This work is dedicated to study of the nature of decadal variations observed in climatic data. As a result of the wavelet analysis of instrumental time series of global temperature and phase relations in the variations of the solar and volcanic activity in the period 1880–1995, it was shown that the combined influence of solar and volcanic activity on the climate is the cause of decadal variations in the global temperature observed in the second half of the 20th century. The phase relations between strong volcanic eruptions and solar cycles played the key role in this process. The solar signal manifests itself in the climate variations only if the corresponding phase correlation of the volcanic activity to the solar cycle is considered. In this case, favorable conditions are formed for intensification of decadal climatic fluctuations as occurred in the second half of the 20th century after strong volcano eruptions.

1. The climate of the Earth, being a complex dynamic system distributed in space, fluctuates in a wide range of time scales [1]. It has not yet been found whether these frequently nonstationary transient fluctuations are generated by the climatic system or if they are caused by external forcing [2, 3]. The nature of decadal variations observed in different climatic time series on the regional and global scales is still a problem. For example, in the second half of the 20th century, a close relation of this climatic variation to the 11-year cycle of the solar activity was found [4–6], which can be evidence of the high sensitivity of the climatic system to external forcing in the conditions of global warming [7]. At the same time, in a series of recent publications, the authors question the solar origin of the decadal variations [8], as well as the role of solar activity in global warming [9].

The solar activity can be manifested in the surface temperature as variations in the total solar radiation and/or ultraviolet radiation or in galactic cosmic rays, whose variations are in the phase opposite to the solar activity [3].

Solar radiation (solar constant) changes synchro-nously with the cycle of the solar activity, and this is reflected in the energetic balance of the entire atmosphere. However, the quantitative changes caused by the 11-year cycle of irradiance are equal only to a fracture of one percent of the background.

The amplitude of the solar ultraviolet radiation varies during the 11-year cycle in a greater range than the total radiation. Variations in the ultraviolet radiation lead to changes in the chemical composition and temperature balance of the upper atmosphere and can influence the state of the troposphere and surface temperature through dynamic processes.

Cosmic ray fluxes, which are also modulated by solar activity, change the ionization rate of the lower atmosphere. This can lead to additional formation of condensation nuclei and influence the radiation balance of the atmosphere.

It is worth noting that the aforesaid physical mechanisms of the possible influence of solar activity on the Earth’s climate have not yet been studied completely.

Volcanic activity can be another external factor influencing the variations in the surface air temperature. It was demonstrated in review [10] that volcanism is a sufficiently powerful factor capable of changing climatic situations over an extended territory and sometimes on the planetary scales (depending on the intensity of the eruption). A stratospheric volcanic eruption can change the state of the lower and upper atmosphere and cause further decrease of the global temperature during subsequent years.

The authors of recent publications (see, for example, [11]) analyzed the contribution of two external factors such as solar and volcanic activity on the Earth’s climate. In this work, we consider the combined influence of the solar and volcanic factors on the Earth’s climate as a possible source of the decadal variations in the climatic data.
2. This research is based on the analysis of coherence and phase relations between the solar and volcanic activity, as well as the global temperature. The solar and volcanic activity are external factors, which admittedly contribute to the climate variations including the variations of surface air temperature. In this work, we consider the annual mean values of indices during the period 1880–1995, which characterize the variations in the aforementioned factors.

We used the Sun spot numbers (SSN) from the Solar Influence Data Center (SIDC) database. This index takes into account the number of sunspots and groups of spots on the visible side of the Sun, thus determining the level of the solar activity. The number of sunspots is one of the longest instrumental time series of the solar data (from the beginning of the 17th century), which reflects the variations in the solar cycle on the decadal and secular time scales.

