Sun's effect on the surface temperature in the Northern Hemisphere

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Abstract.   Series of temperatures measured at 818 weather stations in the Northern Hemisphere and one series of Wolf numbers for the period from 1955 to 2010 are considered. The sun's effect on the surface temperature is estimated by the cosine of the angle between two vectors determined by the series under study for the same months, year by year in the observation interval. The sun's effect is distributed over the weather stations, both in space and time. It has a quasi-monotonic dependence on the average monthly temperature, and reflects the geography of the climate, including the effect of warm ocean currents. Various manifestations of the sun's effect on the surface temperature have been discovered, and the conditions of their occurrence are discussed. The approach proposed in this paper can be used in observational data analysis, analytical transformations, and climate simulations.

1. Introduction

The existence of the solar system suggests that many natural and climatic processes on the Earth are controlled by the Sun. The simulation and forecasting of these processes are limited by the insufficient available body of knowledge, although scientists have studied the solar effect on climate elements for several centuries. The problem of solar-terrestrial relations is complex. We will consider only a few of the numerous aspects.

Along with its direct impact, the Sun regulates other effects on the geospheres. It modulates the flows of cosmic charged particles and the solar wind, which then change the conditions of energy conversion in the troposphere [1-3]. As the Earth passes through the regions of the interplanetary magnetic field, it changes the radiation balance, which leads to changes in the temperature and pressure in the surface atmosphere, with large variability mainly in the ultraviolet part of the solar radiation spectrum which, due to photochemical reactions, regulates the formation of ozone in the stratosphere affecting the surface temperature [4-9].

There is a theory that the effect of solar forcing on the geosphere is insufficient and, therefore, it is not able to change the climate. However, there are mechanisms [1, 10-14] through which a small energy of the regulator can initiate substantial climatic processes.

The solid foundations for climate simulation are fully developed in forms of systems theory, mathematical physics, computer sciences, etc. [15]. Mathematical models that allow studying various climate scenarios have been constructed, and significant results have been obtained. Nevertheless, this is not enough for practical forecasts. Some well-known challenges are: numerical instability of the equations in combination with inadequate initial or boundary conditions and coefficients, uncertainties in the external influences on the climate system, and the presence of many other unknown mechanisms [16]. There is also a need for assumptions about the stochastic properties of the processes forming the time series being analysed [17]. The mechanisms of solar energy transformations in the atmosphere are still subjects of debate. The physical nature of the solar-terrestrial connections has not been fully understood yet, and additional research is required for its clarification.

The natural and climatic processes are manifestations of a complex combination of various factors, and it is almost impossible to identify and estimate all of them. Because of this complexity, the natural processes are fundamentally different from the processes in technical systems which are specially designed to implement some beneficial factors. For these reasons, representing the climate system by means of traditional physical quantities is not a simple task and can be somewhat ineffective.

At this stage, it is advisable to expand the phenomenological foundations of studying and forecasting climate, as well as to allocate the predictive patterns from the properties of observed signals by using general physical principles. In this connection, our goal is to identify such components of the series of observations that can accentuate the patterns of the climate system's response to external forcing.

Tartakovsky's papers [18, 19] based on an analysis of natural temperature series show that synchronicity is an essential property of climatic processes. The so-called initial product moments are used as a measure of synchronicity. Some opposite components of temperature and solar activity with extreme synchronicity have been found and investigated. A phase of temperature oscillations as a measure of their synchronicity was introduced. The cross phasing of temperature series was geographically localized, which leads to an adequate climate classification in the Northern Hemisphere [20].

This paper presents new results on the solar influence on the temperature in the surface layer of the atmosphere taking into account the location of weather stations, under the assumption that solar activity and associated cosmic influences can be characterized by a unique series of Wolf numbers. The Wolf numbers are determined by the calculation of sunspots, which astronomers have been performing for the last 200 years.

2. Data series and calculations

When performing the calculations, we used consecutive average monthly temperatures measured from 1955 to 2010 at 818 weather stations in the Northern Hemisphere. The data were obtained from the University of East Anglia website [21]. A series of average monthly Wolf numbers during the same period was obtained from the website of the Pulkovo Observatory [22]. For each of the 818 weather stations, the temperature series contained $N=56\times12=672$ counts and the sample size was $672\times818=549696$. The Wolf number series also contained 672 counts.

