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THE PERIODICITY OF VOLCANO ACTIVITY AND ITS REFLECTION IN SOME CLIMATE FACTORS

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Abstract Based on the data of 600 years global above class 5 volcanic explosion index (VEI) and the comparison of the northern hemispheric ground temperature, the western pacific high, the northern Atlantic high and the sea surface temperature anomaly (SSTA) in the northern Atlantic westerly region, it is showed that: (1) The global strong volcano activities have obvious century timescale cycles about 88 and 100 years, accounting for about 21.65% of total variance for VEI, an about 33-year interdecadal timescale cycle, and an 11-year cycle associated with solar activity. (2) The western Pacific subtropical high in July has a 33-year period oscillation accordant to the volcanic activity, which is considered to be the response to the 33-year periodic volcanic activity. (3) In the North Atlantic, the volcanic activities inspire the summer North Atlantic sub-tropical high with 88-year cycle oscillation, winter (January) northern Atlantic westerly region SSTA with 100-year oscillation and summer (July) SSTA 88-year cycle oscillation. (4) Analysis shows that the 88-year periodic variation of northern hemispheric ground temperature is the response to the 88-year cycle of volcanic activity.

Key words Volcanic activity, Periodicity, Climate, Ground temperature, Subtropical high, SST

1 INTRODUCTION

In this paper the quasi-cycle of the volcanic activities means the regular frequency of the global Volcano Explosion Index (VEI) of volcanic eruptions above grade 5, with that the active and quiet periods occur alternately. In the study of the effect of volcanic activities on climate, people have observed that the quiet period of volcanic activities corresponds to a global warming period in 1920~1940 decades and the active period of volcanic activities in 1950~1970 decades corresponds to a global cooling period[1~3], and considered that each ice age in the past 2 million years is in correlation with volcanic eruptions on a large scale. It shows that volcanic activities have obvious active and quiet periods. This phenomenon prompts the author to analyze the global volcanic data during the past 600 years, and to review whether the active and drear periods are universal and appear alternatively? If they are, then volcanic activities maybe have quasi-cycle. Though volcanoes erupt randomly, mass of random events may show their cycles. For example, a single photon falls randomly, mass of photons fall by law. If volcanic activities have quasi-cycle, how does this quasi-cycle reflect in global climate variations? This paper will discuss this question based on the 600-years volcanic data.

2 THE CYCLE COMPONENT OF VOLCANIC ACTIVITIES

2.1 Data and Data Processing

The global monthly ground temperature is taken from Ref.[4] and the monthly National Center for Atmospheric Research/National Center for Environmental Prediction (NCAR/NCEP) reanalysis air temperature data with vertical 17 levels. Sea level pressure data and sea surface temperature data of the North Atlantic are from the Hadley Center website (http://hadobs.metoffice.com/hadslp2/). In order to compare and analyze the volcanic activities and temperature time series, it is necessary to transform the discrete volcanic data to successive time series of volcanic activities. Based on the 1000-year's data published by American Smithsonian Institution (Volcanoes of the World chronology[5], volcano eruption database, National geophysical data center (DUNBAR) and the volcanic activity data of NOAA (USA: National geophysical data center, world data

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center'A, 2006). From Volcanoes of the World chronology by Smithsonian Institution, those with VEI over 5 are recorded[6~8] according to their grade, so a time series of the volcanic activities is constructed. In order to stand out low frequency, random noise and high frequency are sieved out. A 17-year running mean has been done to form the volcanic activities time series, VEI(i).

The author and some researchers[9,10] have found that the longer the volcanic data are the worse the information adequacy is. Compared with ice core data, it is showed that there are sometimes gaps in ancient volcanic data. For instance, ice core analysis shows that there are volcanic activities in 1810, 1816 and 1836, but no records in the chronology of the volcanic activities. Along with the advances of observational technique and communication, as well as the growing attention paid to volcanic activities, from 20th century, especially from its 60 decade, when satellite remote sensing and radar remote sensing compose a dense observational net, the records of volcanic activities (especially medium and small volcanic activities) are nicer and more detailed. In this paper, the following equation is used to sieve out the non-volcanic factor trend:

$$\mathrm{VEI}(i) = \mathrm{VEI}(i) + 0.2, i = 1, 2, \cdots, 401; \quad \mathrm{VEI}(i) = \mathrm{VEI}(i) - 0.18, i = 402, 403, \cdots, 605.$$

2.2 The Cycle Component of Volcanic Activities

Based on global volcanic data with a grade over 5 since 1400, the analysis shows that volcanic cycle has a wide frequency spectrum. For instance, there are century scale cycle, interdecadal scale cycle, 22 year and 11 year cycles related with solar activities. Considering the less reliability of long age record, the analysis of this paper is based on the volcanic activities with VEI over 5, those with VEI lower than 5 are only used for long period analysis.

2.2.1 Century scale cycle of the global volcanic activities

In order to observe the volcanic cycle with VEI grade over 5, first of all the power spectrum of the time series of yearly average VEI is analyzed, and the spectral test of the red noise with significance level $\alpha = 0.05$ has been done[9]. The period spectra T_l, the amplitude spectra A_l, and the phase spectra θ_l are calculated with the following formula:

$$T_l = \frac{2m}{l}, \tag{1}$$

$$a_l = \frac{2}{T_l} \sum_{i=l}^{n} x_i \cos\left(\frac{2\pi}{T_l}(i-1)\right), \tag{2}$$

$$b_l = \frac{2}{T_l} \sum_{i=l}^{n} x_i \sin\left(\frac{2\pi}{T_l}(i-1)\right), \tag{3}$$

$$A_l = \sqrt{a_l^2 + b_l^2}, \tag{4}$$

$$\theta_l = \mathrm{tg}^{-1}\left(\frac{a_l}{b_l}\right), \tag{5}$$

here, x_i is specimen, namely the yearly average VEI, i is time sequence number. The results of spectra analysis are listed in Table 1.

It can be seen from Table 1 that the power spectrum value of the 88-year period wave, 0.473951, is much greater than that of the red noise, 0.150760, which means that the 88-year cycle passes the significance test with $\alpha = 0.05$ and displays the highest spectral peak (the figure is omitted). Therefore, 88-year period is century scale cycle of global volcanic activity with VEI grade over 5. Furthermore, the 29-year cycle of wave number 3 and 11-year cycle of wave number 8 also pass the 0.05 significance test, and represent interdecadal variability. This shows that volcanic activities contain some components of solar activities, suggesting that solar activities may somehow excite the volcanic activities.

