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ARTICLE

Most of the Long-Term Solar Radiation Forcing on the Climate Is Due to the Strong Feedback Mechanisms

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ABSTRACT

The main interactions of the Total Solar Irradiance (TSI) variations with the climatic system are considered. This research introduced new physically based indexes for 11-year cycles: the integral relative energetic power of the cycles solar activity (SA) and TSI, as well as the cycle-weighted mean value both of the TSI and sunspot number. The observed cycle-average TSI value in cycles XXII–XXIV has decreased by more than 0.5 W/m^2, indicating its quasi-bicentennial decline. The onset of the Maunder-type Grand minimum phase of the SA and TSI of the quasi-bicentennial cycle (BCC) is expected in the 27th or 28th 11-year cycle in 2042 or 2053. The Earth's thermal inertia will cause a temperature reduction of around 0.25 K due to the deficit in TSI during the declining phase of the bicentennial cycle due to its negative impact on Earth's energy imbalance. As a result, the Bond's albedo will increase, and the abundance of atmospheric water vapor and carbon dioxide will decrease as a response to a direct solar forcing. BCC feedback mechanisms will also continue operating during both its minimum and maximum phases. The feedback mechanisms will continue further in short periods (about 30 years) at the beginning of BCC's growth and decline phases. These long-term self-reinforcing feedback effects will act as a response to the TSI, forcing in such a way as to trigger a strong amplification of the initial direct input to the corresponding temperature changes. They will lead to a significant increasing cooling in 2070 or 2080. Variations of the galactic cosmic rays and cloud cover practically do not affect the climate. The quasi-bicentennial cyclicity of the TSI also provides simultaneous climate variations on all Solar system planets.

***Keywords*:** Solar cycles' new index; Climate; Feedbacks; Grand solar minimum; Earth's energy imbalance; Cloud cover; Cosmic rays; Cooling

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1. Introduction

Quantitative measures of climatic characteristics are determined by the reflection, scattering, and absorption of solar radiation by the atmosphere and the Earth's surface, including both land and the World Ocean (hereinafter – Ocean). This energy is then converted into thermal radiation emitted by the Earth. The vertical and horizontal movement of energy, air, water, as well as minerals, and organic compounds in the Ocean also contribute to these measures. The long-term state of the absolute value of the global Earth's energy imbalance (EEI) and of the thermal state of the entire planet due to the thermal inertia of the Ocean, as a whole, is determined by the variation of the difference between the amount of solar energy reaching the Earth's upper atmosphere and going back into space, the power of the solar radiation reflected by the planet plus its intrinsic thermal radiation. That's why long-term cyclical variations in incoming solar irradiance potentially influence the EEI and the climate. Additionally, long-term solar radiation variations play a role in changes in carbon dioxide concentration in the atmosphere and water evaporation, humidity, and agricultural and ecological processes, which are interconnected with climate [1–5]. The Earth's climatic system is highly intricate and characterized by non-linear behavior. It relies on the combined impact of multiple physical processes, dynamics, and causal feedback loops within the ocean-land-atmosphere subsystems over 30 years or more. A wide range of factors influences these processes. The study of long-term variations of the EEI absolute value under the influence of 11-year and bicentennial cyclical variations of TSI, investigations of the physical state of the surface-atmosphere system and the Bond albedo of the Earth as well as the determination of the physical mechanism responsible for these variations present a crucially important fundamental and applied problem. It is important to study the increase in the subsequent effect of the long chain of secondary non-linear cause-and-effect feedback processes in climatic variations caused by variations in the surface and atmosphere parameters (an increase in the Bond albedo, a decrease in the water vapor concentration, etc.). The fraction of the decline over a long time in the average TSI absorbed by the planet can be accompanied by a response to these external actions from the climatic system (with a large delay due to the ocean's thermal inertia). Studies of substantial climate fluctuations for the last 800,000 years indicate that warming and cooling alternate basically for quasi-bicentennial (at least for the latest 7500 years [3]) and one hundred thousand years of cyclical oscillations of TSI combined with numerous pivotal subsequent causal feedback effects [1–12]. The secondary causal feedback effects, resulting from the cyclical oscillations of Earth's orbit over one hundred thousand years (known as Milankovitch cycles), lead to significant variations in the average yearly Total Solar Irradiance (TSI) forcing. These variations, in turn, contribute to the occurrence of the Great glacial/interglacial cycles. Additionally, the Clausius-Clapeyron relation and Henry law explain how these TSI variations cause notable changes in the amounts of water vapor, carbon dioxide, and other greenhouse gases in the atmosphere [4,11–15]. In the 100-thousand-year oscillations of the TSI of the Milankovitch cycle caused by variations of the shape of the Earth's orbit, it has been established that if the influence of the secondary climate feedback is excluded, then the planetary temperature oscillations may be changed by no more than 1.5 °C instead of the observed change of about 10 °C [14,15].

