How does the Sun affect the surface temperature?

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Abstract. We continue to develop a constructive idea of synchronicity as an essential factor in the solar-terrestrial relations. The results of applying this approach to a Wolf number series and a temperature series measured at 818 weather stations in the Northern Hemisphere from 1955 to 2010 are presented. New manifestations of the solar activity are considered and confirmed. The sun effect on the surface temperature at a weather station is estimated by the cosine of the angle between two vectors defined by the series under study in a cyclic time. The sun effect is distributed over weather stations, in both space and time, and has a quasi-monotonic dependence on the average monthly temperature. Various manifestations of the sun effect are discovered, and conditions of their occurrence are discussed. We believe that further development of our approach will allow the formation of a general view of the phenomenon under study. The approach is expedient for the analysis of observational data, analytical transformations, and climate modelling.

1. Introduction
The complexity of the climate system organization makes it very difficult to classify its responses according to a specific external forcing. In many ways, this is the reason for contradictory conclusions of different authors concerning the sun activity on climate change. It is widely believed that the integral changes in solar radiation entering the Earth's atmosphere are very small and cannot explain the observed climate changes [1]. If we consider different ranges of the solar radiation spectrum, it is established that the flux variations in the ultraviolet range can reach tens of a percent [2]. Such fluctuations, of course, are reflected in the changing radiation balance of the climate system. It is known that there are certain mechanisms [3-6] through which insignificant regulator energy can initiate substantial climate processes. In addition, changes in the state of the thermosphere and ionosphere, in response to the sun activity, have an impact in the lower layers of the atmosphere [7, 8]. The difficulty is that there is high uncertainty concerning the transmission mechanisms of these disturbances.

In general, the nature-climatic processes are characterized by an oscillatory essence. This creates a very complex picture of the state of the geosphere components. There is still no consensus on the extent to which the solar activity changes affect the climate processes. Nevertheless, there are many studies supporting the idea of the solar influence on the climate dynamics [9-14]. Many researchers confirm significant sun activity at changes in the large-scale circulation [12, 15-17], which is the main mechanism for reorganizing the state of the atmosphere.

A consequence of the situation presented above is that it is practically impossible to take into account the entire chain of transformations of external forcing in the geosphere. Therefore, in our works an approach was developed that consists in comparing the external forcing and the response to
it at weather stations. The Wolf numbers are considered as an integral and non-local indicator of the solar influence; the reaction of the geosystem is characterized by changes in the surface temperature. In this approach the reactions are estimated taking into account the synchronicity of the investigated processes and representation of the results in adequate form is used, so that the effects can be identified visually. In this way new manifestations of the sun activity on the surface temperature were revealed (see the authors’ profiles on https://www.researchgate.net/).

The studies of the solar influence on the surface temperature reflected in our paper [18] are in progress. Analysis and physical substantiation of the previous results are mainly presented in this paper.

2. Data series and formulas for calculations

To perform calculations we used the same series of data as in [18]: the series of mean monthly temperatures from 818 meteorological stations of the Northern Hemisphere from 1955 to 2010 (https://crudata.uea.ac.uk/cru/data/temperature). The series of monthly average Wolf numbers for the same period was taken from the website: http://www.gao.spb.ru.

The most commonly used indicator of solar activity is the Wolf numbers or the sunspot indices. A continuous series of these indices has been maintained since the 17th century, and it is provided by the Solar Influence Data Analysis Centre (SIDC). Changes in the sunspot index are manifestations of the internal dynamics of the Sun. They are consistent with changes in the total flux of solar radiation, as well as each part of the solar spectrum, particle fluxes from the Sun. The validity of this index has been regularly questioned, and the known discrepancies were corrected [19, 20].

Quasi-periodic motions occur immanently in the solar system. The carrier oscillation caused by these movements is included, to some extent, in various natural and climatic processes. The development of processes in the system of interest is associated with small deviations from the dominant carrier oscillation. Due to relative smallness, this interesting information can be lost during the analysis. This is one cause for introducing discrete cyclic time for the analysis of climate data. For series of the mean monthly data, the values for one specific month in each year are selected, and of them one new series of twelve is formed [18].

