Interrelation between climate warming in Siberia in the XX century and the activity of tropical volcanoes

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The paper presents analysis of the interrelation between climate warming in Siberia in the first and last decades of the twentieth century with the activity of explosive tropical volcanoes, capable of ejecting the eruption products to the stratosphere. It is shown that strong perturbation of wave activity of atmospheric circulation happened in the period of a series of frequent volcanic explosions from 1963 to 1991, caused an intensification of the North Atlantic oscillations (Azores High and Icelandic Low) accompanied by weakening of the Siberian anticyclone. In the representation of atmospheric activity centers by large-scale vortices, I consider a mechanism that can yield an intense blowing of Siberian regions in winter by warm Atlantic air leading to a significant warming of regional climate. Analysis of long-term chronologies of the North Atlantic oscillations (NAO), the values of the global stratospheric optical depth, and the chronicle of explosive eruptions of volcanoes for over 130-year period has shown that the climate warming in Siberia in the first and last decades of the twentieth century has same nature, with the activity of tropical volcanoes being the common background.

Introduction

High-power explosive volcanic eruptions are capable of breaking through the tropopause and injecting a huge amount of volcanic products into the stratosphere. For example, the eruption of Mt. Pinatubo in June 1991 has delivered about 20 million tons of SO_2 into the stratosphere.[1] From these products of eruption the sulfuric acid aerosol is formed, which resides in the stratosphere during several years depending on the explosion power. Over this period the stratospheric circulation disperses the cloud of volcanic aerosol over the globe, especially if the eruption has occurred in the intertropical convergence zone.

It is traditionally believed that clouds of volcanic aerosol in the stratosphere should decrease the ground temperature.[2] Really, the atmospheric albedo increases, and the fluxes of direct solar radiation reaching the Earth's surface decrease. However, on the regional scale the temperature regime is formed both by the radiation and dynamic (circulation) processes. The dynamic factor can prevail over the radiation one in the joint action of these processes. In this connection let us recall the winter warming in Siberia in the first half of 1990s after the Mt. Pinatubo eruption. High-power explosive volcanic eruptions strongly disturb the general atmospheric circulation, especially its wave activity.

Temperature regime of the south of Siberia since the end of XIX century

Let us analyze the temperature regime of the south of Siberia based on a long series of temperature observations in Tomsk. The foundation of the first behind Ural University in Tomsk in 1881 enabled the arrangement of regular measurements of the surface air temperature. Figure 1*a* shows a series of annual mean temperatures in Tomsk from 1890 until 1995. This figure shows the basic trends of temperatures over this 106-year long observation period using the polynomial trend of the 4th order.

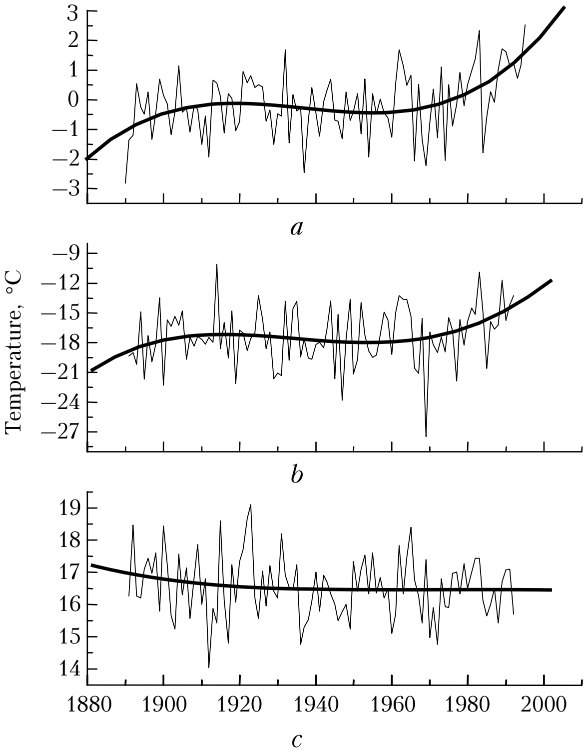

Fig. 1. Series of ground temperatures in Tomsk with polynomial trends of the fourth order; annual mean (*a*); winter mean values (*b*); summer mean values (*c*).

