EARTH'S CLIMATE AND QUASI-BIENNIAL CYCLICITY OF VOLCANIC ACTIVITY

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Abstract. Six reconstructions of the Earth's Northern Hemisphere temperature, three reconstructions of the Southern Hemisphere temperature, and two reconstructions of volcanic activity covering time intervals of 980- 2016 years were analyzed using Fourier and wavelet analysis. It is shown that there is a variation in volcanic activity since the mid-13th century with a period of 170-250 years. A similar periodicity is observed in the temperature of the Northern Hemisphere of the Earth. Statistical analysis using (*a*) wavelet filtering, (*b*) correlation analysis, and (*c*) Fisher's statistical approach showed that the probability that the quasi-bicentennial periodicity in Northern Hemisphere temperature after 1270 is not associated with corresponding variations in volcanic activity does not exceed 7.4×10^{-3}.

In the Southern Hemisphere, no evidence for the influence of quasi-bi-centennial variation in volcanic activity on temperature could be found. Possible reasons for the results obtained are discussed.

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1. INTRODUCTION

One of the most important tasks in global climate change research is to identify the anthropogenic contribution to the global warming of the last 120 years. The solution of such a problem will help to predict climate changes in the near future more accurately, and, therefore, has not only scientific but also significant practical value, since global climate changes have a significant impact on many aspects of human activity. The shortness of available instrumental series significantly complicates such studies. Instrumental data on both terrestrial temperature and various potential climate-forming factors (solar activity, aerosol concentration, atmospheric chemistry) usually cover no more than the last 100-150 years. This is insufficient to detect long-term (decades and centuries) temporal variations and estimate their amplitudes. The study of long-term climatic reconstructions, which are provided by paleoclimatology, allows us to significantly expand our knowledge of secular climate changes. Modern long-term paleoclimatic reconstructions obtained using various natural indicators cover up to the last few millennia. They represent an important source of information on long-term climatic fluctuations with periods of a hundred years or more. The analysis of available paleoclimatic information has shown that there is a quasi-bi-centennial (period of about 200 years) periodicity in the climate of different regions of the Earth [Raspopov et al., 2008; Liu et al., 2009; Breitenmoser et al., 2012; Ogurtsov et al., 2016; Novello etv al., 2016; Ogurtsov, 2022;]. In addition, it was shown in [Ogurtsov, 2025] that this variation is also present in the mean temperature of the entire Northern Hemisphere of the Earth. The causes of this climatic cycle are currently unclear. In [Ogurtsov, 2024, 2025], it was not possible to find a connection between the quasi-biennial temperature variation and the corresponding solar cycle of Suess. In [Ogurtsov, 2024], four Northern Hemisphere temperature reconstructions and one Southern Hemisphere temperature reconstruction were investigated. It turned out that the two-century periodicity in the Northern Hemisphere temperature correlates with the corresponding cycle in volcanic activity. No such relationship was found in the Southern Hemisphere. In the presented work, the study of a possible link between quasi-biennial cycles in volcanic activity and Earth's climate is continued using new data. The corresponding analysis was performed using six Northern Hemisphere temperature reconstructions and three Southern Hemisphere temperature reconstructions.

2. METHODS

The methods used in this paper were:

(*a*) the two longest-lived data series on volcanic activity: sulfate aerosol input to the atmosphere [Gao et al., 2008] and aerosol optical thickness (AOT) of the atmosphere [Crowley and Unterman, 2013]. Both series were derived from the analysis of ice cores extracted in Greenland and Antarctica. These series, spanning the last 1200-1500 years, are shown in Fig. 1a*,b* and described in Table 1. The frequency of volcanic activity is subject to long-term fluctuations as it increases during certain periods, forming clusters of volcanic eruptions. Volcanic series averaged over 50 years were used as indicators of long-term changes in volcanic activity. These are shown in Fig. *1c*.

Fig. 1

(*b*) Six Northern Hemisphere Earth temperature reconstructions reconstructing the temperature of different seasons over 1210-2016 years, obtained from [Moberg et al., 2005; Christiansen and Ljungqvist, 2012; Schneider et al., 2015; Wilson et al., 2016; Guillet et al., 2017; Büntgen et al., 2021]. These series were derived using various temperature indicators including annual ring width (TRW), maximum latewood density (MXD), stable isotope $\delta^{18}O$ concentration in terrestrial archives, pollen data (P), temperature measured in boreholes (BT), melted ice layer thickness (IM), ice accumulation rate (AC), banded lake sediments (VS), documentary information (D), and coral calcification (C). These reconstructions are summarized in Fig. *2a-e* and described in Table 1.