Table 1 shows that the 88-year period has an amplitude of $A = 0.405$, initial phase angle $\theta_l = 2.2001$, then period function, $\mathrm{BO}_{88}(i)$ is

Table 1 Results of spectra analysis of the time series of volcanic activities above VEI 5 in 1400~2000

Wave number	Power spectra	Test spectra	Amplitude spectra	Period spectra	Initial phase angle
0	0.000599	3.683444	2.000000	∞	0.00000
1	0.473951	0.150760	0.405437	88.000	2.20011
2	0.109181	0.038933	0.138635	44.000	1.38118
3	0.153076	0.017443	0.171450	29.000	0.59857
4	0.072017	0.009861	0.094436	22.000	–0.05950
5	0.018431	0.006341	0.076195	17.000	0.30195
6	0.021824	0.004427	0.033764	14.000	0.01320
7	0.006169	0.003271	0.025035	12.000	1.06035
8	0.009882	0.002521	0.014408	11.000	–0.42979
9	0.008171	0.002007	0.004094	9.000	–1.04419
10	0.008019	0.001639	0.004293	8.000	0.62671

$$\mathrm{BO}_{88}(i) = 0.405 \sin\left(\frac{2\pi}{88} i + 2.2\right) \quad i = 1, 2, \cdots, 601. \tag{6}$$

Using Eq.(6), the 88-year cycle curve in Fig. 1 can be obtained. It can be seen from Fig. 1 that the crest and trough of the quasi 88 year cycle are consistent with those of the VEI curve of the volcanic activities. The global strong volcanic activities go through 6 active periods in recent 600 years, each of which appears at wave peak of 88 year cycle curve and drear period appears at wave trough. This shows that the global volcanic activities with VEI over 5 have an 88-year century scale cycle.

After filtering out the 88 year cycle from VEI(i), a new $\mathrm{VEI}_2(i)$, which does not contain 88-years cycle, is obtained, namely:

$$\mathrm{VEI}_2(i) = \mathrm{VEI}(i) - \mathrm{BO}_{88}(i).$$

In order to review the new sequence, the power spectrum of the time series of yearly averaged VEI is analyzed, and the significance test of the red noise spectra with $\alpha = 0.05$ has been done. The result shows that the new sequence has a 100 year cycle, its amplitude spectrum $A = 0.429$, and the initial phase angle $\theta_l = 2.50$, the period function is

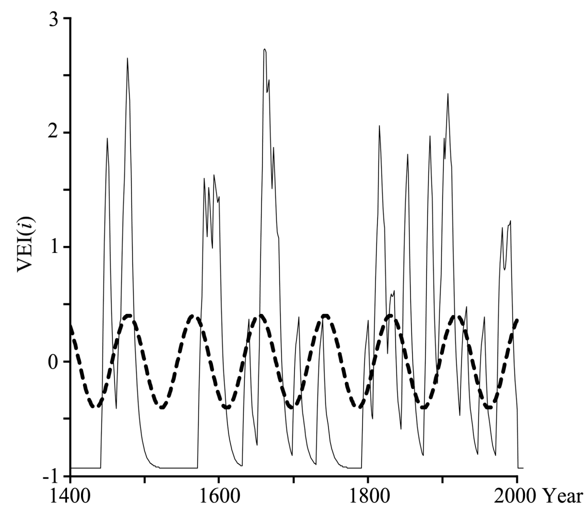

Fig. 1 17 year moving averaged curve (solid line) and 88 year quasi cycle curve (dashed line) of Global volcanic activities above VEI 5 in 1400~2000

$$\mathrm{BO}_{100}(i) = 0.429 \sin\left(\frac{2\pi}{100} i + 2.50\right), \quad i = 1, 2, \cdots, 601. \tag{7}$$

By using Eq.(7), the 100 year cycle curve is obtained and is shown in Fig. 2. From Fig. 2, it can be seen that the crest and trough of the quasi 100 year cycle are consistent with those of the VEI curve of the volcanic activities (filtered out the 88-years cycle). Most of the global strong volcanic activities are in accord with the wave apex and drear period in accord with wave trough. This shows that in the global volcanic activities with VEI over 5 also exists a 100 year century scale cycle.

In Fig. 1 and Fig. 2 the VEI(i) curve is used to prove that in the global volcanic activities with VEI over 5 there are 88 year cycle and 100 year cycle. The analysis shows that 88 year and 100 year cycles contribute 21.64% to VEI(i) sequence in 1400~2000, and they are an important feature of volcanic activities.

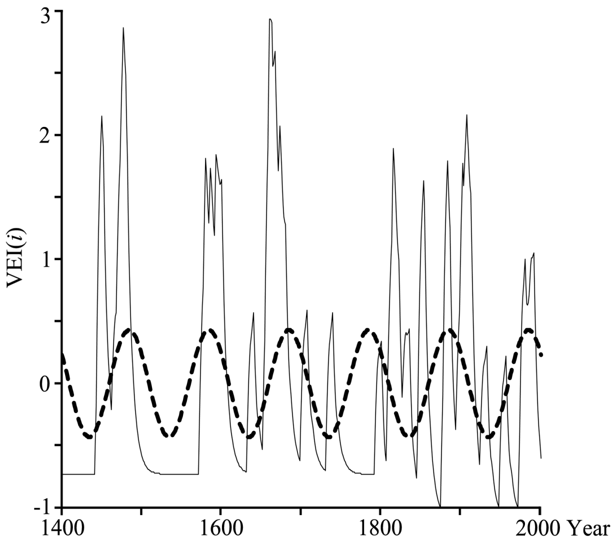

Fig. 2 Average curve of global VEI(i) over 5 (sieved out 88-years cycle) (solid line) and 100 year cycle curve (dash line) in 1400~2000

2.2.2 Interdecadal scale cycle of global volcanic activities

Interdecadal and interannual timescales always overlay on century scale cycles. This makes century scale cycle not smooth enough to identify. For the interdecadal and interannual scale cycle has a small amplitude and a short wave length, when they overlay on a century scale cycle, it is hard to analyze. So in this paper the century scale cycle is filtered out from the time series, in order to analyze the interdecadal scale cycle. First filter out the 88-year and 100-year cycle from VEI(i) sequence, and get a new time series $\mathrm{VEI}_3(i)$, namely

$$\begin{aligned}\mathrm{VEI}_3(i) =& \mathrm{VEI}(i) - \mathrm{BO}_{88}(i) - \mathrm{BO}_{100}(i)\\ =& \mathrm{VEI}(i) - 0.405\sin\left(\frac{2\pi}{88}i + 2.200\right)\\ & - 0.429\sin\left(\frac{2\pi}{100}i + 2.50\right)\\ & i = 1, 2, \cdots, n. \end{aligned} \tag{8}$$

The power spectrum of time sequence of yearly averaged $\mathrm{VEI}_3(i)$ is analyzed, and the significance test of red noise spectra with $\alpha = 0.05$ has been done[9]. The results are listed in Table 2.