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It is seen from this figure that the trends of regional temperatures in Tomsk, as a whole, agree with the global climate changes. After the temperatures rise late in XIX century and in the first quarter of the XX century (the so-called warming of the 1930s) a slight cooling was observed until the 1960s, and then an active temperature rise occurred. It should be noted that the climate changes in Siberia are mainly determined by winter and not by summer temperatures. This is seen from the trends of winter and summer mean temperatures in Tomsk (Figs. 1*b* and *c*) described by the polynomial of the 4th order. In their turn, winter temperatures strongly correlate with January temperatures (the correlation coefficient exceeds 0.75). Therefore, only the January mean temperatures are considered in what follows.

In winter, as known, the centers of atmospheric action, which largely determine the regional peculiarities of the climate regime, achieve their maximum activity.

Characteristics of the activity of the North-Atlantic oscillations and Siberian anticyclone in the second half of the XX century

Atmospheric centers of action are the large-scale elements of the general atmospheric circulation structure. Based on data by Monin and Shishkov[3] there exist three axes in the general atmospheric circulation: the axis of intertropical convergence, along which the subrotation is formed, i.e., slower rotation of equatorial air about the Earth's axis, than the rotation of the solid planet, and two axis of the north and south subtropical jet streams, along which supplementary angular momentum of zonal flows is transfered under the action of "negative viscosity" of the statistical ensemble of Rossby–Blinova waves thus producing a superrotation. The shifts of zonal velocities at these axes between subrotation and superrotation can lead to the formation, due to Helmholtz instability mechanism, of subtropical anticyclones and subpolar cyclones that behave themselves as small balls in ball bearings.

Quasistationary positions of such vortices are termed the atmospheric action centers (AAC). Their presence shows the deterioration of zonality due to unzonal factors of heating and cooling of the atmosphere over the oceans and continents having different temperature. In the Northern hemisphere, for example, we can recognize two pairs of constant ocean AACs: Azores High and Icelandic Low, and Hawaiian anticyclone – Aleutian Low. Under the influence of monsoon effects, the seasonal continental AACs can be formed. In winter in the Northern hemisphere the Siberian and Canadian anticyclones are formed, and in summer the south-Asiatic and Californian cyclones are formed.

The activity of three AACs, the Azores High, Icelandic Low, and Siberian anticyclone play a key role in the temperature regime of Siberia in summer. The center of the first ocean AAC, drifting slightly, is positioned close to the Azores, and the second ocean AAC is located between Iceland and the south coast of Greenland. The center of Siberian anticyclone is located, as a rule, in the northern Mongolia. The activity of these AAC can be estimated by the pressure difference at their center and mean pressure in the Northern hemisphere at sea level. This difference is commonly called the AAC intensity. Figures 2*a*–*c* show the interannual variations of the intensity of the considered three AACs in winter for the second half of the XX century based on the observation data[4] and reanalysis.[5]

The joint variations of intensities of a pair of ocean AACs characterize the North-Atlantic oscillations (NAO). The NAO indices are determined by pressure differences at the centers of the Azores High and Icelandic Low or by the intensity differences of this pair of AACs. The obtained differences in hPa are transformed to the dimensionless indices I_i using a standard formula $I_i = (x_i - \bar{x})/\delta x$, where x_i, $\bar{x}$, and δx are respectively, the current value of the series, its mean and rms deviation. Figure 2*d* shows a series of NAO indices for the second half of the XX century obtained using data from Figs. 2*a* and *b*.

Figures 2*a* and *b* show good agreement between the observation data and reanalysis for the ocean AACs (the correlation coefficient is, on the average, about 0.95). It is, of course, clear that the NAO indices in this case (Fig. 2*d*) well correlate too (the correlation coefficient is 0.97).

The situation with the Siberian anticyclone is yet disputable. The observation data presented in Fig. 2*c* and data of reanalysis differ significantly (the correlation coefficient is 0.3). Besides, these data according to Ref. 6 contradict (with the negative correlation coefficient) the data from Refs. 7–9. These mismatches between the data allow contradictory estimates of the trends in variations of the Siberian anticyclone, especially during the periods of winter warming in Siberia in the last decades of the XX century.

According to data from Refs. 7–9 the winter warming events are associated with the strengthening of the Siberian anticyclone. According to other data[10–12] the trend toward weakening of the Siberian anticyclone can be traced in the last decades that agrees with the data of observations from Ref. 4.