(*c*) Three reconstructions of Southern Hemisphere Earth's temperature, reconstructing the temperature of different seasons over 980-1780 years, obtained from (Jones et al., 1998; Mann and Jones, 2003; Neukom, 2014). These time series are shown in Fig. *2j-i* and described in Table 1.

Fig. 2

The spectral properties of these time series were investigated using wavelet and Fourier analysis. The wavelet spectra obtained using the Morlet complex basis were normalized to a confidence level of 0.95 calculated for red noise with the corresponding AR(1) coefficient according to the methodology described in [Torrence and Compo, 1998]. From all time series used in this work, 2nd order polynomial trends were preliminarily subtracted, since the strong long-term (multidecadal and longer) variations present in many geophysical series can seriously complicate the analysis of shorter-term variations. To isolate the quasi-bicentennial variations, all temperature series were subjected to wavelet filtering in the 171-282 year scale band using a valid MHAT (Mexican Hat) basis (see [Torrence and Compo, 1998]). The significance of the correlation between the series filtered in this band was evaluated using the statistical experiment described in [Ogurtsov, 2024; Ogurtsov, 2025].

3. RESULTS

The local wavelet spectra of the data series on sulfate aerosol injection into the atmosphere and aerosol optical thickness are shown in Figs. *1g-e*. As Fig. *1g-e* shows, the variation with a period of 170-240 years has been present in volcanic activity since the mid-13th century. The global wavelet spectra of temperature paleoreconstructions calculated for the full time intervals covered by the corresponding series are shown in Fig.3. Figure 3 shows the presence of quasi-bicentennial variation in the spectra of five of the six Northern Hemisphere temperature reconstructions and one of the Southern Hemisphere temperature reconstructions. Fourier analysis of these time series gives similar results.

Fig. 3

Correlation coefficients between temperature and volcanic data series wavelet-filtered in the bicentennial band are shown in Table 2 along with their significances (in parentheses). They were calculated on time intervals from 1270 to the end of the 20th century, with the temperature series shifted by 20 years to maximize correlation. As can be seen from Table 2, the quasi-bi-centennial cycles in many of the series describing Northern Hemisphere temperature have a significant negative correlation with the corresponding cycles in volcanic activity. This effect is not observed in the Southern Hemisphere. If we consider the significance of the volcano-climate correlation derived from reconstructions [Moberg et al., 2005; Christiansen and Ljungqvist, 2012; Schneider et al., 2015; Wilson et al., 2016; Guillet et al., 2017; Büntgen et al, 2021], as the results of six independent null hypothesis tests for quasi-biennial temperature variation in the Northern Hemisphere, then we can use Fisher's method [Fisher, 1925] to estimate the joint probability. Using Fisher's method, the values of the statistic were calculated:

$$\chi_F = -2\sum_{i=1}^{k} \ln(p_i) \quad , \quad (1)$$

where p_i is the probability of the null hypothesis obtained using the *i-test* and *k* is the number of tests. For bicentennial correlations with the atmospheric sulfate aerosol injection (SLF) and aerosol optical thickness (AJD) data series we have:

$$\chi_F^{SLF} = -2\ln(0.47 * 0.062 * 0.129 * 0.015 * 0.28 * 0.081) = 27.1 \; ,$$

$$\chi_F^{AOD} = -2\ln(0.52 * 0.053 * 0.051 * 0.011 * 0.18 * 0.022) = 32.2. \quad (2)$$

According to Fisher [29], if all tests are independent and all null hypotheses are true, the statisticχ_F has the distribution χ^2_{2k} . The probabilities of the null hypothesis for the obtained values of χ^2_{12} are:

$$P^{SLF}(27.1) = 7.4\times10^{-3},$$

$$P^{AOD}(32.2) = 1.3\times10^{-3}. \quad (3)$$

Thus, the study performed using: (*a*) wavelet filtering, (*b*) correlation analysis, (*c*) Fisher's statistical approach , showed that the probability that the quasi-bicentennial periodicity in Northern Hemisphere temperature after 1270 is not associated with corresponding fluctuations in volcanic activity , is extremely low.