The significant positive correlation between solar proxy and climatic records observed during the Holocene can be explained only by the fact that solar radiation changes had a decisive effect. It had a considerable climatic impact throughout the Holocene at multiple time scales [16–22]. However, a model simulation claims that the Sun's direct influence has a modest climatic effect because of, in fact, the changing long-term direct influence of the total solar irradiance on the Earth's climate insignificantly. At the same time, it is necessary to carefully study the possible cause and conditionality of a large part of the solar impact on the environment by subsequent nonlinear mechanisms of climatic feedback. Therefore, if we consider the important natural influences of secondary feedback effects, the climatic sensitivity to them may significantly differ from the climatic sensitivity to the direct radiative forcing. The total impact of solar energy and the influences generated after climatic feedback on the Earth's climate may be significantly greater than the direct effect of TSI alone. Therefore, it is necessary to evaluate how the Sun influences the Earth's climate not only through variations in quasi-bicentennial direct irradiance, but also through the greatest influence of many other significant subsequent physical mechanisms of the climate feedback, which is a very important duration of their impact. All subsequent Sun-climate interactions should be considered to properly assess the real role of the Sun in climate change. The lowering of the yearly average TSI after three 11-year solar cycles (due to the Ocean's thermal inertia) results in variations of optical and radiative parameters of the underlying terrain and the atmosphere. The optical parameters include the albedo of the underlying surface and the atmosphere. In contrast, the radiative ones include the degree of their blackness and the transmission of the surface radiation to space by the atmosphere within its spectral transparency windows. Nevertheless, the prolonged shortfall in the fraction of TSI absorbed by the Earth during the declining phase of the 200-year cycle since 1990 has not been offset by a reduction in the Earth's inherent thermal energy emitted into space. This is because the Earth, with its substantial heat capacity and thermal inertia, does not have sufficient time to cool down and continues to radiate more heat than it absorbs [4–5].

2. The quasi-bicentennial cyclicity of the solar radiation, activity, and diameter

The natural quasi-periodical variability of the climatic system in the distant past without any industrial impact on the environment indicates the corresponding long-term cyclical variations in the solar energy influx in these periods. A search for the presence of dependence of deep climate variations in the past on long-term variations of registered known phenomena in the Sun will make it possible to understand possible climate variations. Therefore, a search of global dependences of climate variations led to a necessity to study and quantitatively estimate the relation between periods of deep global climate variations and the corresponding substantial variations of the sunspot activity level. The sunspot number is the only solar index that is directly known for the last 400 years and reconstructed for 11,400 years [23]. Solar activity, overall, has two basic cycles, about (11 ± 3) and (200 ± 70) years, and their double quasi-periods last about 22 and 400 years. In a short series, Hershel noticed such a correlation between the sunspot number and climate for the first time in 1801 during a period known as the Dalton minimum and before this minimum period [1]. In the previous millennium, the cold extended time intervals always correlated with bicentennial cyclical periods of extended low SA levels: the historical minima of Oort (~1040–1080), Wolf (~1280–1340), Spörer (~1450–1550) and Maunder (~1645–1715), and Dalton minimum (~1790–1830). And, of course, there was not a Grand minimum in every quasi-bicentennial period. Important triggers of the lower temperatures were, primarily, the weak solar irradiance during these prominent solar minima. The period of very extended deep cooling during the 14th and 19th centuries was associated with combined effects of the Wolf, Spörer, Maunder, and Dalton minima, but with warmings events between them, and that's why it should not be considered a single grand Little Ice Age [9]. They should be regarded as single Little Ice Ages depending on the depth and duration of the SA minimum period. My definition of the quasi-bicentennial Little Ice Age differs from that in the literature in that a long period of global cooling during the 14th and 19th centuries was interrupted by several warming periods, and this big period was not a single grand period of deep cooling. Bicentennial cyclic climate changes are always the climate system's response to corresponding cyclic external influences of the Sun.