It is usually supposed[6] that weakening of the Siberian anticyclone is a consequence of the global warming, which, as a rule, is considered to be due to anthropogenic factor. However, there are no less grounds to assume that a marked decrease of the activity of the Siberian anticyclone is not the effect but the cause for winter warming in Siberia in the first and last decades of the XX century. Let us consider the peculiarities of the second half of the XX century in a more detail.

Consider the schematic diagram of a joint effect of NAO and the Siberian anticyclone on the winter temperature behavior in Siberia (Fig. 3) in the AAC representation by large-scale vortices. Figure 3*a* shows the situation of neutral behavior of NAO and active Siberian anticyclone, which is, evidently, typical for the 1950s and 1960s. Figure 3*b* shows the situation of disturbed NAO and the weakened Siberian anticyclone, which was typical for the last quarter of the XX century.

A pair of ocean AACs, similar to the aerodynamic vortex pump, sucks in warm air from the Atlantic ocean and forms an airflow along the direction toward the Eurasian continent. The active Siberian anticyclone blocks a zonal transfer of warm air to Siberia dissipating the airflow to the northeast (Fig. 3*a*). In this case, the temperature condition in the blocked Siberian regions is characterized by reduced temperatures, which interannual variation should not be associated with the NAO indices variations.

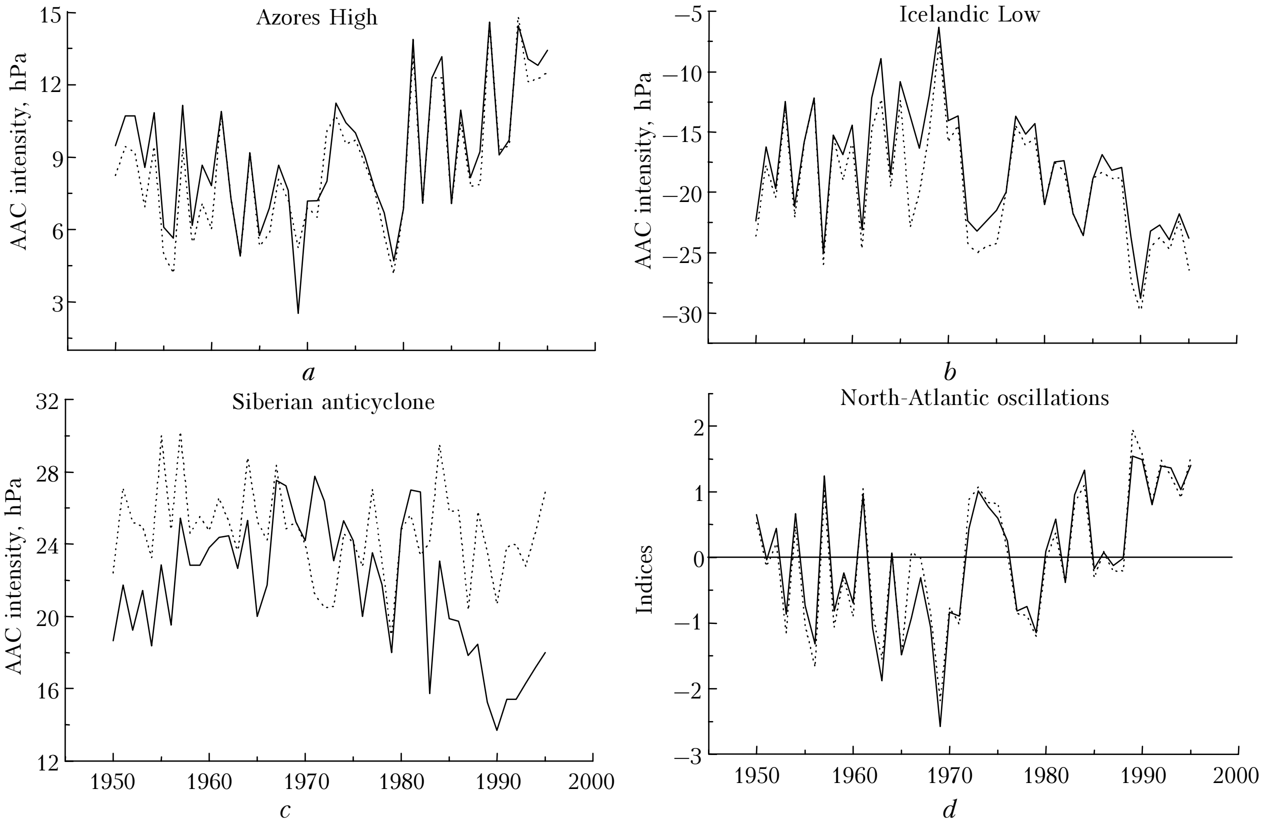

Fig. 2. Characteristics of intensities of the atmospheric action centers in the second half of the XX century (solid line – observations, dashed line – reanalysis).

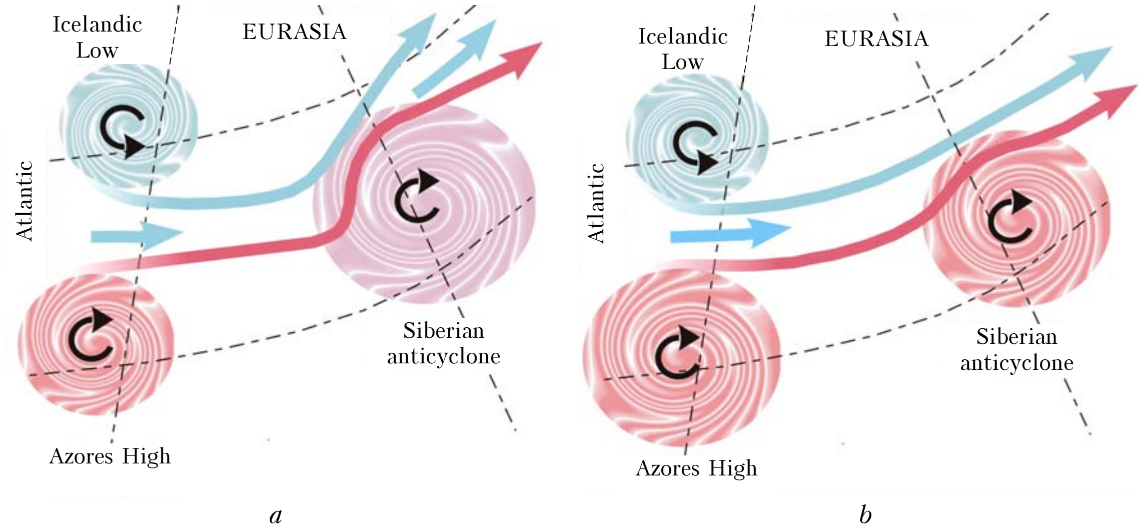

Fig. 3. Schematic representation of blowing of Eurasia during winter by the Atlantic airflow in the representation of atmospheric action centers (AAC) by large-scale vortices for two situations: neutral ocean AAC and active Siberian anticyclone (*a*); strengthened ocean AAC and weakened Siberian anticyclone (*b*).