Table 2 Analysis results of $\mathrm{VEI}_3(i)$ of volcanic activities with $\mathrm{VEI}_3(i)$ over grade 5, in 1400~2000

Wave number	Power spectra	Test spectra	Amplitude spectra	Cycle spectra	Initial phase angle
0	0.001377	2.233935	2.000000	∞	0.00000
1	0.339095	0.233545	0.036679	100.000	–1.11462
2	0.144222	0.063414	0.045465	50.000	–1.56726
3	0.158422	0.028682	0.157472	33.000	–2.40001
4	0.150664	0.016262	0.202247	25.000	1.46196
5	0.030646	0.010466	0.091277	20.000	–0.98437
6	0.038392	0.007305	0.131304	16.000	0.49838
7	0.005825	0.005395	0.032373	14.000	0.03635
8	0.008745	0.004153	0.024125	12.000	1.15606
9	0.001820	0.003301	0.012659	11.000	0.01853
10	0.003712	0.002692	0.014115	10.000	–0.98499

It can be seen from Table 2 that the power spectrum value of the 33 year cycle of wave 3 of 0.158422 is much higher than that of the red noise spectrum value of 0.028682, which means that the 33 year cycle passes the significance test and displays the highest spectrum apex (the figure is omitted). Therefore, the 33 years cycle is the interdecadal scale cycle of the global volcanic activity with VEI over 5. Furthermore, the power spectrum value of the 100 year cycle of wave 1 is much higher than that of the red noise spectra value, and passes significance test. This means that in $\mathrm{VEI}_3(i)$ there is the 100 year cycle in VEI. But its amplitude of 0.037 is much less than that of the 33 year cycle 0.158, and is too small to affect the 33 year cycle. The 12 year cycle of wave 8 also passes the significance test and displays the spectrum apex, so it is the decadal cycle. This shows that volcanic activities contain some component of solar activities.

It can be known from Table 2 that the 33 year cycle has amplitude $A = 0.158$, initial phase angle $\theta_l = -2.40$, and the period function is

$$\mathrm{BO}_{33}(i) = 0.158 \sin\left(\frac{2\pi}{33} i - 2.4\right) \quad i = 1, 2, \cdots, 601. \tag{9}$$

By using Eq.(9), the quasi-33-year cycle in Fig. 3 can be obtained. In order to compare the cycle curve and the actual curve clearly, in figure 3 only recent 200 year data are included. From figure 3, it can be seen that the crest and trough of the quasi-33-year cycle is consistent with those of the VEI curve of the volcanic activities (filtered the 88 year and 100 year cycle). Most of the global strong volcanic activities accord with the wave apex and the drear period with the wave trough. This shows that the global volcanic activity with VEI over 5 has the 33 year decade scale cycle. The analysis shows that the 33 year cycle contributes 18.93% variance to VEI(i) series in 1400∼2000, and is an important feature of volcanic activities.

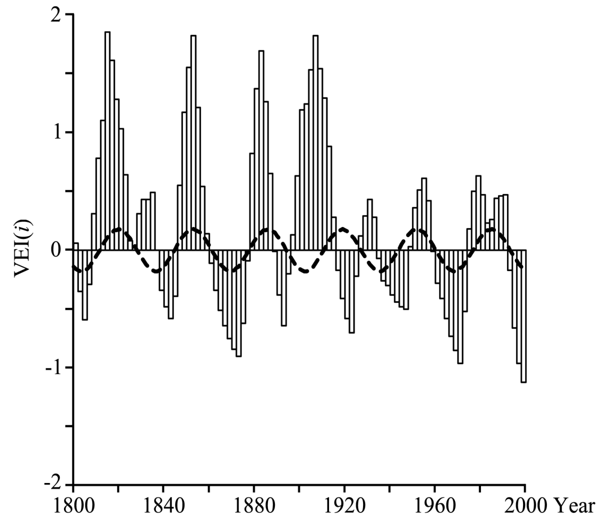

Fig. 3 The curve of VEI above 5 (after filtering out the 88 year and 100 year cycle) (solid line) and 33 year cycle curve (dash line) in 1800∼2000

The relationship between the quasi-33-year cycle and the 29 year cycle: The cycle length in the table relates to choice of the largest lag length, M. When we investigate the significance of 88 year cycle, we set M as 44. Once M is selected, other small scale cycles are also determined. They are 44, 29, 22, 17, 14, 12, 11, and 9, $\cdots$, so the 33-year cycle is not in these spectrums. While the 29-year cycle close to the 33-year cycle in table 1 also passes the significance test. Then is it the 33 year or the 29 year cycle? The authors investigated the 36, 33, 32, 30, 29 year cycles separately. Results show that the 33 year cycle has the largest spectrum value and variance contribution, so the 33 year cycle is the most prominent interdecadal cycle. Fig. 3 shows clearly that the 33 year cycle reveals the interdecadal cycle of volcanic activities.

The relation between the quasi 11 year cycle and the 12 year cycle: Table 1 shows that the 11 year cycle is significant by passing the 95% confidence level, as well as the 12 years cycle in Table 2. Then is the 11 year or the 12 year cycle more significant? Based on solar macula data in 150 years, J. Rudolf Wolf found that macula has a revised quasi 11.1-year cycle. Some other researches show that solar activities have a 11.2-year cycle and the cycle changes with active degree of the sun[11∼14]. If we consider that the volcanic activities are related to solar activities, then neither of the cycles is strictly 11 years or 12 years, but roughly between 11 and 12 years, or as general speaking, 11 year cycle or so.