Based on the analysis of these data, Eddy in 1976 reliably established a mutual relation between the periods of substantial SA variations during the entire past millennium and deep climate variations, both in the phase and in the amplitude [2]. The climate variations were so substantial that they affected the lives of nations and individual states, producing economic and demographic crises. In 1988, geophysicist Borisenkov (former director of the Voeikov Main Geophysical Observatory of the Russian Federal Service for Hydrometeorology and Environment Monitoring) [3] found that for the last 7500 years, in each of the established 18 Grand deep minima of Maunder-type, there was a deep cooling, and in the periods of maxima SA warming. Every time SA has experienced its bicentennial peak, global warming starts with a time lag of about 30 years, determined by the thermal inertia of the oceans (despite the absence of anthropogenic forcing), and each deep descent into the SA caused a corresponding cooling. However, a statistically reliable mutual relation and high correlation of the periods between substantial SA variations and deep climate variations in phase and amplitude do not prove their cause-and-effect relationship. The nature of these observed high correlations by Eddy and Borisenkov between substantial climate variations and the SA level for 7500 years was that 11-year and bicentennial cyclical SA, TSI, and Sun's diameter variations result from the same physical processes in deep interiors of the Sun. They are present accompanying phenomena that display interdependent and aligned identical paces in their phase and amplitude [6] (**Figure 1**). Thereby, there is a reliable correlation: the temperature of the Earth is always lower in the periods of the minimum of the TSI and SA bicentennial cycle and warmer in the periods of their high [1–4,8,9]. Provisional global reconstructions of the sea surface temperature (SST), starting from the XVII century, suggest that around 1700, that is, in the coldest part of the Little Ice Age, SST could be approximately by 1.0–1.5 °C colder than the period 1950–1980. It considers the influence of the corresponding variations in Bond albedo and atmospheric water vapor and carbon dioxide concentrations [29]. Other authors have also observed a strong correlation between variations in solar irradiance and the Earth's global surface temperature [2,3,30–32]. These empirically based studies find that solar changes have a decisive and considerable climatic impact.

The established correlation between TSI and SA is a significant finding, as it allows for using the relatively brief (since 1978) time series of precise TSI measurements outside the Earth's atmosphere to estimate and reconstruct its corresponding variations over centuries and millennia. This estimation is based on long-term records spanning 11,400 years that document the variations in solar activity [23]. The above situation makes it possible to study the variations of TSI during the past centuries and even millennia, when no industrial effect on nature existed, and to compare them with the corresponding cli-

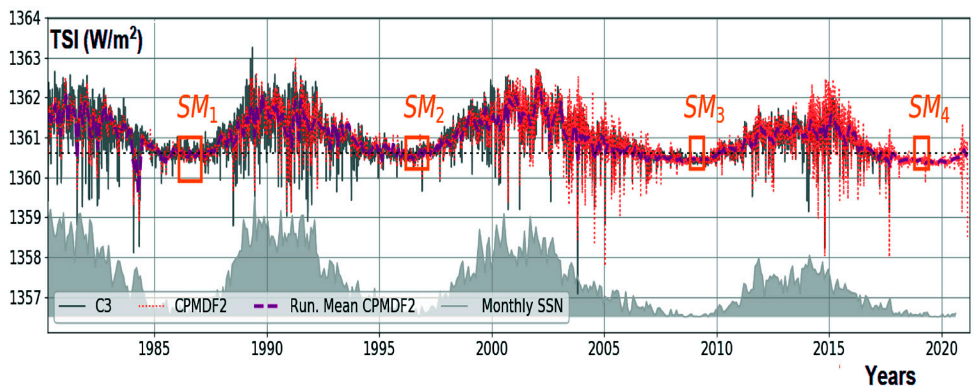

Figure 1. The new Composite is based on merging 41 years of TSI measurements taken from the website [24,25]. The total cycle-average TSI value in cycles XXII–XXIV has decreased by more than 0.5 W/m^2. The monthly sunspot numbers (SSN) are also displayed at the bottom. The orange boxes are associated with each solar cycle's solar minima (SM). The solar minimum periods are chosen by looking at the lowest value in the yearly-averaged sunspot number and then averaging the irradiance values over a one-year interval centred on that date [26,27]. The 11-year and bicentennial cyclic variations of the TSI and sunspot number are synchronized and inter-correlated in phase and amplitude. The radius of the Sun will also increase depending on the level of SA [28].