Disturbed and strengthened ocean AAC increase the intensity of winter blowing of the Eurasian continent by warm air from the Atlantic Ocean. If Siberian anticyclone during this period is found to be weak, then the situation similar to that in Fig. 3*b*, ought to be realized. In this case the blowing by the airflow from Atlantic can occur over vast areas of Siberia even to the east of the location of the Siberian anticyclone. In this situation the Siberian anticyclone vortex not only does not block the air current but, turning the current, produces a supplementary acceleration along the zonal direction. The variations of winter temperatures in the area of the influence of the Atlantic airflow must correlate with the NAO activity and be an indicator of the winter warming.

To check the validity of the assumptions on the situations, described above and presented in Fig. 3, we shall analyze January temperatures at different meridian sections of the Atlantic airflow in Siberia in zones of its probable influence. Table 1 shows the results obtained from correlation analysis of January surface temperatures at different stations in Siberia with the NAO indices. Two 15-year periods, 1960–1974 and 1975–1989 were chosen with the negative and positive values of the NAO indices according to Fig. 2*d*. The temperature data have been taken from the web site: http://meteo.ru. The first meridian section (Kustanai – Kurgan – Leushi) was chosen according to the western meridian in Siberia, 65°E (east longitude), the second (Barnaul – Tomsk – Kolpashevo) – about 84°E, the third (Irkutsk – Vanavar – Tura) – about 102°E, the fourth (Kirensk – Erbogachen – Olenek) – about 110°E, and the fifth meridian section (Skovorodino – Aldan – Vilyuisk) – in the extreme last of Siberia – about 124°E.