3 RESPONSE OF VOLCANIC ACTIVITIES ON CLIMATE AND CLIMATE ELEMENT VARIATION

Researches show that volcanic activities are very important factor in climate variation[15∼51], especially the strong volcanic activities with VEI over 5, which have global effect. Then, does the cycle of volcanic activities correspond to the climate variations? The answer is yes. In the followings, we discuss it using sea level pressure (SLP) decadal variation of two important subtropical high-pressure systems, namely the northern Pacific subtropical high (NPSH) and the northern Atlantic subtropical high (NASH), northern hemispheric ground temperature variation and the sea surface temperature (SST) variation over the northern Atlantic westerly area.

3.1 Periodicity of Volcanic Activities and the Northern Subtropical High Anomaly

Subtropical high is mainly located in the northern hemispheric area (20°N∼40°N), where the northern Atlantic subtropical high and northern Pacific high are the most important system. In summer, the NPSH distributes along east and west direction, its strongest centre locates north of the Hawaiian Islands. There is a sub-high center at its west area which is called the western pacific subtropical high (WPSH). On the one hand, the intensity and the advance and retreat of the WPSH determines not only rain belt and rain intensity of East Asia and east China, but also the track and affecting range of the tropical cyclone or typhoon. On the other hand, there are denser and more detailed observation data in WPSH with longer record time than in deep oceans, so in this paper the 1000 hPa geopotential height data for the WPSH is selected to analyze. From SLP data since 1920, it can be seen that the variation trends of the WPSH and the NPSH are basically the same. This means that the WPSH could stand for the NPSH.

3.1.1 Western Pacific subtropical high

Let us see the frequency spectrum of the WPSH SLP variation. The power spectrum analysis of the July SLP time series from 1850 to 2000 over the WPSH region (25°N∼40°N, 130°E∼170°E) and its significance test have been done. The results show that the power spectrum value 0.7151 for 45 year cycle of wave number 2 is much larger than the spectrum value of the red noise test of 0.1112, passing the significance test of the red noise with $\alpha = 0.05$ and is the peak value in whole frequency field. This means that the time series has a 45-year cycle, but volcanic activities have not the corresponding cycle. We filter this cycle out from the time series and analyze it again. According to (1)∼(5), the amplitude $A = 0.26$, initial phase angle $\theta_l = 3.0$ of 45-year cycle can be calculated, and by using the following function the wave filter is obtained

$$p(i) - \mathrm{BO}_{45}(i) = y(i) - 0.26\sin\left(\frac{2\pi}{45}i + 3\right), \quad i = 1, 2, \cdots, 151. \tag{10}$$

The results of SLP after filtering are shown in Fig. 4. The power spectrum value 0.5017 for 33-year cycle of wave number 3 is much larger than that of the 0.05 significance level of red noise test 0.0970, and is the maximum peak spectrum value. This means that the time series of WPSH has a 33-year cycle, which corresponds to the 33-year cycle of the volcanic activities.

Based on (1)∼(5), the amplitude $A = 0.151$, initial phase angle $\theta_l = 0.5$ of the 33-year cycle can be obtained and the wave function $\mathrm{BO}_{33}(i)$ is:

$$\mathrm{BO}_{33}(i) = 0.151\sin\left(\frac{2\pi}{33}i + 0.5\right), \quad i = 1, 2, \cdots, 151. \tag{11}$$

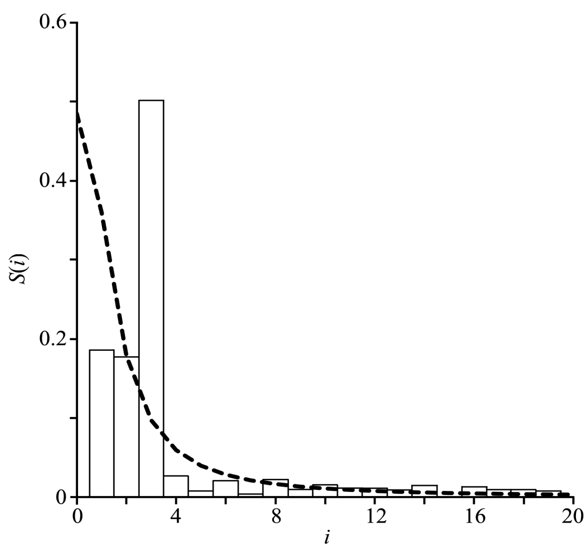

Fig. 4 The SLP spectra of northern pacific subtropical high after filtering out the 45 year cycle

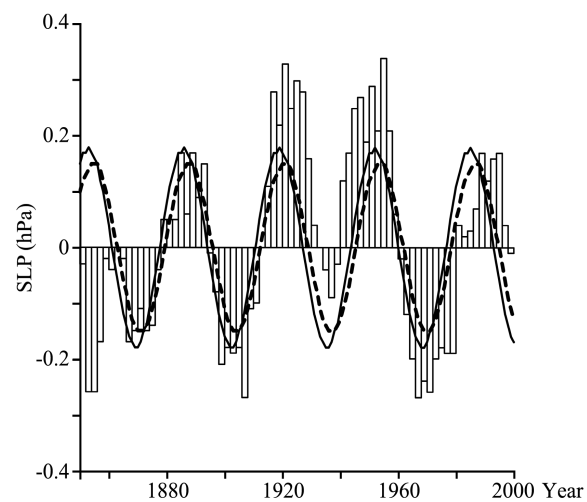

Fig. 5 SLP of western pacific subtropical high pressure (filtered out the 45 year cycle), VEI of the 33 years cycle (solid line) and SLP of the 33 year cycle (dash line) in July