4. DISCUSSION AND CONCLUSIONS

Spectral analysis of paleoreconstructions of volcanic activity has shown that in volcanic activity from the mid-13th century onwards there was a cyclicity with a period of 170-240 years. This variation is most likely the result of internal geotectonic oscillations, but further studies are needed to clarify this issue. A similar variation is also manifested, although in different degrees, in the six paleoreconstructions of the Northern Hemisphere temperature. Over the indicated time interval, quasi-bicentennial cycles in Northern Hemisphere temperature are negatively correlated with the corresponding variations in volcanic activity, although not all correlation coefficients are significant at $p<0.10$. A Fisher's test for joint probability, conducted using six separate values ofp_i , showed that the probability of the null hypothesis - the assumption of no relationship between two-century variations in volcanic activity and Northern Hemisphere temperature - is no more than 7.4×10^{-3}. The corresponding value obtained in [Ogurtsov, 2024] based on the analysis of four reconstructions of the Northern Hemisphere temperature was equal to 1.1×10^{-2}. Thus, taking into account two additional temperature series allowed us to significantly reduce the value of the null-hypothesis. The influence of long-term variations of volcanic activity on the climate of the Northern Hemisphere of the Earth has received a new serious confirmation. It may be noted that the short-term climatic effect of volcanic eruptions is well known. Volcanic eruptions release ash and sulfur dioxide gas into the atmosphere, which turns into sulfate aerosol. Large ash particles fall quickly to the Earth's surface, but aerosols can remain in the stratosphere for several years, reducing the amount of solar radiation reaching the Earth's surface, lowering the temperature of the troposphere, and altering atmospheric circulation patterns. The direct cooling effect can last up to several years, depending on the eruption. It is possible that it can be further prolonged by feedback mechanisms. To date, there are indications that clusters of volcanic eruptions can cause cooling of the Earth's surface lasting up to centuries [Gleckler et al., 2006; Zhong et al., 2011; McGregor et al., 2015] and even millennia [Baldini et al., 2015] due to the feedback system between ocean and sea ice temperatures.

In most cases, the highest correlation is observed when the bicentennial periodicity of volcanic activity precedes the corresponding temperature change by 20 years. This lag time most likely reflects the characteristic response time of the ocean to the radiative forcing associated with volcanic impacts [Ogurtsov, 2024].

In the Southern Hemisphere, no evidence of the influence of the quasi-bi-centennial variation of volcanic activity on the temperature could be found. Thus, the conclusion obtained in [Ogurtsov, 2024] based on the analysis of one temperature paleoreconstruction was confirmed using three reconstructions. The absence of a connection between long-term variations in volcanic activity and temperature in the Southern Hemisphere is consistent with the results of modeling [Zhong et al., 2011], which showed that the temperature response to volcanic impact in the Southern Hemisphere is much weaker than in the Northern Hemisphere. It was also shown in [Monerie et al., 2017] that volcanic activity generally has a weaker effect on the Southern Hemisphere climate than on the Northern Hemisphere climate. This difference may be due to the fact that the Southern Hemisphere climate is influenced by internal factors more than external factors [Wilmes et al., 2012; Neukom et al., 2014]. And this, in turn, may be due to the fact that the Southern Hemisphere is much more covered by oceans, whose significant heat capacity can effectively mitigate external influences [Stouffer et al., 1989].

It should be noted that our knowledge of the past quasi-biennial cycles in the Earth's temperature and volcanic activity is still insufficiently complete. The remaining uncertainties in estimating quasi-biennial temperature variations may be related to the fact that (*a*) modern paleoreconstructions of temperature cover only a small part of the globe (see Fig. 1 [Christiansen and Ljungqvist, 2012] and Fig. 1 [Büntgen et al., 2021]), (b) the error in temperature determination increases as we go deeper into the past. Indeed, the number of individual temperature indices used in its reconstruction decreases, for example, from 40 [Wilson et al., 2016] and nearly 800 [Schneider et al., 2015] in the early 20th century to a low of 20 [Wilson et al., 2016] and less than 200 [Schneider et al., 2015] in the 9th century. (*c*) It is not entirely clear whether the problems with the reconstruction of long-term temperature variations have been fully resolved in modern dendrochronology.