Table 1. The correlation coefficients between the ground temperature and NAO indices (*R*) and slope of temperature trends (*B*)

#	Observation point	Coordinates, N/E	1960–1974		1975–1989	
			R	*B*	*R*	*B*
1	Kustanai	53.22/63.62	–0.16	–6.15	**0.57**	**0.94**
	Kurgan	55.47/65.4	–0.17	–5.93	0.51	–0.14
	Leushi	59.62/65.78	–0.15	–4.98	0.26	–1.18
2	Barnaul	53.33/83.70	0.21	–4.09	0.6	**2.08**
	Tomsk	56.43/84.97	0.16	–4.73	**0.68**	1.59
	Kolpashevo	58.30/82.90	0.08	–4.57	0.65	0.3
3	Irkutsk	52.27/104.4	0.35	–0.73	0.66	**2.10**
	Vanavara	60.33/102.27	0.1	–1.74	**0.68**	1.81
	Tura	64.17/100.07	–0.12	–2.8	0.61	0.16
4	Kirensk	57.77/108.12	0.32	–0.17	0.61	2.71
	Erbogachen	61.27/108.02	0.09	–1.34	**0.71**	**2.75**
	Olenek	68.50/112.43	–0.08	4.48	0.6	–0.19
5	Skovorodino	54.0/123.97	–0.22	–1.39	0.56	0.29
	Aldan	58.62/125.37	0.27	0.51	**0.72**	**1.60**
	Vilyuisk	63.77/121.62	–0.08	–0.41	0.62	0.23

Table 1 shows that in the first period analyzed no significant correlation of January temperatures at the observation points was observed with the NAO indices; and *vice versa*, in the second period high significant values of the correlation coefficient *R* were obtained everywhere (excluding Leushi) including last meridian section beyond the eastern boundary of the Siberian anticyclone. In this case, based on the maximum values of *R*, the Atlantic airflow axis path is well followed along zonal direction with a small shift to the north, especially for 3rd and 4th meridian sections in the area of action of weakened Siberian anticyclone.

Table 1 also shows the slope values of temperature trends *B* during the corresponding periods. It is seen that for the first period from 1960 until 1974 for most of observation points (except for Olenek and Aldan) the trend of January temperatures is negative. For the second period, from 1975 until 1989, on the contrary, the winter warming is typical over the vast area of Siberia (except for Kurgan, Leushi, and Olenek). At the same time, the areas of maximum warming (*B*) are mainly located along the path of the Atlantic airflow axis. Thus the results of analysis of January temperatures, given in Table 1 for two periods, completely correspond to the two situations shown in Fig. 3. They, in particular, show uniquely that in the period from 1975 to 1989 simultaneously with the NAO strengthening a significant weakening of Siberian anticyclone occurred that was favorable for an effective blowing of the vast areas of Siberia by warm Atlantic airflow in winter. What could the cause of such perturbations of atmospheric activity centers?

If we closer analyze the correlation of January temperatures, for example, in Tomsk with NAO indices over a period from 1950 to 1995 using sliding average with the window of 15-year duration in a one-year step (Fig. 4), we shall see that all the bursts of the correlation coefficients were observed during years when explosive eruptions of tropical volcanoes occurred, the products which were recorded in the mid-latitude stratosphere with lidar.[13,14] To speak generally this result could be predicted because the eruptions of such volcanoes strongly perturb the atmospheric circulation and its wave activity.