The considered series of temperatures $x_{l,k}$ in degrees Celsius and the series of Wolf numbers s_k (dimensionless) represent the processes under study in an interdependent one-to-one manner. These series are real and have a finite energy. Here k is a discrete argument characterizing the time required in order to take N values in the observation interval, and l is the number of the series and the weather station where it was obtained.

By construction, the series under consideration are a sequence of values of smoothed natural processes at discrete moments of continuous time. In the solar system, quasi-periodic motions occur, and this is the reason for the analysis of climatic data in the same months, year by year in the observation interval. In this case, the values of the series of average monthly Wolf numbers and temperatures are selected and used to form a new series by calculating the index k as follows:

$$k = m + 12(j-1); \quad m \in [1,12]; \quad j \in [1,56]; \tag{1}$$

where m is the month's number and j is the year's number. Then the matrix of the average multi-year temperature at the weather stations with the number $l \in [1,818]$ for each month m of the 56 years was calculated according to the traditional formula:

$$T_{l,m} = \frac{1}{56}\sum_j x_{l,m+12(j-1)}. \tag{2}$$

The series under consideration can be continued over the entire real axis in a periodic even fashion. For such series, using the discrete Fourier transform, the real periodic spectra $X_{l,v}$ and S_v were

calculated. To equalize the lengths of the series and compare the spectra, the counts were preliminarily interpolated to $N = 2^{12}$ in both cases.

Let $\nu \in [1, N]$ be the discrete frequency. Then we can estimate the spectral density P_ν for all 818 temperature series, as well as the square of the modulus of the Fourier spectrum W_ν, which replaces the spectral density for the series of Wolf numbers:

$$P_\nu = \sum_{l=1}^{818} X_{l,\nu} \cdot X_{l,\nu}^* \; ; \quad X_{l,\nu} = \frac{1}{N} \sum_{k=1}^{N} x_{l,k} \exp(-i2\pi\nu k/N) \; ; \quad P_\nu = P_\nu / \max(P_\nu) \; ;$$

$$W_\nu = S_\nu \cdot S_\nu^* \; ; \quad S_\nu = \frac{1}{N} \sum_{k=1}^{N} s_k \exp(-i2\pi\nu k/N) \; ; \quad W_\nu = W_\nu / \max(W_\nu) , \tag{3}$$

where i is the imaginary unit and the asterisk denotes complex conjugation, although in this case it is redundant, since the spectra are real functions.

The series introduced in accordance with Eq. (1) can be considered as 12 temperature vectors $x_{l,m}$ for each weather station with number $l \in [1, 818]$ and 12 vectors of Wolf numbers s_m for all weather stations. Initially, each vector had 56 components in accordance with the duration of the observation interval:

$$x_{l,m} = \{x_{l,m+12(j-1)}\}, \quad s_m = \{s_{m+12(j-1)}\}, \quad j = 1,2,...,56 . \tag{4}$$

For these vectors, we calculated the normalized initial product moments for each month and each weather station. This moment is the cosine of the angle between the vectors $x_{l,m}$ and s_m. This value denoted by $\alpha_{l,m}$ characterizes the external cosmic and solar effect on the earth's surface temperature. The calculation of $\alpha_{l,m}$ can be performed in the following way:

$$\alpha_{l,m} = \cos(x_{l,m}; s_m) = \sum_j x_{l,k} s_k \bigg/ \left(\sum_j x_{l,k}^2 \cdot \sum_j s_k^2 \right)^{1/2} , \tag{5}$$

where the index k is calculated as in Eq. (1). Evidently, the smaller the acute angle between the vectors $x_{l,m}$ and s_m, the greater the positive sun's effect on the surface temperature; and the larger the obtuse angle, the greater the negative sun's effect.