The influence of volcanic eruptions on the climate was estimated using annual mean values of the global Dust Veil Index (DVI) from the database of the NOAA/NGDC Paleoclimatology Program, Boulder, Colorado, United States (IGBP Pages/World Data Center for Paleoclimatology, Data Contribution series #2000-075 [12]). The main function of the DVI suggested by Lamb in 1970 [13] is estimating climatic consequences of volcanic eruptions. When calculating this index, characteristics were taken into account such as attenuation of solar irradiance due to eruptions, temperature decrease, and the amount of volcanic dust (in cubic meters) scattered in the atmosphere. In order to calculate the final value of the index, all values were normalized by the Krakatau Volcano eruption (1883), which serves as a mean characteristic does not reflect all details of the variation over land from the NASA-GISS database (calculated relative to 1951–1980) was analyzed as the characteristic of the climatic system as a whole, as well as to reveal some general tendencies of synchronous behavior relative to 1951–1980.

A complex Morlet wavelet was selected as the basic function or parent wavelet

\[ \Psi(\eta) = \pi^{-1/4} \exp(i\omega_0\eta) \exp\left(-\frac{\eta^2}{2}\right), \]

where \( \omega_0 \) is the dimensionless frequency. Here \( \omega_0 = 6 \) (it is selected from the consideration of optimum time-frequency resolution); \( \eta \) is the dimensionless time parameter.

Owing to the errors in the wavelet spectrum (as well as spectrum of wavelet coherence) related to the finite duration of the time series, the most reliable results are those within the so-called cone of influence, which is calculated with account for the edge effects.

Cross wavelet analysis is an extension of wavelet transform. It allows us to distinguish the frequencies and time periods of coherence between two time series considered, as well as to determine their phase relation at any moment in time. According to [15], wavelet coherence (WCO) of two time series \( X \) and \( Y \) is determined as

\[ \text{WCO}_{xy}(s) = \frac{|\text{WCS}_{xy}(s)|}{(\text{WPS}_{x}(s)\text{WPS}_{y}(s))^{1/2}}, \]

where \( \text{WCS}_{xy}(s) = \langle W_n(s)W_n(s)^* \rangle \) is the wavelet cross-spectrum (WCS) obtained from wavelet spectra of each of the two time series \( X \) and \( Y \) separately. The Morlet wavelet at \( \omega_0 = 6 \) is used for calculation of cross-spectra, while 95% excess over the red noise level is considered statistically significant. \( \text{WCS}_{xy}(s) = |\text{WCS}_{xy}(s)|\exp(i\Phi_{xy}(s)) \) is decomposition of the wavelet cross-spectrum with respect to the amplitude and phase. \( \text{WPS}_{x}(s) = \langle W_n(s)W_n(s)^* \rangle \) is the wavelet power spectrum (WPS).

In both cases of wavelet-spectra and wavelet-coherence, the important fact is how long and stable in time the domain of the distinguished frequency of the wavelet-spectrum is. For example, the wavelet-spectrum of random distribution can give short-time “patches” of distinguished frequencies. In the case of realistic time series, the appearance of such “patches” can indicate the existence of unstable fluctuations of the dynamic system as well as its response to any external forcing.
The results of wavelet-analysis and analysis of wavelet-coherence of time series are shown in the graphs in which the cone of influence and statistically significant regions of the amplitude-frequency spectrum are shown, while the values of the amplitudes of the spectrum are distributed according to the color chart shown in the graph. The relations between the phases in the analysis of wavelet-coherence between two time series is calculated for the zones of statistically significant spectrum amplitudes. They are visualized using the arrows over the spectrum pattern. In the calculations of wavelet coherence between time series \( X \) and \( Y \) of the experimental data, the direction of arrows from left to right means that time series \( X \) and \( Y \) are in-phase; the direction from right to left means that they are in the opposite phase; a downward direction means that \( X \) is ahead of \( Y \) by one-quarter of a period; the upward direction means that \( Y \) is ahead of \( X \) by one-quarter of a period (or, which is the same, an increase in the values of time series \( X \) is followed by a decrease in the values of time series \( Y \) with a time-lag of one-quarter of a period: the opposite phase with a time lag). In the opposite case, during the calculation of wavelet-coherence between time series \( Y \) and \( X \), time series \( x \) and \( Y \) change places [14].