The dating of sulfate peaks in Antarctic ice also remains uncertain. After the beginning of the 12th century, the dating accuracy improves significantly due to the possibility of comparing sulfate peaks in Antarctic and Greenland cores [Crowley and Unterman, 2012]. Peaks in Greenlandic ice during this period are reliably dated due to information on volcanic eruptions in Iceland. Earlier than the twelfth century, the documentation of Icelandic volcanic eruptions rapidly dwindles.

It may also be noted that there are still some problems with the application of the Fisher test. It is unclear whether the temperature reconstructions used in this paper are completely independent. Some of these time series may include the same individual temperature indicators [Ogurtsov, 2024]. Thus, the results of [Ogurtsov, 2025] are confirmed using a broader empirical base. However, for the final conclusions about the influence of long-term changes in volcanic activity on the Earth's temperature, it is desirable to further develop the methods of paleoclimatology and obtain new paleoreconstructions based on completely independent individual indicators. This will make it possible to more adequately apply various statistical methods, including the Fisher method, and, as a consequence, to produce more reliable estimates of the temperature-volcanic relationship. It is also desirable to expand the spatial coverage of the individual temperature indicators used for hemispheric-scale reconstructions, thereby making these reconstructions more representative.

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CONFLICT OF INTERESTS

The author declares that he has no conflict of interest.

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Table 1. Temperature reconstructions used in the paper.

Source	Time interval	Response season	Geographic coverage	Data type
Crowley and Unterman [2013]	501-2000	Annual average	Greenland, Antarctica	SO_4^{2-} ions , conductivity
Gao et al. [2008]	800-2000	Annual average	Greenland, Antarctica	SO_4^{2-} ions , conductivity
Moberg et al. [2005]	1- 1979	Annual average	Northern Hemisphere	Multireconstruction (TRW, $\delta^{18}O$, P, BT, IM)
Christiansen and Ljungqvist [2012]	0-1973	Annual average	Extratropical Northern Hemisphere (φ>30^0 N)	Multireconstruction (TRW, MXD, $\delta^{18}O$, VS, D, P, speleothem-preature)
Schneider et al. [2015]	600-2002	June-August	Extratropical Northern Hemisphere (φ>30^0 N)	Dendrodata (MXD)
Wilson et al. [2016]	800-2010	May-August	Northern Hemisphere	Dendrodata (MXD)
Guillet et al. [2017]	500-2000	June-August	Northern Hemisphere	Multireconstruction (TRW, MXD, $\delta^{18}O$)
Buntgen et al. [2021]	1-2016	June-August	Northern Hemisphere	Dendrodata (TRW)
Jones et al. [1998]	1000-1980	December-February	Southern Hemisphere	Multireconstruction (TRW, $\delta^{18}O$, $\delta^{13}O$, C)
Mann and Jones [2003]	200-1980	Annual average	Southern Hemisphere	Multireconstruction

				(TRW, $\delta^{18}O$, BT, VS, Mg/Ca)
Neukom et al. [2014]	1000-2000	Annual average	Southern Hemisphere	Multireconstruction (TRW VS, D, C, speleo-temperature)

Table 2. Correlation between temperature reconstructions and volcanic data filtered between 171-259 years.

	Moberg et al. [2005]	Christiansen and Ljungqvist [2012]	Schneider et al. [2015]	Wilson et al. [2016]	Guillet et al. [2017]	Büngtgen et al. [2021]	Jones et al. [1998]	Mann and Jones [2003]	Neukom et al. [2014]
Crowley and Unterman [2013]	-0.29 (0.51)	**-0.66** (0.053)	**-0.61** (0.051)	**-0.74** (0.011)	-0.49 (0.18)	**-0.74** (0.022)	-0.41 (0.21)	0.25 (0.45)	-0.11 (0.55)
Gao et al. [2008]	-0.29 (0.47)	**-0.61** (0.062)	-0.54 (0.129)	**-0.71** (0.015)	-0.36 (0.28)	**-0.59** (0.081)	-0.38 (0.31)	0.29 (0.52)	-0.27 (0.59)

Note. Numbers in parentheses show the significance of the correlation coefficient. Small bold numbers show correlation coefficients with significance $p<0.10$, large bold numbers show $p<0.05$.