When calculating the sun's effect as in Eq. (5), there is no centring, and there may be a non-zero mean value in the series, which may have a physical meaning. An example is the constant component of solar forcing. It is interesting that the normalization in Eq. (5) eliminates a coefficient independent of the time index (k or j) in the series. This coefficient could be used to describe the latitudinal dependence of solar forcing. However, it is not obvious that the Wolf numbers are related to geometry; they must be considered as an integral indicator of external forcing acting on the Earth as a whole. In this context, they characterize the only external input to the climate system, and the reactions of all of its internal mechanisms are displayed at the weather stations. No assumptions are made about any properties of the system. Only the interrelationships between the inputs and outputs are investigated using the completely correct tool, see Eq. (5).

3. Results and discussion

In Figure 1, the spectral densities W_ν and P_ν are compared for the cases of time according to Eq. (1) and of discrete continuous time. In the first case, the spectra W_ν and P_ν rapidly decrease, and it is clear that they have a common frequency band both in January and June. In the second case, the spectra W_ν and P_ν slowly decay, and, thus, aliasing above the Nyquist frequency is possible. They also have a weak intersection of the information-significant frequency intervals. For these reasons, the search for interrelations is more promising in the case of time calculated by Eq. (1), since this approach eliminates the periodicity and consolidates the information about the deviations occurring at present and those that have occurred in the course of many previous cycles. In the case of discrete

continuous time, it is expedient to study a spectral interval in the vicinity of the carrier frequency associated with the annual cycle. Both variants were developed in [18-20].
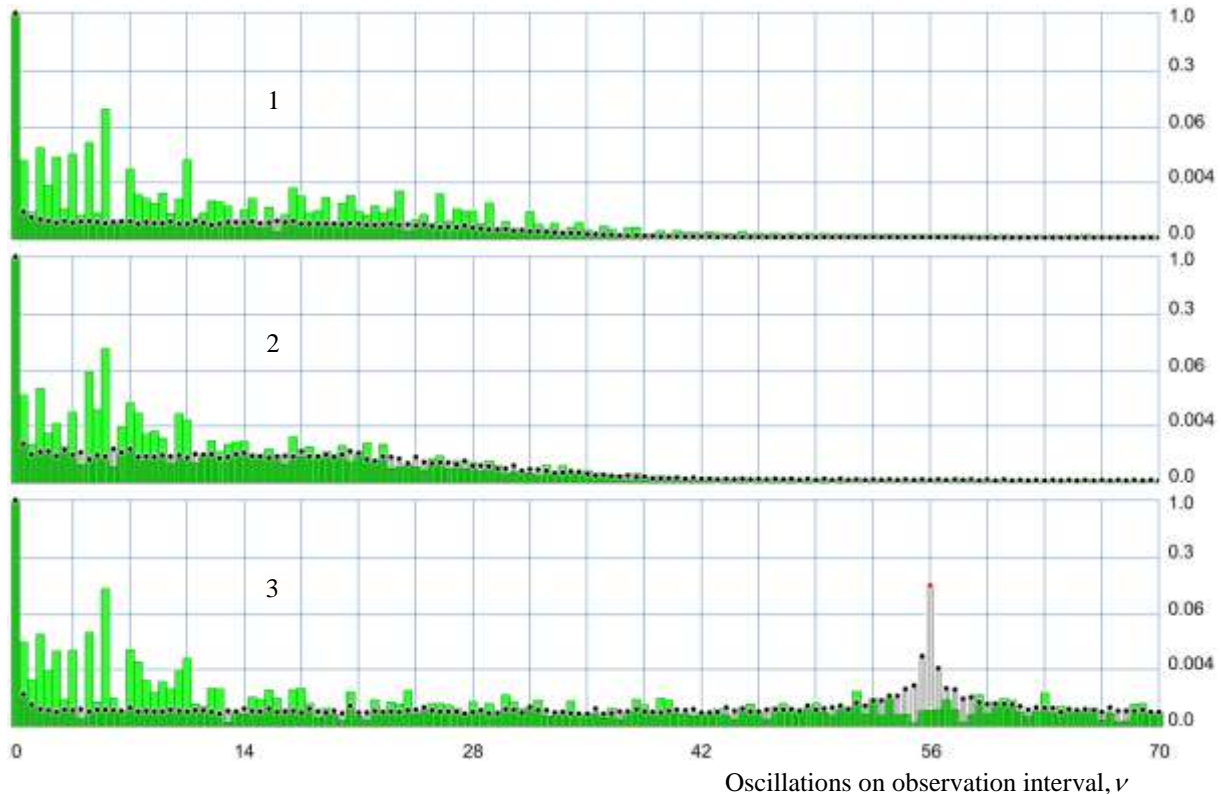