mate variations in the same periods. In 2003–2007, Abdussamatov scientifically established the onset of a next new Maunder-type Grand minimum both for SA and for TSI in 2042 or 2053, which will lead to increased cooling in 2070 or 2080 [6,7,33]. Here, we should stress that cyclical variations of SA, an accompanying phenomenon of physical processes in deep interiors of the Sun, do not significantly affect either TSI variations or climate variations [6,34]. The maximum smoothed change in the absolute value of TSI in an 11-year cycle (during the maximum BCC) is only about 0.07% (about 1 W/m^2). The total maximum and minimum difference in BCC can be up to 0.3% (≈ 4 W/m^2) [35–38]. Such TSI variability also appears to be supported by certain astrophysical evidence. For example, Judge et al. [38] examined a sample of 72 Sun-like stars and set a limit on the solar forcing of Earth's atmosphere equal to 4.5 W/m^2 since 1750. That's why the solar forcing of climate change may be a significantly larger factor.

There is an observed sequential downward trend of TSI decline in three consecutive cycles (**Figure 1**). The total average cyclic value of TSI in the XXIII cycle decreased by about 0.15 W/m^2 relative to its value in the XXII cycle, and in the XXIV cycle, it has already reduced by more than 0.5 W/m^2. The observed accelerating decline in total cycle average TSI value indicates its quasi-bicentennial decline [6]. The overall rate of decline in TSI from cycle to cycle is accelerating and is expected to reach its maximum acceleration in the next solar cycle. We will approach the Grand solar minimum in a few decades when the Sun may be the weakest throughout the last double bicentennial cycle. The Earth's temperature trends follow the bicentennial solar cycle with a delay of about 30 years due to thermal inertia. The weakly variable Sun is the sole energy giver for warming the Earth's surface, atmosphere, and all things, including the energy for photosynthesis and the power to drive the air, water, and vegetation. Therefore, there is no doubt that any, even small, long-term changes in the Sun will lead to corresponding natural, logical consequences for geophysical conditions and climate changes. It is known that there is a long-term cyclical TSI variation $S_\odot$ is determined by corresponding variations of the solar radius $R_\odot$ and the effective temperature T_e of the photosphere using the equations (1) and (2):

$$S_\odot = \frac{\sigma R_\odot^2 T_e^4}{A^2} \tag{1}$$

where A is the astronomical unit, and

$$\frac{\Delta S_\odot}{S_\odot} = 2\frac{\Delta R_\odot}{R_\odot} + 4\frac{\Delta T_e}{T_e} \tag{2}$$

Consequently, cyclic changes in TSI are associated with corresponding fluctuations in the radius. A close relation is established between variations in the level of SA and the radiation flux in the bicentennial and 11-year cycle with the corresponding radius variations. Studying transits of Mercury across the solar disc from 1631 to 1973, Sveshnikov [28] found centennial and 11-year cycles in the variations of the solar radius $R_\odot$ and their positive correlation with the corresponding variations of the W index of sunspot number. Note that a larger amplitude of radius variations is generally observed in cycles with an enhanced activity level. In contrast, in the cycles with a lowered level of activity, the amplitude is smaller, that is, the 11-year and centennial variations of the radius, the activity level, and the TSI are intercorrelated both in the phase and in the amplitude [4,6,7,28].