4. Figure 1 (lower panel) shows a graph of variations in the global temperature and smoothed variations by a polynomial of the fifth power during the period from 1880 to 1995. It is seen from the graph that the curve of the global temperature is a superposition of short-term variations over a temperature trend reflecting the global warming, which is likely related to anthropogenic influence. We also analyzed the deviations of the global temperature evolution relative to the approximating curve. Figure 1 (upper panel) illustrates the behavior of the solar and volcanic activity in the time period considered here. One can clearly see the 11-year variations in the solar cycle and peaks of volcanic activity caused by the powerful eruptions of volcanoes El Chichon (1982) and Mount Pinatubo (1991). Correspondingly, the DVI index in 1982 and 1991 was as high as 366 and 500, respectively. The index formed two clearly pronounced peaks on the graph of variations in the volcanic activity. The solar activity and volcanic activity are a priori two independent factors; however, both aforementioned eruptions occurred during the period of a decrease in the solar cycle. In addition, the time between the eruptions was nine years, which is close to the period of the solar cycle, thus it formed a time-localized “volcanic cycle” close to the 11-year cycle. One can see from Fig. 2 that, during this time, precisely (1980–1990) a peak in the wavelet spectrum of the global temperature variations is found at a frequency corresponding to the 11-year cycle.

Figures 3 and 4 show the results of wavelet-coherence analysis between the variations in the solar and volcanic activity and anomalies of the global temperature. Beginning approximately from the 1970s, high coherence is observed between the solar activity and temperature anomalies, which are in-phase (see Fig. 3; we recall that the reliable results are located within the cone of influence; beyond the cone of influence another relation between phases is observed, which is not reliable). In addition, in the same time period, high coherence is observed between volcanic activity and temper-
ature anomalies (Fig. 4), but the latter appear with a long time lag, which is seen from the directions of arrows after 1970. This means that in this case the response of the global temperature to volcanic forcing is opposite in sign to the response to the solar signal. Hence, an increase in the solar activity causes an increase in temperature, while an increase in the volcanic activity generally causes a decrease in temperature. We note that the level of volcanic activity is also quite high at the beginning of the 20th century. Powerful volcanic explosions occurred with the volcanic explosivity index (VEI) exceeding 5 (for example the eruptions of El Chichon and Mount Pinatubo volcanoes were characterized by a VEI equal to 5. Decadal variation was not pronounced in the variations of the global temperature in that period because an unfavorable phase relation between the solar and volcanic activity was different from the one at the end of the 20th century.

As seen from Fig. 1 (upper panel), after 1920, there were almost no eruptions that caused global climatic changes. The authors of [5] note that the correlation between the solar activity and climate started much earlier than the second half of the 20th century, namely, in the 1920s and at a frequency close to 22-year periodicity. Figure 3 demonstrates a high coherence level between the solar and temperature time series at this frequency from 1920 to 1960. We can suppose that a period of 22 years in the coherence appears as a result of a double solar cycle (Heil cycle) and specific noise in the climate without specific frequencies from 1920 to 1960 (Fig. 2).

Thus, high coherence is observed in the cross-spectrum of time series of volcanic activity and global temperature, which corresponds to decadal variations. Starting approximately from the 1960s, quasi-11-year periodicity is observed also in the spectrum of wavelet coherence between the time series of the solar activity and global temperature.

As a result of our analysis, we can conclude that the combined impact of the solar and volcanic activities on the climate is the cause of decadal variations in the global temperature observed in the second half of the 20th century. Phase relations between strong volcanic eruptions and solar cycles played a key role in this effect.

The solar signal manifests itself explicitly in the variations of climate only if volcanic activity is specifically correlated with the solar cycle. In this case, favorable conditions are formed for the intensification of decadal climatic fluctuations as was observed in the second half of the 20th century after strong volcanic eruptions.
We suppose that a high coherence level between the solar and temperature time series from 1920 to 1960 at a frequency corresponding to 22-year periodicity is explained by the lack of volcanic eruptions that cause strong global climatic changes.

REFERENCES