To realize the cyclic time in the calculations, two time-characterizing indices are needed: the month number \( m \in [1, 12] \) and the year number \( j \in [1, 56] \). Compositions of these indices allow converting the original monthly averages into vectors in the cyclic time:

\[
\tilde{x}_{lm} = \{x_{l, m+12(j-1)}\}; \quad \tilde{s}_m = \{s_{m+12(j-1)}\};
\]

(1)

here \( \tilde{x}_{lm} \) is the temperature vector; \( \tilde{s}_m \) is the vector of solar activity; and \( l \in [1, 818] \) is the number of the weather station where the temperature series was measured. The components of these vectors are selected from the original average monthly series.

In the cyclic time, the average multi-year estimates: correlation coefficients, covariations, and variances are calculated by the index \( j \):

\[
\text{corr}(\tilde{x}_{l, m+12(j-1)}, \tilde{s}_{m+12(j-1)}) ; \quad \text{cov}(\tilde{x}_{l, m+12(j-1)}, \tilde{s}_{m+12(j-1)}) ; \quad \text{var}(\tilde{x}_{l, m+12(j-1)}) ; \quad \text{var}(\tilde{s}_{m+12(j-1)}) ;
\]

(2)

and the average multi-year temperatures at weather stations:

\[
T_{l,m} = \text{mean}(\tilde{x}_{l, m+12(j-1)}).
\]

(3)

For the vectors (1) the normalized initial product moments (the sun effect) was introduced in [18]

\[
\alpha_{l,m} = \cos(\tilde{x}_{l,m} \cdot \tilde{s}_m).
\]

(4)

Here we use the expression (4) to discover new interconnections of the external input vector \( \tilde{s}_m \) and
many internal output vectors $x_{i,m}$ for the climatic system of the Earth.

3. Correlation coefficients

The correlation coefficients of the temperature series and solar activity in the cyclic time were calculated: $\text{corr}(x_{i,m+12,j-1}, S_{m+12,j-1})$. Figure 1 shows the distribution of these correlation coefficients among the weather stations for different seasons depending on the average multi-year temperature $T_{i,m}$. It is clear that the coefficients are insignificant; there is no dependence on the season.

Figure 1. Correlation coefficients of average multi-year series of temperatures and Wolf numbers in Northern Hemisphere. Each point corresponds to one of the 818 weather stations within one of the 12 months during the year. Summer is marked by red points, winter by blue, spring by green, and autumn by yellow ones. The varying density of the point distribution is due to uneven distribution of the weather stations along the climatic zones.

The comparison method, resulting in Figure 1, showed that the surface temperature variations are inconsistent with the solar activity. However, anyone can hardly say that the solar activity does not affect the surface temperature. The climate system is permeated with many poorly explored and uncontrolled feedbacks. Therefore, it is necessary to find and apply other estimates of the influence. Remembering that climate is a complex composition of elements, let us consider a space, for instance, of three elements and make sure that the process can be investigated in a much deeper way.

4. Climatic forms in 3D

The average multi-year temperature, the sun effect, as well the month increment of the sun effect were
compared. At a specific weather station these three characteristics of climate are parametrically dependent on months. Figure 2 shows three-dimensional phase portraits for the climate characteristics formed over the entire observation period. In these climate forms green points characterize the location of all weather stations for March (a) and October (b). It can be clearly seen that all green points are located at the opposite edges of the climatic forms having a view of a narrow strip. In the forms constructed for other months (not shown here), there is a gradual transition of green points from one edge of the form to another. Particularly, in July the points are localized in the red peak.

Characteristically, within the space of the climate elements, some regions having a rather simple shape can be observed. Thus, the internal structure of the climatic forms shows certain functional connections. The task is to localize such areas in a climatic form linking them to the terrain and time and revealing their physical content. We will consider some of the numerous aspects below.