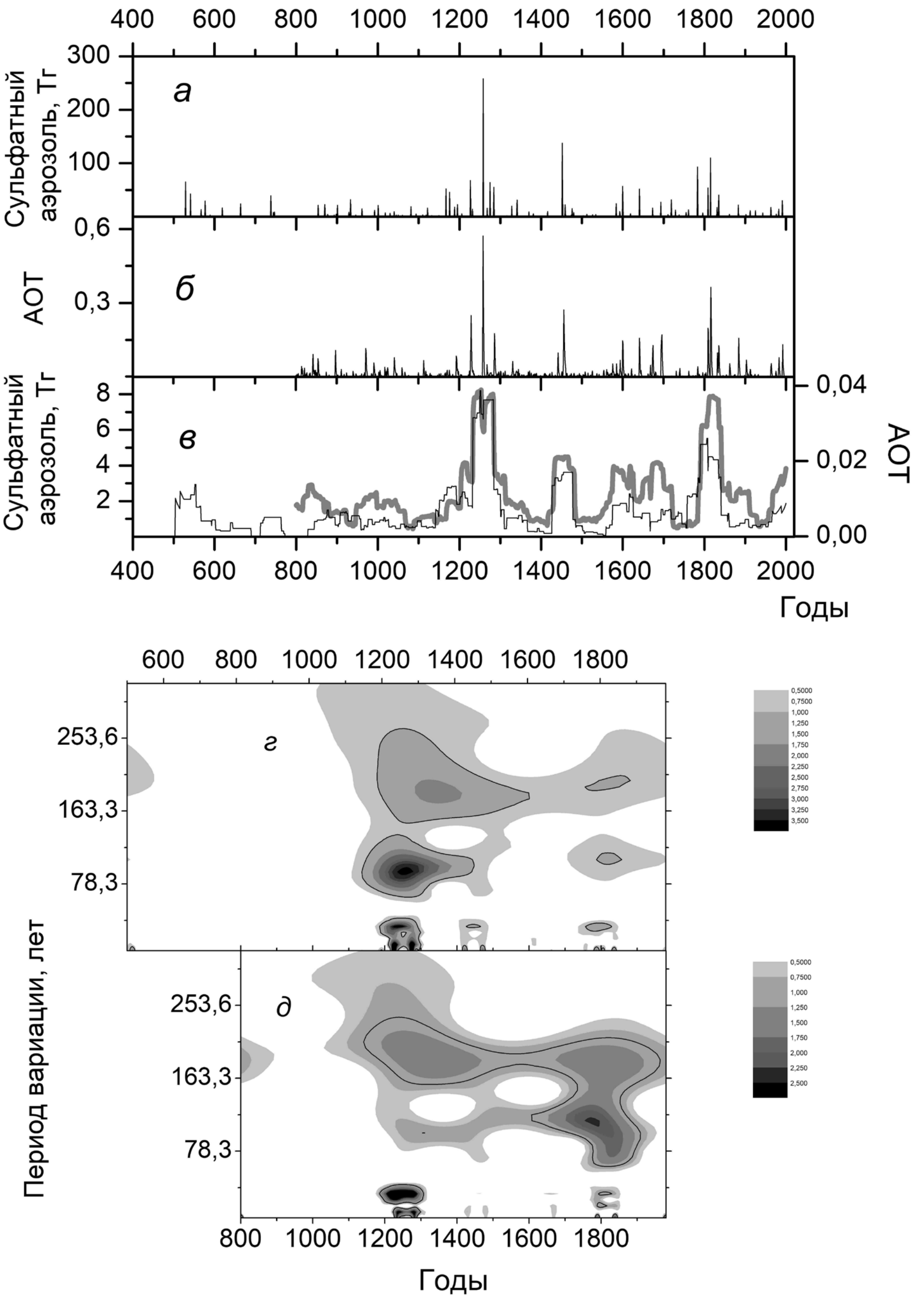
FIGURE CAPTIONS

Fig. 1. (*a*) - injection of sulfate aerosol into the atmosphere by Gao et al. [2008]; (*b*) - aerosol optical thickness of the atmosphere [Crowley and Unterman, 2013]; (*c*) - the same series but smoothed over 50 years; (*d*) - local wavelet spectrum of the series of Gao et al. [2008]; (*e*) - local wavelet spectrum of the series [Crowley and Unterman, 2013]. The contour line corresponds to a confidence level of 1.0.