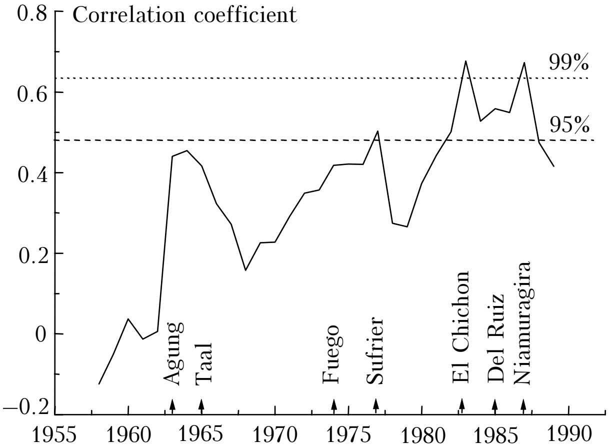

Fig. 4. The correlation coefficients of January temperatures in Tomsk with NAO indices at 15-year sliding average window and one-year step over a period from 1950 to 1995 and moments of explosive eruptions of tropical volcanoes.

Figure 4 shows that as a result of a series of volcanic eruptions, following one after another, swinging of the entire atmospheric oscillation system occurs and in the peak perturbation of the atmospheric activity centers the values of the correlation coefficients exceed the level of statistical significance not only 95% but also 99% even at relatively weak eruptions such as Niamuragira in Zair in 1986.

Explosive volcanic eruptions and activity of the North-Atlantic oscillations in the XIX and XX centuries

Figure 5*a* shows the chronology of NAO indices from 1865 to 1998 based on data from the web site: http://www.cru.uea.ac.uk/cru/data/nao.htm. Results of NAO indices smoothing using FFT filter with the a 3-year window are shown by bold line.

Figure 5*b* shows the behavior of the global aerosol optical depth τ_a based on the results reconstructed from aerosol inclusions in the ice samples according to the data from Ref. 15. A detailed chronicle of high-power explosive volcanic eruptions, occurred in the tropical zone and in the Northern hemisphere over a period from 1850 to 1991, is given in Table 2 based on the data from Ref. 15 supplemented by data from Ref. 14.

In Ref. 15 the series τ_a has been divided into four periods: the first – 1850–1882; the second – 1883–1959; the third – 1960–1978, and the fourth – 1979–1990. Figure 5*b* shows the series τ_a subdivided also into four periods, but with different time intervals: the first – 1860–1882; the second – 1883–1914; the third – 1915–1959; and the fourth – 1960–1998. Table 2 shows the volcanic eruptions classified in a similar way. This is due to general characteristics clearly defined in both parts of Fig. 5.

As is seen from Fig. 5 and Table 2, the period I is characterized by infrequent eruptions of a moderate power and neutral oscillations of NAO indices. The period II is given by high-power and frequent eruptions during 30 years and by the trend toward increase of NAO indices.

For the period III the infrequent eruptions of moderate power and normalization of NAO indices oscillation are typical.

Finally, in the period IV the burst of high-power and frequent eruptions happens again, resulting in greater NAO perturbation than in the period II that is evident from the behavior of the trends of NAO indices for these periods.

It should be noted (see Fig. 1*a*) that it is precisely during these periods the maximum rise of temperatures in Tomsk was observed. Based on the general characteristics the periods II and IV are similar. From this similarity we can assume that both in late XX century and at the border of XIX and XX centuries, the series of explosive eruptions of tropical volcanoes, disturbing the wave activity of atmospheric circulation, intensified the activity of the ocean centers of atmospheric action in the Atlantic and weakened the Siberian anticyclone.

This gave rise to the long-term intense blowing of Siberian Regions in winter by warm air from the Atlantic Ocean and warming of the regional climate related to it.