Figure 1. Comparison of normalized spectral density of mean monthly temperatures (black segments with dots) with squared modulus of Fourier transform of Wolf numbers (green dashes) from 1955 to 2010. The first panel corresponds to the time calculated by Eq. (1) for January, and the second one, for June. The discrete continuous time is represented by the third panel. The red dot indicates the carrier frequency due to the annual cycle. The power scale with the exponent ¼ is used along the ordinate axis. The samples are interpolated up to 2^{12} in order to equalize the lengths of the series before performing the Fourier transform.

3.1. The sun's effect on the surface temperatures for each weather station in each month

We will analyse the relationship between $\alpha_{l,m}$ (see Eqs. 1 and 5) and the average multiyear temperature $T_{l,m}$, which are functions of the index parameters: l is the number of the weather station and m is the month. A point-portrait of the compared values turns out to be very informative and is shown in Figure 2.

The spread in the points on the graph is quite small, such that a monotonic stepwise approximation is adequate. Some of its asymmetry is a consequence of the different numbers of points at negative and positive temperatures. There are fewer points to the left of zero and more to the right. It is important to note that the argument of this simple function in Figure 2 is the temperature $T_{l,m}$, which is quite complex distributed both spatially (index l) and temporally (index m).

Near zero, there is certain linearity in the arrangement of points, especially in the interval of ±1.5°C. Within this range, a linear regression was performed (nrms = 0.6% for the temperature axis). The slope of the straight line with respect to the abscissa is 7.5. This roughly corresponds to 1.4 rad. Therefore, within the regression interval of ±1.5°C, the temperature rise by one degree is caused by an

increase in the value of the sun effect $\alpha_{l,m}$ by approximately 1.4 times and it reaches about ±0.3 at the boundaries of the interval.
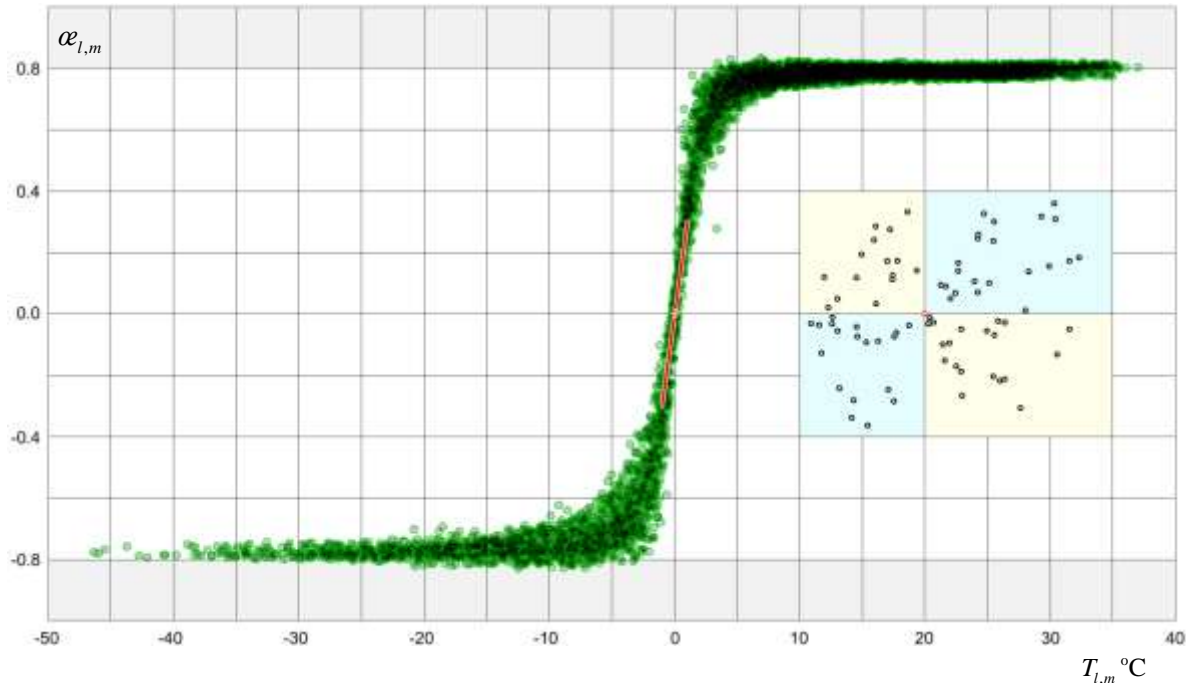