From Fig. 5 it can be seen that in more than 100 years since 1900, the wave crest and trough of the 33-year cycle (dashed line) are consistent with those of SLP of WPSH area (25°N∼40°N, 130°E∼170°E). This proves that the 33-year cycles prevail throughout the WPSH area. Then, what is the relation between the 33 year cycle of volcanic activities and the 33 year cycle of WPSH? Based on (9), we have obtained the 33 year cycle time series of VEI in recent 151 years in Fig. 5. It can be seen that the wave crest and trough of the 33 year cycle curve of the volcanic activities (solid line) are consistent with those of the WPSH, but somewhat go in advance. The SLP of WPSH behaves similarly. We have obtained the correlation function $R(i)$ between the 33 year cycle of the WPSH and the volcanic activities in 1850∼2000, and listed it in the second column of Table 3, where the first column is the lag years. It can be seen from Table 3 that the simultaneous correlation coefficient between the 33 year cycle of the volcanic activities and WPSH is $R(i) = 0.93$, and the lag correlation coefficient between them is $R(i) = 0.98$ with the WPSH lagging by 2 years. This means that the components of the 33 year cycle of volcanic activities are obviously correlated to the 33 year cycle of WPSH by 2 years in advance. It undoubtedly reveals that the periodic surge of global strong volcanic activities inspires the same periodicity surge in air movement. We obtain the variance of 17-year running mean time series $p(i)$ of the WPSH SLP:

$$S^2 = \frac{1}{n}\sum_{i=1}^{n}(p(i) - \overline{p})^2 = 0.0603, \tag{12}$$

here $\overline{p}$ is the climatological mean SLP of the WPSH in 1850∼2000.

After filtering out the 45 year cycle and the 33 year cycle, the variance of the WPSH SLP time series $S_2^2 = 0.0164$. Then the variance contribution of the 45 year cycle and the 33 year cycle to the WPSH SLP is:

$$\mathrm{SS} = ((S^2 - S_2^2)/S^2) \times 100\% = ((0.0603 - 0.0164)/0.0603) \times 100\% = 72.76\%. \tag{13}$$

Using the same method, we have obtained the variance contribution of the 45 year cycle as 54.04%, therefore, the variance contribution of 33 year cycle is 72.76%–54.04%=18.72%. This means that strong volcanic activities have more than 18% contribution to the variation of SLP of the 33 year cycle of the WPSH.

3.1.2 North Atlantic subtropical high

Let us see the SLP decadal variation of the North Atlantic subtropical high (25°N∼40°N, 10°W∼40°W). Rudiment analysis shows that the NASH SLP time series $p(i)$ in July has the 120 year cycle, but there is no corresponding cycle in the volcanic activities. Filter out this cycle components from the time series to do further analysis. Based on Eqs.(1)∼(5), the amplitude and initial phase angle of the 120 year cycle can be obtained, then filtering $\mathrm{BO}_{120}(i)$:

$$p(i) - \mathrm{BO}_{120}(i) = p(i) - 0.27\sin\left(\frac{2\pi}{120}i + 2.31\right), \quad i = 1, 2, \cdots, 151. \tag{14}$$

The results of SLP after filtering out the 120-year components are shown in Fig. 6. The power spectrum value 0.7339 for 88-year cycle of wave number 1 is the most significant, far exceeding that of the 0.05 significance spectrum value of the red noise test of 0.3737. This means that the NASH has obvious 88 year cycle, and this cycle is corresponding to the 88 year cycle of the volcanic activities. Based on (1)∼(5), the amplitude $A = 0.202$, initial phase angle $\theta_l = -3.47$ of the 88 year cycle can be obtained. The wave function $\mathrm{BO}_{88}(i)$ is

$$\mathrm{BO}_{88}(i) = 0.202\sin\left(\frac{2\pi}{88}i - 3.47\right), \quad i = 1, 2, \cdots, 151. \tag{15}$$

From Fig. 7 it can be seen that in more than 100 years since 1900, the wave crest and trough of the quasi 88 year cycle (dash line) of NASH are consistent with those of SLP of NASH (25°N∼40°N, 10°W∼40°W). This proves that the 88 year cycle prevails throughout the NASH pressure area. Then, what is the relation between the 88 year cycle of volcanic activities and 88 year cycle of NASH? Based on (6), we obtain 88 year time series in recent 151 years. From Fig. 7 it can be seen that the wave crest and trough of the 88 year cycle curve of the

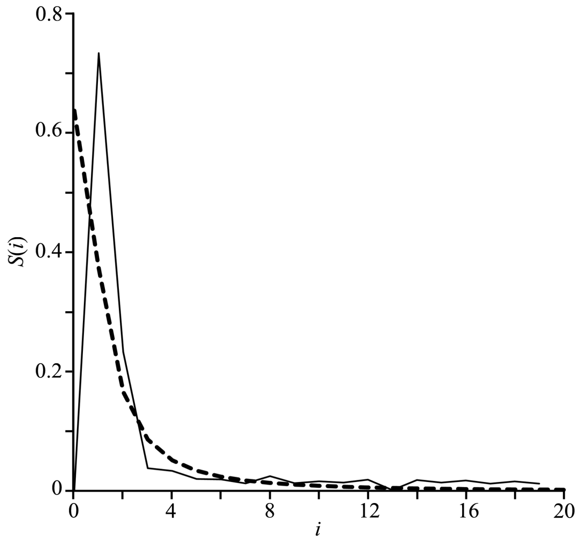

Fig. 6 SLP spectra of the NASH after filtering out the 120 year cycle

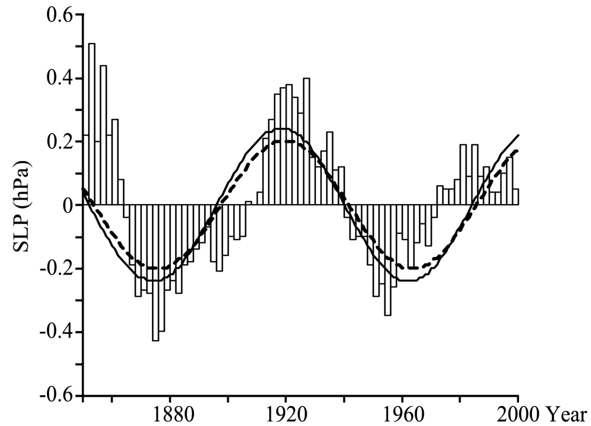

Fig. 7 SLP of the NASH (filtered out the 120 year cycle, bar), VEI of the 88-years cycle (solid line) and SLP of the 88 year cycle of NASH (dash line)

Table 3 The correlation coefficients $R(i)$ between strong volcanic activities cycle and climate factors