Figure 2. Climatic forms. Each point corresponds to one of 818 weather stations in one of 12 months. Red points mark the weather stations from tropical and subtropical zones; blue points mark weather stations of another location. In March (a) and October (b) all weather stations are additionally marked by green points.

The studies on the climatic forms have shown that these objects acquire their final form after 40 years. Extending the observation period to 56 years slightly changes the form of the examined point portraits. Thus, this fact characterizes the time interval for the climatic estimates.

5. Sun effect

We will continue to analyse the relationship between the sun effect $\alpha_{s,m}$ and the average multi-year temperatures $T_{s,m}$. The point-portrait of the compared values turns out to be very informative and is shown in Figure 3. In contrast to the picture given in [18], it shows the monthly stratification.
Sun effect in the cube

Average multi-year temperature, °C

Figure 3. Sun effect on surface temperature as a function of average multi-year temperature $T_{i,m}$ °C within the interval from 1955 to 2010. In total, there are 9816 points in the graph, 1977 of which are at a negative temperature and 7839 are at a positive temperature. The months are indicated by Roman numerals and are aligned with the colour scale.

Let us represent the series under study as the sum of their mean values and fluctuations:

$$x_{i,m} = \{\bar{x}_{i,m} + \bar{x}_{i,m+12(j-1)}\}; \quad s_m = \{\bar{s}_m + \bar{s}_{m+12(j-1)}\}.$$  \hspace{1cm} (5)

Next we introduce representations (5) in the expression for the sun effect (4) and study the conditions under which it reaches a certain saturation level with increasing positive and negative temperatures. It is necessary to take into account the smallness of the correlation coefficient of temperature and solar influence $x_{i,m}$ and $s_m$ (see Figure 1) in comparison with the product of the means in equation (5). In addition, we take into consideration that the temperature variances are small, in comparison with the square of their mean values in areas of the sun effect saturation of about $\pm 40^\circ\mathrm{C}$, i.e. for anticyclone stagnant conditions. Thus, equation (4) for the sun effect (see also [18]) takes an approximate form:

$$\alpha_{i,m} = \left[\bar{x}\bar{s} + \text{cov}(\bar{x},\bar{s})\right]/\left[\left(\bar{x}\bar{x} + \text{var}(\bar{x})\right)\left(\bar{s}\bar{s} + \text{var}(\bar{s})\right)\right]^{-1/2} \approx [1 + \text{var}(\bar{s}/\bar{x})]^{-1/2}$$  \hspace{1cm} (6)

The indices in the right-hand side of equation (6) are omitted; the components of the vectors, as before, are determined by the annual index $j \in [1, 56]$ over which the summation is made.

The average value calculated by the original data for the Wolf numbers is $\bar{x} = 70.18$; the variance of ratio $\text{var}(\bar{s}/\bar{x}) = 0.621$; which gives the values of the sun effect in saturation areas of equation (6) $\alpha_{i,m} = 0.785$. This estimate of the saturation level is close to that observed in Figure 3: 0.785 (0.015) and $-0.758 (0.032)$ for the mean values of the sun effect, taking into account its mean-square deviations outside the interval of $\pm 7^\circ\mathrm{C}$. Thus, the theoretical estimate (6) is adequate to the measured data.

Introducing a power scale for the ordinate axis (see Figure 3) makes it possible to detail this fact, as well as to reveal the monthly stratification of the sun effect saturation levels at a positive temperature $T_{i,m}$. It can be seen from Figure 3 that the relative thickness of the layers is about 0.01. At negative temperatures such stratification is not observed.

Outside the temperature range of $\pm 7^\circ\mathrm{C}$, the Wolf numbers basically determine the sun effect. If their average value $\bar{x}$ increases, the saturation level also increases up to unity; if vice versa, it drops to zero. When fluctuations $\bar{s}$ increase, the saturation level $\alpha_{i,m}$ tends to zero, and when they decrease, it tends to unity.