Figure 2. Sun's effect on the surface temperature as a function of the average multi-year temperature $T_{l,m}$ °C within the interval from 1955 to 2010. In total, there are 9816 points on the graph, of which 1977 are at a negative temperature and 7839 are at a positive temperature. The regression line is drawn in the range of ± 1.5°C, within which 535 points are located. The solid grey colour fills the range beyond ±0.8. Enlarged neighbourhood of the origin is in the inset panel. All 35 points in the even quadrants are located in the temperature range from about −0.077 to 0.083°C, and they correspond to the sun's effect from −0.201 to 0.289.

We note that the series of temperature and Wolf numbers are not centered, there is no such operation in Eq. (5); therefore, the location of points in the neighborhood of zero in Figure 2 can only be explained by some physical interaction of the processes under study. In particular, a linear change in the solar effect as a function of temperature in the interval about ±1.5°C suggests that a manifestation of phase transitions of water in the surface atmosphere is displayed.

Let us look at the facts concerning this assumption, although, of course, more research is needed. The growth of the sun's effect and the forced transition of water from the solid state to the liquid state do not lead to an increase in its temperature, since all energy is expended on breaking the intermolecular bonds. When water freezes, a heat energy is released without lowering the temperature, and the sun's effect has a negative growth in Figure 2. These processes are symmetrical: the more energy is absorbed, the more is allocated. In general, the location of the points in Figure 2 does not contradict this. However, the temperatures of phase transitions depend on many parameters of water, on the moisture content of the surface air at different observation points, and this may affect the spread of points in the range of realization of the sun's effect on temperatures.

As follows from Figure 2, most of the 9,816 points are in the odd quadrants. This is why the signs of the sun's effect $\alpha_{l,m}$ and of the average monthly temperature $T_{l,m}$ coincide. Only 35 points are in the even quadrants. They are located near the origin of coordinates in a computed temperature range

from about −0.077 to 0.083°C and for the sun's effect from −0.201 to 0.289. It is not yet clear what the reason is for this.

As follows from the Parseval theorem, the location of most of the points in the odd quadrants at extreme levels is equivalent to the coincidence of the signs of a large number of similar spectral harmonics with significant energy of the investigated processes. This is a manifestation of the synchronizing influence of the Sun on natural and climatic processes [19].

Beyond the interval of ±1.5°C and up to ±15°C, the values of $œ_{l,m}$ are gradually moving towards saturation of up to ±0.8. It occurs with increasing in both positive and negative temperatures. Therefore, beyond the interval of ±15°C, the maximum possible inherent consistency of the series of Wolf numbers with all the series of the average monthly temperature is realized.

The values of $œ_{l,m}$ are bounded as the cosine function in Eq. (5), but the absolute value of the saturation level is essentially less than one. This fact can be explained by the real ratio of values of the temperature and the Wolf numbers, also taking into account the physical meaning of these quantities. Here, we state only what is clear: the moduli of the sun's effect on the temperatures (5) in space and time are majorized by 0.8 already for the observed temperatures and not by a theoretically possible value equal to one.

3.2. Monthly variations of the sun's effect on the surface temperature

Let us perform a qualitative analysis of the sun's effect $œ_{l,m}$ on the surface temperature at the 818 meteorological stations in the annual course. As seen in Figure 3, the sun's effect can have positive values throughout the year and can change the sign from negative in a cold period to positive in a warm period. The range of changes, as already noted, is equal to approximately ±0.8.

