its maximum for the globe and the Southern Hemisphere — the 1970's. It was the largest for the Southern Hemisphere and second largest for the globe, following the 1920's. For the Northern Hemisphere, the value of F was the largest in the 1920's, followed by the 1960's, with the smallest in the 1970's. Larger F value indicates higher confidence level which passes tests of corresponding degree of freedom, implying stronger signal of abrupt change. Otherwise is true. It is clear that the signal for abrupt change of mean temperature in the globe and the two hemispheres are differently shown with time. Even for a signal over the same period, the intensity varies depending on the globe and hemispheres. It was the strongest in the 1920's for the globe and Northern Hemisphere. For the Southern Hemisphere, it was the strongest in the 1970's, followed by the 1920's and then by the end of the 19th century. For the Northern Hemisphere, it was the strongest in the 1920's, followed by the 1960's and then by the 1970's. For the globe, it was the strongest in the 1920's, followed by the 1970's and then by the end of the 19th century.

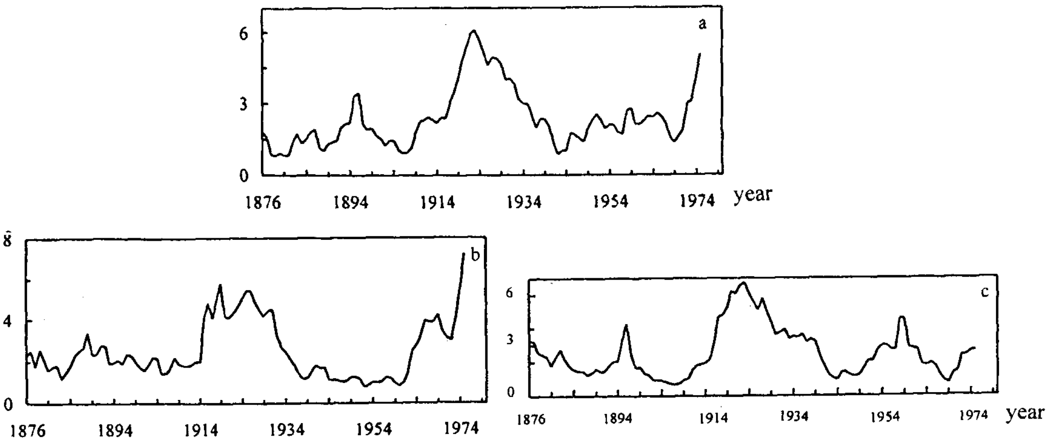

Fig.6 Fields of variation of F value with decades through smoothing T^2 test. a. globe; b: Southern Hemisphere; c: Northern Hemisphere

The smoothing T^2 test for the annual variation pattern actually incorporates abrupt changes of temperature mean in all months. Generally, it is consistent with the results obtained with the *t* test that employs the single-element smoothing of annual mean temperature. For instance, there are three events of abrupt change in the globe and the hemispheres and an extra event that differs in the Northern Hemisphere from the globe and Southern Hemisphere (illustrated as the third time in Table 2). As shown in the experiment, the result of *t* test for the single-element of annual mean temperature is consistent with the T^2 test for the annual variation pattern if there is only minor

Tab.2 Results of T^2 test conducted for the annual variation modes of mean temperature for the globe and Northern / Southern Hemispheres (NS / SH). Contents inside the brackets are the results of *t* test.

	1st event	2nd event	3rd event	4th event
Globe	*1897～1898(1902)	**1925(1925～1930)	**1977(1977)	
SH	*1890(1897)	**1921(1925～1930)	**1977(1977)	
NH	*1898(1902)	**1925(1925～1927)	**1960～1961(1956)	1977

difference of long-term variation between monthly or seasonable mean temperature. Otherwise is true. As described above, there is large difference of long-term mean temperature in the Northern Hemisphere from month to month (seasonal variation of the anomalies) so as to cause large difference in long-term annual variation on the monthly or seasonal scale. It may be the main reason behind the differences between the two test results. It can thus be seen[2] that the T^2 test for the annual pattern of variation may be more reasonable than the t test in the sense that it is able of reflecting the overall morphology of annual variation.

6 CONCLUDING REMARKS

a. Apart from the 10-year TEEOF for the Northern Hemisphere, the first mode over other domains of time takes up more than 50% of the total variance contribution, representing the annual variation anamalous mode that is related with seasonal change of the climate. As the temporal scale varies in the annual oscillation (1, 3, 6 and 10 years), long-term variability can be easily recognized for all modes of oscillation. The first variation mode on the 10-year scale, for example, is showing strong increasing tendency in wintertime temperature and the variation of the corresponding first primary component (TPC1) tends to go consistently with that of the anomalous sequence of observed temperature. The most recent two events of abrupt change, in particular, are sensitively displaying the long-term variability of short-term climatic oscillatory modes.

b. For the whole globe and Southern and Northern Hemispheres, the second mode of annual oscillation over all domains of time have shown patterns of annual variation, most of which represent individual short-term tendencies with some differences among them. Their matching with corresponding primary components (of long-term variation dominated with positive and negative waves) is just the right signal for all quasi-periodic oscillations (quasi-2 ~ 3, quasi-4 ~ 5, quasi-5 ~ 6, etc.). The patterns of oscillation and the variation of their primary components for other modes are also reflecting characteristics of long-term variability in various short-term annual oscillations.

c. As shown in the results of the work, it is in some sense more reasonable to use the T^2 test rather than the single-element t test to assess the abrupt change in the vector of climatic states. The time in which three abrupt changes appeared in the Southern Hemisphere and the globe were basically consistent with the results of the single-element test for annual mean temperature, specifically in the 1890's, 1920's and 1980's. It was somewhat different in the Northern Hemisphere, for which there were three or four events of abrupt change and the third one was ill-defined. It is therefore accepted with general confidence that there are only three events of abrupt change and the third one may be associated with the length of years smoothed. The issue will be discussed in separate papers.

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