Fig. 2. Northern Hemisphere temperature reconstructions used in the paper: (*a*) -

multireconstruction of Moberg et al. [2005]; (*b*) - multireconstruction by Christiansen and Ljungqvist [2012]; (*c*) - dendro-reconstructions Schneider et al. [2015]; (*d*) - dendroreconstruction of Wilson et al. [2016]; (*e*) - multireconstruction by Guillet et al. [2017]; (*e*) - dendroreconstructions by Büntgen et al. [2021]; (*g*) - multi reconstruction by Jones et al. [1998]; (*h*) - multi-reconstruction by Mann and Jones [2003]; (*i*) - multi-reconstruction by Neukomet al. [2014].

Fig. 3. Global wavelet spectra of temperature series: (*a*) - multireconstructions of Moberg et al. [2005]; (*b*) - multireconstructions of Christiansen and Ljungqvist [2012]; (*c*) - dendroreconstructions of Schneider et al. [2015]; (*d*) - dendroreconstructions of Wilson et al. [2016]; (*e*) - multireconstructions of Guillet et al. [2017]; (*f*) - dendroreconstructions by Büntgen et al. [2021]; (*g*) - multireconstructions of Jones et al. [1998]; (*h*) - multireconstructions by Mann and Jones [2003]; (*i*) - multireconstructions by Neukom et al. [2014]. Dotted lines are confidence level 0.95.