The climatic conditions of the zones from the equatorial to the sub-tropical are known to be the most stable in the annual course. It turned out that at most of the weather stations of these zones (orange in Figure 3) the sun's effect has maximum values near a level of 0.8 throughout the year. However, in the period from November to March, at some stations these values decrease as compared to the top level. Such variability occurs at stations located in transitional zones with temperate climate.

For most weather stations in the temperate zone (black in Figure 3), the sun's effect values are clustered near a top level of 0.8 in the period from April to October. From November to March, the values of the sun's effect at these stations are lowered to a level of −0.8.

At the stations of the sub-arctic and arctic zones, the sun's effect is saturated to a bottom level of −0.8 during the winter months and during the transitional seasons, as well as during the polar night (black in Figure 3). In the summer months, the values of the sun's effect are close to a top level of 0.8.

There is a significant climate-regulating influence of large warm currents on the geosystem. The heat transferred by the water softens the climate of the regions so that they approach the conditions of the lower latitudes in terms of the temperature changes throughout the year. Based on the values of the sun's effect on the surface temperature, we selected those stations in the temperate zone which are most susceptible to the influence of the global warm currents. The following locations of weather stations are included: the coast of North-West Canada and South Alaska where the sun's effect is due to the warm Alaska Current (blue in Figure 3) and the weather stations influenced by the Gulf Stream (green in Figure 3). A list of these two groups of stations is given in [19].

There are also weather stations in the sub-tropical zone with negative values of $œ_{l,m}$ and $T_{l,m}$ in the winter months. These stations are characterized by high altitudes above sea level. The climatic conditions are more severe than in the surrounding territories. The type of relief and features of orography are well known to significantly affect the structure of temperature fields. These unusual stations are listed in Table A.1; the sun's effect changes are shown in black in Figure 3.

The delivery of solar energy to specific places occurs mainly through direct heating of the surface and atmosphere in accordance with the climatic zone, as well as heat transfer in accordance with the

global and regional circulation processes. It has been stated previously [19] that the annual course of the second initial moments of the series of Wolf numbers' extreme components shows the existing geography of the climate. Note that the annual course of the sun's effect on the surface temperature in Figure 2 also displays this geography.
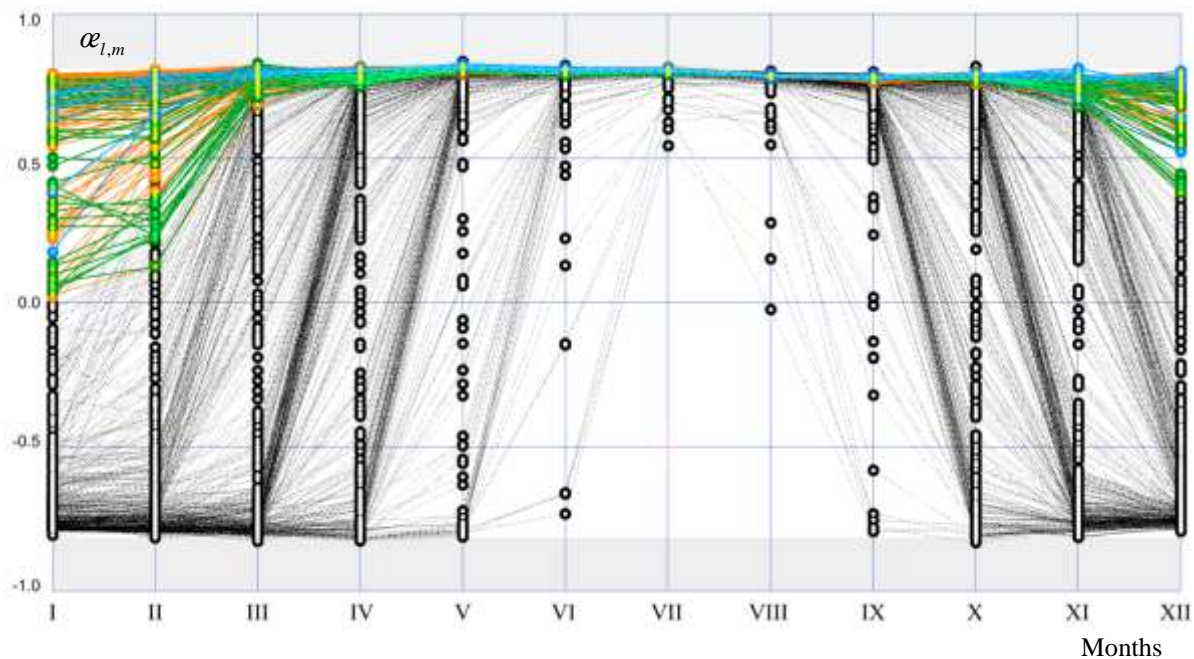