Lagged time (year)	VEI and the 33 year cycle of the WPSH $R(i)$	VEI and 100 year cycle of the NASH $R(i)$	VEI and 100 year cycle of NA SST $R(i)$ in Jan	VEI and 88 year cycle of NA SST $R(i)$ in July	VEI and 88 year cycle of NHGT $R(i)$
0	0.93	0.98	–0.61	–0.34	0.31
1	0.98	0.99	–0.66	–0.27	0.38
2	0.98	0.99	–0.70	–0.20	0.44
3	0.96	0.99	–0.74	–0.13	0.50
4	0.90	0.98	–0.77	–0.06	0.56
5	0.80	0.96	–0.80	0.01	0.62
6	0.68	0.95	–0.83	0.08	0.67
7	0.53	0.92	–0.86	0.16	0.72
8	0.36	0.89	–0.88	0.23	0.77
9	0.18	0.86	–0.90	0.30	0.81
10	–0.01	0.82	–0.92	0.36	0.85
11	–0.19	0.78	–0.93	0.43	0.89
12	–0.37	0.74	–0.94	0.49	0.92
13	–0.54	0.69	–0.94	0.55	0.94
14	–0.69	0.64	–0.94	0.61	0.96
15	–0.81	0.58	–0.94	0.67	0.98
16	–0.90	0.52	–0.93	0.72	0.99
17	–0.96	0.46	–0.92	0.77	0.99
18	–0.99	0.40	–0.91	0.82	0.99
19	–0.98	0.33	–0.89	0.86	0.99
20	–0.93	0.27	–0.87	0.89	0.98
21	–0.85	0.20	–0.85	0.92	0.96
22	–0.74	0.13	–0.82	0.95	0.94
23	–0.60	0.06	–0.79	0.97	0.92
24	–0.45	–0.01	–0.75	0.99	0.89
25	–0.27	–0.08	–0.71	1.00	0.86
26	–0.09	–0.15	–0.68	1.00	0.82

volcanic activities (solid line) are consistent with those of the NASH, but somewhat go in advance. The SLP of NASH behaves similarly. The correlation coefficients $R(i)$ between 88 year cycle of NASH and the 88 year cycle of volcanic activities in 1850∼2000 is obtained and listed in the third column of Table 3. From Table 3 it can be seen that the simultaneous correlation $R(i) = 0.9829$, and the maximum lag correlation $R(i) = 0.9904$ when NASH lags behind VEI by 2 years. This means that the 88 year cycle of the volcanic activities closely correlates to the 88 year cycle of the NASH, which reveals that the periodic surge of global strong volcanic activities inspires the same century periodicity surge in NASH.

Similar to (12) and (13), we have obtained the variance contribution of 88 year cycle of NASH, which is 25.94%. This means that the strong volcanic activities have more than 25% variance contribution to inspire SLP of the 88 year cycle of the NASH.

3.2 Periodicity of the Volcanic Activities and the SST over the North Atlantic Westerly Area

The North Atlantic (NA) sea surface temperature, especially the SST over the North Atlantic westerly region, affects not only the North Atlantic climate, North Atlantic oscillation, North Atlantic high latitude sea ice, and environmental ecosystem of this area, but also the Northern Hemisphere (NH) climate. The NA SST, an important factor of Earth climate system, exerts very important effect and takes much attention of researchers[52∼62]. The power spectrum analysis of the 17-year running averaged time series of SSTA(i) over the NA westerly area and the significance test of the red noise have been done. The following is spectra result in January and July.

3.2.1 Winter (January)

The analysis shows that SSTA(i) of NA in January has been rising continuously since 1850, and the rising function is $k(i) = -0.12 + 0.0015i$. After filtering out the SST rising trend $\mathrm{SSTA}_1(i) = \mathrm{SSTA}(i) - k(i)$, the results of spectra analysis show that the power spectrum value for 56-year cycle of wave number 2 is the most significant, larger than that of the red noise test of 0.183349, which passes the 0.05 significance level (the figure is omitted). This means that the NA SST has a 56-year cycle, but in the volcanic activities there is no corresponding cycle. We filter out this period from the time series and analyze it again. Based on (1)∼(5), the amplitude $A = 0.172$, initial phase angle $\theta_l = 2.830$ of 56 year cycle are obtained, and by filtering $\mathrm{BO}_{56}(i)$ $\mathrm{SSTA}_2(i)$ can be calculated

$$\mathrm{SSTA}_2(i) = \mathrm{SSTA}_1(i) - \mathrm{BO}_{45}(i) = \mathrm{SSTA}_1(i) - 0.172\sin\left(\frac{2\pi}{56}i + 2.83\right), \quad i = 1, 2, \cdots, 151. \tag{16}$$

The result of the spectra analysis of the filtered $\mathrm{SSTA}_2(i)$ time series shows that the power spectra value 0.472709 for 100-year cycle of wave number 1 is obviously larger than that of the red noise test spectra value of 0.306356, passing the $\alpha = 0.05$ significance level (the figure is omitted). This means that the NA SST has a 100-year cycle. Based on (1)∼(5), the amplitude $A = 0.154$, initial phase angle $\theta_l = 1.60$ of 100 year cycle can be obtained, and by using the following function the wave filter $\mathrm{BO}_{100}(i)$ can be calculated

$$\mathrm{BO}_{100}(i) = 0.154\sin\left(\frac{2\pi}{100}i + 1.6\right) \quad i = 1, 2, \cdots, 151. \tag{17}$$