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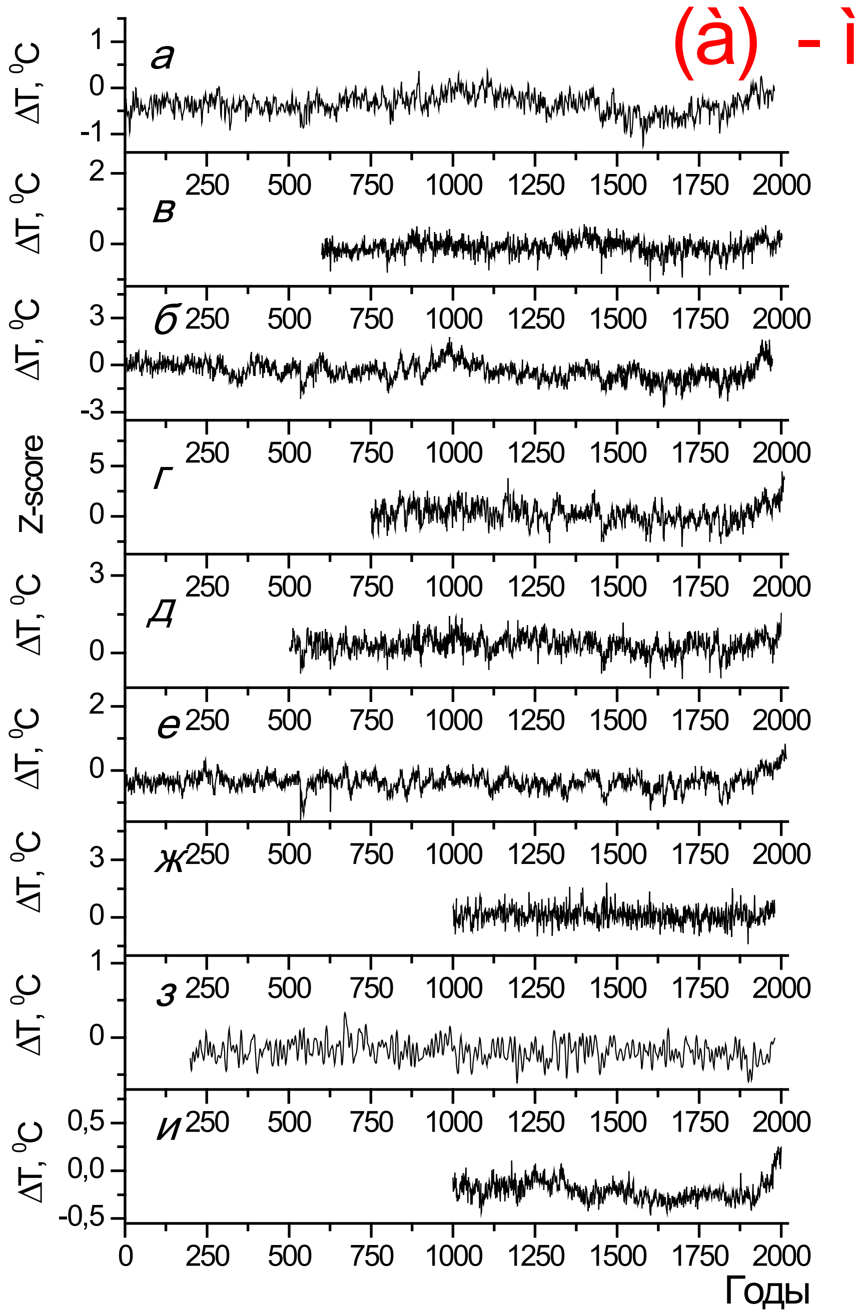
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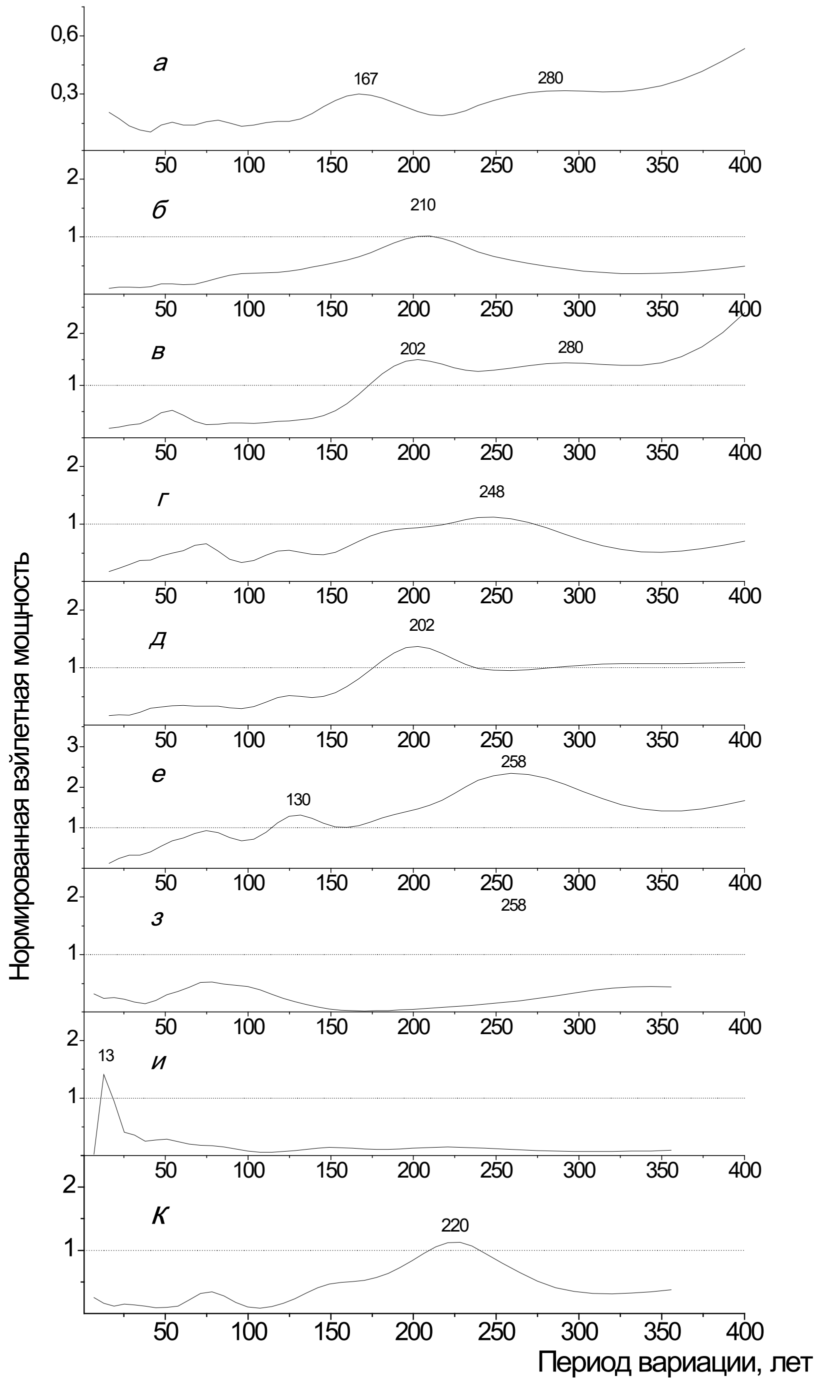
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Fig. 3.