Let us consider changes in the sun effect $\alpha_{i,m}$ in the vicinity of the origin, with a width of
approximately ±1.5°C along the abscissa axis and about ±0.3 along the ordinate axis. It can be seen that the value characterizing the consistency of temperatures and solar influence essentially increases in the direction from the centre of the area where it is close to zero. The localization of this supposed zero in the terrain coincides with the boundary of the snow cover. Figure 4 shows that the continents are dominated by the sun effect saturation regions; and the main changes of the sun effect are localized near the snow cover boundary. Thus, high consistency with respect to equation (7) exists along with an insignificant correlation coefficient of temperature and solar activity, as in Figure 1.

**Figure 4.** Spatial distribution of the sun effect in February, March, October, and November (II, III, X, XI) from 1955 to 2010. Turquoise circles correspond to the sun effect for average multi-year temperature of around 0°C, blue circles are for temperature from -0.1 to -5°C, and red circles are from 0.1 to 5°C; ☯ are for the saturated sun effect when the temperature is below -5°C, and ☯ when it is above 5°C.
By definition, the sun effect \( \omega_{l,m} \) is a normalized moment. Therefore, turning it to zero cannot be a consequence of the zeroing temperature. The process of turning to zero takes place only through a decrease in the numerator in the expression for the sun effect (4), i.e. through a decrease in consistency of the values of \( x_{l,m} \) and \( s_n \).

The course of the sign change for the sun effect at crossing the snow cover boundary (Figure 4) is explained well by phase transitions of water while freezing and thawing. It is known that changes in the aggregate forms of water occur with some delay in relation to the external action; changes in the water temperature are delayed also. It is established that the absorbed energy and the released energy, after changing the aggregate form, are equal in terms of molecular scales, thus, oscillations of temperature arise. These elementary processes are blurred due to varied volumes of water being converted around zero degrees Celsius. On the whole, around zero-temperatures the energy supply and its runoff do not reach predominance and there occur fluctuations, which reduces the coordinated temperature response to the solar action. It should be noted that the calculations are suggested for average monthly temperatures, which obviously preserve the features in question in their behaviour, as confirmed by an insignificant sun effect in the vicinity of the origin in Figure 3. It is characteristic that, beyond the limits of this small vicinity, the sun effect increases rapidly enough, showing restoration of consistency of the investigated processes. Therefore, it cannot be assumed that these processes can be changed arbitrarily.

In Figure 1 from [18] 35 points are in even quadrants. Such an arrangement is a specific feature, and it is observed only in the vicinity of zero. This fact is due to the presence of negative mean monthly temperatures in the case of a positive average multi-year temperature for 56 years and, conversely, the presence of positive mean monthly temperatures in the case of a negative average multi-year temperature.

6. Conclusions
There are opinions stating that the influence of solar activity on climate is weak, as well as those that claim that it is significant. Both views turn out to be valid because of the diversity and complexity of the solar-terrestrial relations. In the present paper, the conditions necessary for the appearance of regions with the sun effect saturation and its behaviour in the vicinity of zero temperature have been clarified.

A series of Wolf numbers as an integral indicator of external forcing and the only input signal for the Earth climate system was compared with many output signals, namely, a temperature series measured at 818 weather stations of the Northern Hemisphere between 1955 and 2010.

New details of the solar influence on the temperature in the climate system have been revealed. Detection of this effect is achieved by using a cyclic time and by applying a new estimation to the problem, which was called the sun effect.

Correlation coefficients of series of mean monthly temperatures and solar activity in the cyclic time have been found in the range of \( \pm 0.5 \).

Within the space of three elements of climate, there are areas in which the internal structure is characterized by certain functional connections.

The saturation levels of the sun effect are controlled by the variance of the ratio of the fluctuation and the constant component of solar activity.

At a positive average multi-year temperature, a monthly stratification of the sun effect has been detected, the relative thickness of the layer being equal to about 0.01.

The growth of the temperature module beyond 5 degrees Celsius is not accompanied by a change in the share of assimilated solar activity energy.

A tendency to zero of the Sun effect together with the average multi-year temperature is hypothetically provided by mechanisms of phase transitions of water.

The main changes of the sun effect are localized near the boundary of snow cover, while far from the boundary, on the continents, saturation regions are predominant.
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