Figure 3. Monthly variations of the sun's effect on the surface temperature from 1955 to 2010 at weather stations with indices l. The yellow and orange colours represent 351 stations from $-0.5°$S to 45.8 N (degrees of latitude). The green colour marks 39 stations in the North Atlantic from 46 to 62.9 N. The blue and light-blue colours mark nine stations on the north-west coast of America from 45.6 to 55 N. The black colour marks 419 stations that do not coincide with the previous from 29.7 to 80.6 N. The months (the index m) are denoted by Roman numerals along the abscissa. The solid grey colour fills the range beyond ± 0.8.

4. Conclusions

The sun's effect on the surface temperature was detected by applying a new estimation to the problem under study which corresponds to the cyclic motions in the solar system. In addition, a useful graphic display was used.

A series of Wolf numbers as an integral indicator of the external forcing and the only input signal to the earth's climate system was compared with many output signals, namely, temperature series measured at 818 weather stations of the Northern Hemisphere between 1955 and 2010. The investigation of the sun's effect on the surface temperature revealed new details of the global energy redistribution in the climate system.

   ◦ The sun's effect is distributed over the weather stations in space and time, and its dependence on the average monthly temperature can be approximated by a monotone function.

   ◦ In the range of $\pm 1.5°$C, a one-degree rise in temperature is caused by an increase in the sun's effect of approximately 1.4 times.

   ◦ The sun's effect is saturating on a constant level of about ± 0.8, with an accompanying increase in the absolute value of temperature.

   ◦ The maximal sun's effect is approximately 80% of that which is theoretically possible, and this is achieved in ranges from approximately 2.5 to 45°C both for negative and positive temperatures.

∘ The sun's effect varies during the year in accordance with the geography of the climate and, in particular, the warm global ocean currents.

Acknowledgements

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Appendix A

Table A.1. Weather stations in the sub-tropical zone with negative values of the sun's effect on the surface temperature.

#	ISI	Latitude, °	Longitude, °	Altitude, m	Alpha-2 ISO 3166-1	T,°C, Jan
1	55591	29.7	91.1	3650	CN	−1.4
2	56137	31.2	97.2	3316	CN	−2.0
3	52836	36.3	98.1	3191	CN	−10.0
4	72486	39.3	−114.9	1909	US	−3.8
5	72564	41.1	−104.8	1872	US	−2.6
6	17096	39.9	41.3	1758	TR	−9.0
7	72576	42.8	−108.7	1696	US	−6.4
8	17170	38.5	43.4	1661	TR	−3.6
9	72569	42.9	−106.5	1612	US	−4.7
10	52533	39.8	98.5	1477	CN	−9.4
11	72476	39.1	-108.6	1473	US	−3.0
12	51828	37.1	79.9	1375	CN	−4.6
13	72578	42.9	−112.6	1358	US	−4.5
14	72583	40.9	−117.8	1315	US	−1.2
15	51709	39.5	76.0	1291	CN	−5.6
16	72572	40.8	−112.0	1289	US	−1.7
17	72666	44.8	−107.0	1209	US	−5.6
18	17092	39.7	39.5	1154	TR	−2.9
19	72465	39.4	−101.7	1124	US	−2.0
20	53614	38.5	106.2	1111	CN	−8.1
21	72677	45.8	−108.5	1091	US	−4.1
22	17244	37.9	32.5	1031	TR	−0.0
23	72662	44.1	−103.1	1030	US	−4.8