From Fig. 8 it can be seen that in more than 100 years since 1850, the wave crest and trough of the quasi 100 year cycle (dash line) are consistent with those of SSTA of the NA westerly area (47.5°N∼67.5°N, 7.5°W∼52.5°W) in January. This proves that the 100 year century cycles prevail throughout the NN westerly area. Then, what is the relation between the 100 year cycle of volcanic activities and the 100 year cycle of the NA SSTA(i)? Based on (7), we obtain the 100 year cycle time series of VEI in recent 151 years. Fig. 8 shows that the wave crest and trough of the 100 year cycle curve of volcanic activities (solid line) are out-of-phase with those of the 100 year cycle curve of NA SSTA(i), and there is more than Pi/4 phase difference between them. This means that when the volcanic activity reaches its strongest, the SST does not reach the lowest immediately, but lags some years later. This is because that, on the one hand, the volcanic aerosol and dust curtain formed by strong volcanic activities will stay in stratosphere for some years and produce lasting "umbrella effect" at low level atmosphere and sea surface. On the other hand, the variations of low level atmosphere movement aroused by "umbrella effect" will be reflected in the ocean circulation and in the change of the SST distributing. So the change of the SST always lags behind the volcanic activities. We obtain the correlation coefficients $R(i)$ between 100 year cycle of NA SSTA(i) and the 100 year cycle of volcanic activities in January during 1850~2000, and listed in the third column 4 of Table 3. From Table 3 it can be seen that in the simultaneous correlation coefficient $R(i) = -0.6109$, and the maximum lag correlation coefficient $R(i) = -0.9426$, with the SST lagging behind VEI by 14 years. This means that the 100 year cycle of the volcanic activities is negatively correlated to 100 year cycle of NA SSTA(i), and the 100 year cycle of SST lags by 14 years behind that of the volcanic activities. The above analysis reveals that the periodic surge of the global strong volcanic activities inspires the same century periodic surge in NA SST.

3.2.1 Summer (July)

The spectra analysis of the NA SSTA(i) time series in July shows that the power spectrum value 0.603417 for 88-year cycle of wave number 1 is significant at 95% confidence level (figure omitted). This means that in the time series of NA SST in summer there is the 88-year cycle. Based on (1)~(5), the amplitude $A = 0.16$, initial phase angle $\theta_l = 1.05$ can be obtained and $\mathrm{BO}_{88}(i)$ is

$$\mathrm{BO}_{88}(i) = 0.16 \sin\left(\frac{2\pi}{88} i + 1.05\right) \quad i = 1, 2, \cdots, 151. \tag{18}$$

From Fig. 9 it can be seen that in more than 100 years since 1850, the wave crest and trough of the quasi 88 year cycle (dash line) are consistent with those of the NA SST (47.5°N~67.5°N, 7.5°W~52.5°W) in July. This proves that the 88-year century cycle prevails throughout the SST over NA westerly area. Then, what is the relation between the 88 year cycle of the volcanic activities and the 88 year cycle of the SSTA(i) in the NA westerly area?

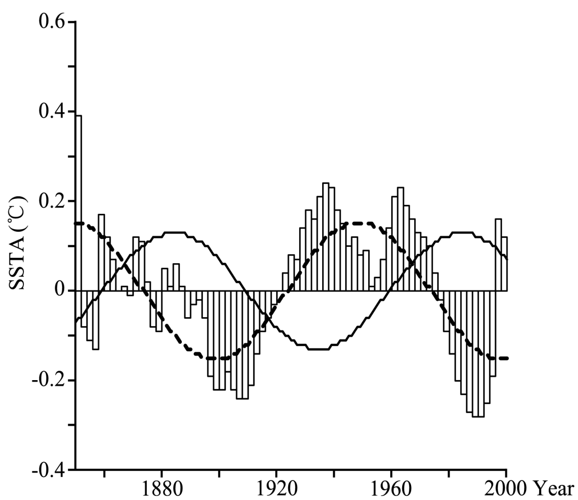

Fig. 8 Time series of SSTA of NA westerly area (filtered out the 56 year cycle), VEI of the 100 year cycle (solid line) and NA SSTA of the 100 year cycle (dashed line) in January

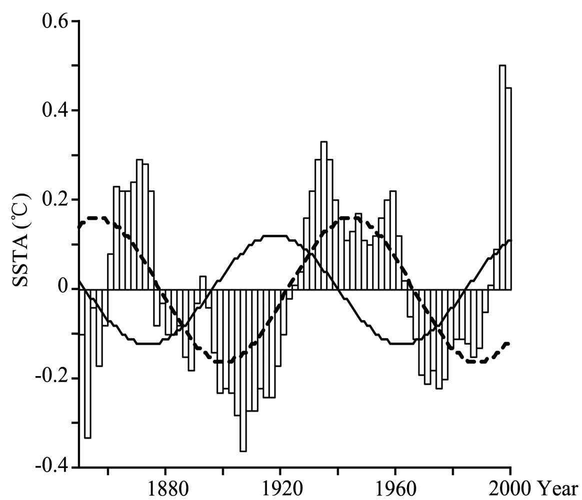

Fig. 9 SSTA of the Atlantic west wind drift area, the 88 year cycle of VEI (solid line) and the 88 year cycle of NA SSTA (dash line) in July

Based on (6), we obtain the 88-year cycle time series of VEI in the recent 151 years. Fig. 9 shows that the wave crest and trough of the 88 year cycle curve of volcanic activities (solid line) are out-of-phase with those of the NA SSTA(i) of the 88 year cycle curve. Correlation coefficients $R(i)$ between the 88 year cycle of NA SSTA in July during 1850~2000 and the 88 year cycle of volcanic activities are listed in the column 5 of Table 3. From

Table 3 it can be seen that in the simultaneous correlation $R(i) = -0.3399$, and the maximum lag correlation coefficient $R(i) = 1.0$ with the NA SST lagging behind VEI by 26 years. This means that the 88 year cycle of volcanic activities is reversely correlated to the 88 year cycle of NA SST. The correlation becomes positive from negative when the SST lags behind VEI by 5 years, and reaches almost 1 when the NA SST lags by 26 years. This reveals that the periodic oscillation of global strong volcanic activities inspires the same century periodicity oscillation in the NA SSTA(i). Compared to the case in January, the century cycle scale becomes shorter and the location of the wave crest and trough change. This reveals the different seasonal response of NA SST to volcanic activities between winter and summer.

3.3 The Periodicity of Volcanic Activities and the Variation of Ground Temperature in the Northern Hemispheric

Many researchers consider that the density of greenhouse gas in atmosphere has been increasing since Industrial Revolution; especially the increase of CO_2 has resulted in continuous rise of global temperature. The 5-year running averaged curve of ground temperature (GT) in Northern Hemisphere (NH) in 1841∼2000 shows that the GT rising trend is basically consistent with CO_2 rising trend[63,64]. Some researchers[65,66] also point out that the NH GT rising is not linearly increasing as that of CO_2 density does, while there are a few cases of temperature cooling. The most distinct cooling among them was the cooling in the early 1900s and 1960s∼1970s. So the author speculates that GT of the NH has not only long-term rising trend, but periodic oscillations overlapping on the rising trend.