In global variations of the spatial and physical characteristics of the Sun, BCC is the most intense solar cycle. The intensity of the 11-year TSI and SA cycles grows consistently with the simultaneous decrease in their duration for the period of the BCC growth phase (about 35–65 years), which substantially increases the generating capacity of the cycles per unit of time. This results in a growth in the fraction of increasing TSI absorbed by the Earth and subsequent corresponding variations in geophysical processes. During the phase of the BCC decline, an opposite pattern is seen. It has been numerically established that in the phase of the BCC decline, the duration P of the SA and TSI 11-year cycles is always longer (P = 11.2 ± 0.4 years [39,40]) than that in the growth and maximum phases, which is a consequence of the BCC influence (**Figure 2**, **Table 1**). The same dependence, determined by the BCC, can also explain the trend of a decrease in the average duration of the eight 11-year cycles (15th to 22nd) down to P = 10.4 years, developed in the epoch growth and maximum phase of the BCC, compared to the duration P = 10.95 years averaged for all 15 (10th to 24th) reliably determined cycles (**Table 1**). The qualitative Waldmeier effect (the Waldmeier rule) states that high cycles display steep and short growth branches [41], i.e., the anticorrelation between the length of the cycle and its amplitude also qualitatively indicates that 11-year cycles in the BCC growth and maximum phases display a shorter duration. So, there is an empirical relationship: the amplitude of the given cycle of SA depends on the length of its ascending branch (Waldmeier rule) or the full cycle length from minimum to minimum. The observed consistent increase in the amplitude of the oscillations of the intensity of 11-year cycles, along with the simultaneous decrease in their duration within the BCC growth phase and the inverse pattern in its decline phase, indicates the pivotal role of BCC in the given consistent interdependent variations of their intensity and duration (**Table 1**). Note that traditionally used time series of variations of the SA index and the maximum level of the sunspot number W (**Figure 3a**) do not describe adequately and reliably the physical state and a precise relative numerical characteristic of their cyclical variations due to the difference in the duration of 11-year cycles P. These time series, which serve to determine the relative numerical characteristic of the activity of each cycle, are not reliable parameters to estimate and accurately characterize the mutual relation between the relative integral energetic power of all SA cycles and their subsequent geoeffective manifestations. The Sun follows 11-year cycles with maximum activity levels, known as the sunspot number. However, the rates of growth and decline of these cycles and their duration vary significantly in terms of their overall physical characteristics and impact on various geophysical processes. In other words, their combined ability to generate effects differs considerably. Therefore, we have developed and introduced new physically based and more reliable indices for SA 11-year cycles: the cycle-averaged sunspot number index (a level of activity) and the relative integral energetic power of the cycle, independent of the cycle duration. The index of the cycle-averaged (weighted mean) level of the sunspot number, a weighted average for the entire 11-year cycle, $\overline{W}$ is determined as equation (3):

$$\overline{W}_{(cycle)} = \frac{\sum W \cdot \Delta t}{\sum \Delta t} \tag{3}$$

where W is the sunspot number, Δt the time interval between consecutive observations for the entire 11-year cycle. Only this SA index level, independent of the cycle duration, and the weighted average for the whole cycle, can objectively and accurately determine a reliable relation of the average level of the activity index for all cycles. The most important and reliable index of the relative integral energetic power of the SA 11-year cycle is determined as a product of the weighted-average sunspot number $\overline{W}$ for the entire cycle and the duration P of the cycle in years. **Figure 3b** presents thereby determined indices of relative integral energetic powers $\overline{W}P$ for all 11-year cycles, which represent their most reliable relative quantitative energy parameters, independent of the duration of the cycle. Here, for the total relative estimate of subsequent effects of the $\overline{W}P$ index on geophysical processes, the Sun is conventionally considered cool in a given cycle (the intensity of the radiated energy below the average level) if the index of the relative integral energetic power of the cycle $\overline{W}P \leq 700$, and if $\overline{W}P > 700$, the Sun is considered hot. The above is suggested based on a comparison of the data for variations of the relative energetic power of the cycles and the corresponding physical processes occurring on the planet for extended periods. Comparing **Figures 3a** and **3b**, we see clear and substantial variations in relations between the indexes' maximum activity level and the relative integral energetic power of the cycles. These variations are the most clearly seen, especially for cycles 4th, 9th, 10th, 15th, and 20th. This fact indicates that to study the patterns of SA development reliably, the variations of mutual relations between relative energetic powers of all observed cycles, and also to determine their subsequent effects on the global geophysical processes, it is necessary to use the most reliable data that we determined, i.e., the index of the relative integral energetic power for the 11-year SA cycles. The most reliable data is presented in **Table 1** within the scope of these obtained. We additionally plotted the dependence of the oscillations of the index of the relative integral energetic power $\overline{WP}$ for all 11-year cycles observed from the 1st to the 24th from variations of the BCC phase (**Figure 4**). **Figure 4** reliably reveals a clearly consistent growth of the index of the relative integral energetic power of 11-year cycles from the minimum to maximum BCC phase and its consistent decline from its maximum to minimum phase.

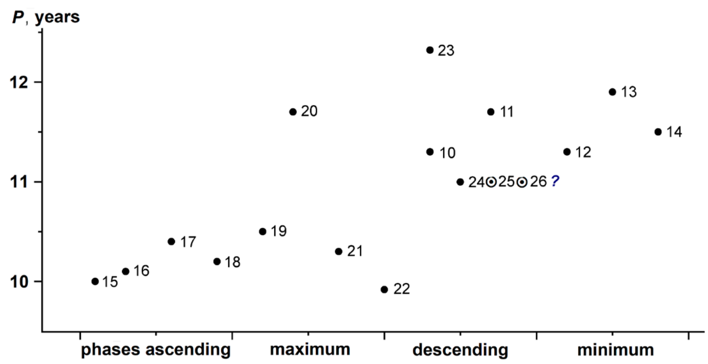

Figure 2. The length *P* of all reliable 11-year cycles from 10th to 24th as a function of phases of the bicentennial cycle, where the predicted lengths of subsequent 25th and 26th cycles are also shown.