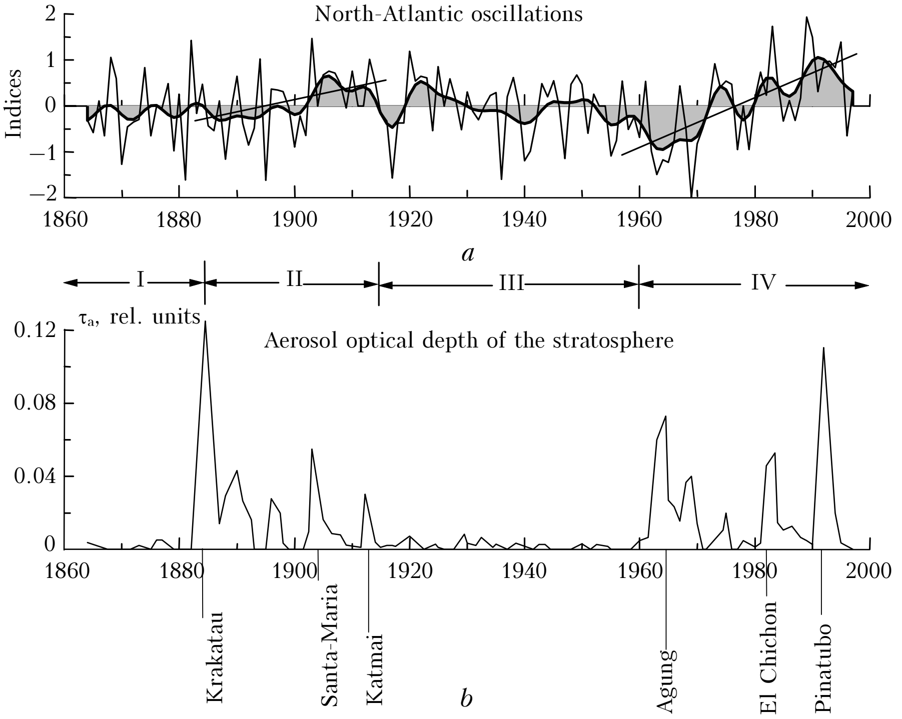

Fig. 5. NAO indices (fine line) and results of their smoothing by FFT filter by three points (bold line) (*a*); reconstructed values of aerosol optical depth of the stratosphere at 0.55 μm wavelength and moments of volcanic explosive eruptions (*b*).

Table 2. Explosive volcanic eruptions in the tropical zone and in the Northern hemisphere over a period from 1850 to 1991 and the indices of volcanic explosions (VEI)*

Period	Years of eruption	Volcanoes	Latitude/ longitude	VEI
I	1855–1856	Kotopakhi	1°S/78°W	–
	1856	Avu	4°N/125°E	–
	1861	Makjun	0°N/127°E	4
	1875	Eskiya**	65°N/17°W	5
II	1883	Krakatau	6°N/105°E	6
	1888	Ritter	6°N/148°E	–
	1888	Bendei San**	38°N/140°E	4
	1892	Avu	4°N/125°E	–
	1902	Mont-Pele	15°N/61°W	4
	1902	Sufrier	13°N/61°W	4
	1902–1904	Santa-Maria	15°N/92°W	5–6
	1907	Styubelya**	52°N/158°E	5
	1912	Katmai**	58°N/155°W	6
III	1947	Gekla**	64°N/20°W	4
	1953	Maunt-Sper**	61°N/152°W	4
	1956	Bezymyannaya**	56°N/161°E	5
IV	1963	Agung	8°N/116°E	4
	1965	Taal	14°N/121°E	–
	1966	Avu	4°N/125°E	4
	1968	Fernandiny	0°N/92°W	4
	1974	Fuego	14°N/91°W	4
	1976–1977	Sufrier	16°N/62°W	–
	1979	Sufrier	13°N/61°W	–
	1979	Sierra-Nergo	13°N/87°W	–
	1980	St-Helens**	46°N/122°W	5
	1981	Alaid**	51°N/156°E	–
	1981	Niamuragira	1°N/29°E	–
	1982	El Chichon	17°N/93°W	5
	1985	Del Ruiz	5°N/76°W	–
	1986	Niamuragira	1°N/29°E	–
	1989	Redubt**	61°N/153°W	–
	1991	Pinatubo	15°N/120°E	5

* Indices of volcanic explosions (VEI) 4, 5, and 6 based on data from Ref. 16 indicate the volume of volcanic product (km^3) 0.1–1, 1–10, and 10–100, respectively.
** Volcanoes outside the tropical zone.

Conclusion

Thus we can draw the following conclusions:

1. Periods of sharp changes of Siberian climate due to winter warming coincided with periods of increased volcanic activity, first of all, of the tropical volcanoes. The increased volcanic activity is characterized by the increased frequency of explosions capable of injecting the eruption products into the stratosphere.
2. Series of volcanic explosive eruptions disturb the wave activity of atmospheric circulation, at which the activity of ocean centers of atmospheric action in the Atlantic is increased, and the Siberian anticyclone weakened.
3. At such perturbation of the North-Atlantic oscillations and the Siberian anticyclone intense blowing of Siberian regions during winter by warm Atlantic air takes place, which leads to a significant warming of the regional climate.

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