This paper presumes that if there is no other external forcing, the ground temperature rising trend should be the same as that of the CO_2 density. So we can take the CO_2 density trend as the trend of GT rising and filter it out of the time series. Namely, deducting the CO_2 density trend $l(i)$ from original temperature time series $t(i)$, we can obtain temperature time series $t_1(i)$, which does not contain climate trend or effect of CO_2 density

$$t_1(i) = t(i) - l(i), \quad (i = 1, 2, \cdots, n). \tag{19}$$

Following (12), we get the variance of the original temperature sequence $S^2 = 0.0522$. We also found that after filtering out the density trend of CO_2, $S_1^2 = 0.0195$, then the variance contribution SS of CO_2 density to the temperature field is

$$\mathrm{SS} = ((S^2 - S_1^2)/S^2) \times 100\% = ((0.0522 - 0.02)/0.05) \times 100\% = 60\%.$$

This means that the CO_2 density rising has the variance contribution of nearly 63% on the NH ground temperature. From Fig. 1 it can be seen that the global volcanic activities with VEI over 5 weakened from 19th century to 20th century, especially from the end of 19th century to 20th century, the global volcanic activities of VEI over 3 decreased even more clearly. The decreasing trend of volcanic activities is inversely correlated to CO_2 density increase trend. The "umbrella effect" of volcanic activities and the "greenhouse effect" of CO_2 density increasing produce the increase of the GT of the NH in recent 100 years. So the 63% variance contribution should include both the contribution of CO_2 density increase and that of the volcanic activities[63,64].

Deducting the CO_2 density as a token of the climate trend from the original temperature sequence, we get the temperature sequence, which does not contain the climate trend or the effect of CO_2 density. The spectrum analysis of the filtered temperature sequence shows that the power spectrum value 0.556737 for the 88-year cycle of wave number 1 is obviously significant at 95% confidence level (figure omitted). This means that the GT obviously has the 88-year cycle. Based on (1)∼(5), the amplitude $A = 0.12$, initial phase angle $\theta_l = 1.0$ and the function of the GT in NH $\mathrm{BO}_{56}(i)$ is

$$\mathrm{BO}_{88}(i) = 0.12 \sin\left(\frac{2\pi}{88} i + 1\right), \quad i = 1, 2, \cdots, 151. \tag{20}$$

Figure 10 shows that in more than 100 years since 1850 the wave crest and trough of the quasi 88 year cycle (dash line) are consistent with those of the GT field in NH. This proves that the 88-year century cycle prevails throughout the GT field of the NH. Then, what is the relation between 88 year cycle of volcanic activities and the 88 years cycle of the GT of the NH? Based on (6), we obtain the 88 year cycle sequence in recent 151 years. From Fig. 10 it can be seen that volcanic activities curve goes in advance about 20 years than that of the GT. We obtained the correlation function $R(i)$ between the 88 year cycle of the GT in NH and the 88 year cycle of the volcanic activities in 1850~2000, and listed in the column 6 of Table 3. From Table 3 it can be seen that the maximum correlation coefficient $R(i) = 0.9912$ between the VEI and GT with the GT lagging behind VEI by 17 years. This means that the wave crest and trough of the 88 year cycle of the GT of the NH lag behind the 88 year cycle of the volcanic activities by 17 years.

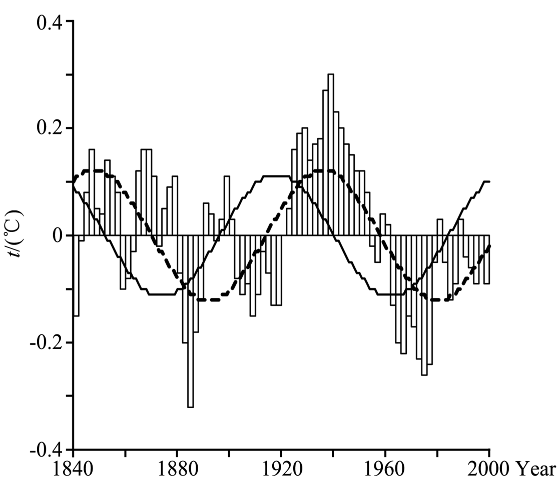

Fig. 10 Northern hemispheric ground temperature, the 88 year cycle of VEI (solid line) and the 88 year cycle of SSTA (dash line) in 1841~2000

Deducting the CO_2 density and the 88 year cycle from the original temperature sequence, the spectra analysis shows that the GT in the NH has a 50-year cycle. Because there is no corresponding volcanic activity cycle, in this paper this is not discussed. Some previous research obtained the 80 year cycle and 40~50 year cycle by different data and method, for example, Lin et al.[65] use empirical mode decomposition (EMD) and the data of the GT in NH for 400 years from 1600 to 2000[51,66]. The results we obtained are consistent with those of previous work, confirming that the GT in the NH has century scale and inter-decadal scale cycles.

4 CONCLUSIONS

Based on more than 600 years data of global volcanic activities over VEI 5 and the northern hemispheric ground temperature, the western Pacific high SLP and SSTA of the Northern Atlantic westerly area, the analysis shows that:

(1) The global strong volcanic activities have the obvious 88 year cycle and 100 year century cycle, and also have the 33 year decade cycle and the 11 year cycle, which correlates to the solar activities.

(2) The western Pacific subtropical high has an obvious 33 year cycle in summer and this is consistent with the 33 year cycle of the global strong volcanic activities, but it lags somewhat. The analysis shows that the 33-year cycle of western Pacific subtropical high pressure is the response to that of volcanic activities.

(3) The 88 years cycle of volcanic activities is closely consistent with that of the North Atlantic subtropical high in summer and goes in advance somewhat. The analysis shows that the 88 year cycle of western Atlantic subtropical high is the response to that of volcanic activities.

(4) The 100 year cycle of volcanic activities is inversely correlated to SSTA of the North Atlantic westerly area in winter, and goes in advance somewhat. The 88 year cycle of volcanic activities is inversely correlated to SSTA of the NA in summer, and goes in advance somewhat.

(5) The 88 years cycle of volcanic activities is basically consistent with that of northern hemispheric ground temperature, and goes in advance somewhat.

The analysis shows that the periodicity of volcanic activities has been reflected in every climate factor. However, the responses of the climate factors to the volcanic activity are very different.

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