Table 1. The known 13-month monthly smoothed total sunspot number data *W* was obtained in the new, completely redesigned version 2.0 sunspot counting (WDC-SILSO, Royal Observatory of Belgium, Brussels [42]). It is determined by the main parameters of all the observed SA cycles from 1st to 24th and predicted parameters of subsequent 25–26 cycles depending on phases of the bicentennial cycle.

Cycle number	Cycle beginning, year	Cycle length *P*, years	Lengths of ascending branches, years	Heights and dates of maxima, year	New weighted mean index of a cycle SA, $\overline{W}$	A new index of a cycle SA relative energetic power, $\overline{WP}$	Phases of the bicentennial cycle			
							ascending	maximum	descending	minimum
1	1755.204	11.251	6.251	144.1 1761.455	69.363	780.4	0.4			
2	1766.455	9.0	3.252	193.0 1769.707	98.521	886.7	0.8			
3	1775.455	9.253	2.916	264.3 1778.371	110.433	1021.8		0.4		
4	1784.708	13.6	3.416	235.3 1788.124	102.554	1394.7		0.8		
5	1798.288	12.335	6.835	82.0 1805.123	38.268	472.0				0.3
6	1810.623	12.665	5.75	81.2 1816.373	30.725	389.1				0.8
7	1823.288	10.586	6.586	119.2 1829.874	62.187	658.3	0.5			
8	1833.874	9.664	3.33	244.9 1837.204	111.379	1076.4		0.3		
9	1843.538	12.42	4.586	219.9 1848.124	98.873	1228.0		0.7		

Table 1 continued

Cycle number	Cycle beginning, year	Cycle length *P*, years	Lengths of ascending branches, years	Heights and dates of maxima, year	New weighted mean index of a cycle SA, $\overline{W}$	A new index of a cycle SA relative energetic power, $\overline{WP}$	Phases of the bicentennial cycle			
							ascending	maximum	descending	minimum
10	1855.958	11.246	4.166	186.2 1860.124	91.643	1030.6			0.3	
11	1867.204	11.754	3.419	234.0 1870.623	88.281	1037.7			0.7	
12	1878.958	11.246	5.0	124.4 1883.958	56.480	635.2				0.2
13	1890.204	11.838	3.838	146.5 1894.042	64.586	764.6				0.5
14	1902.042	11.539	4.081	107.1 1906.123	53.104	612.8				0.8
15	1913.581	10.0	4.042	175.7 1917.623	73.426	734.3	0.1			
16	1923.581	10.126	4.709	130.2 1928.290	67.681	685.3	0.3			
17	1933.707	10.417	3.581	198.6 1937.288	95.285	992.6	0.6			
18	1944.124	10.164	3.247	218.7 1947.371	108,150	1099.2	0.9			
19	1954.288	10.503	3.916	285.0 1958.204	128.275	1347.3		0.2		
20	1964.791	11.665	4.083	156.6 1968.874	84.976	991.2		0.4		
21	1976.456	10.251	3.502	232.9 1979.958	112.740	1155.7		0.7		
22	1986.707	9.917	3.167	212.5 1989.874	105.451	1045.8		1.0		
23	1996.624	12.33	3.666	175.2 2000.290	81.931	1010.2			0.3	
24	2008.958	11.0	5.33	116.4 2014.288	49.156	540.7			0.5	
25	2019.958	11.0 ± 0.6?	4.2 ± 0.6 ?	120 ± 25? 2024.7?	50.0?	550.0?			0.7?	
26	2031.000?	11.0 ± 0.6?	4.0 ± 0.6 ?	60 ± 35? 2035.0?	25.0?	275.0?			0.9?	
Average: on cycles 10th–24th on cycles 1st–24th		 10.933 11.032	 3.98 4.28	 180.00 178.50	 84.078 82.644	 912.21 899.61	 10.2 10.2	 10.6 10.9	 11.6 11.6	 11.5 11.9
Lengths of ascending branches for reliable cycles 10th –24th							3.9	3.7	4.2	4.3
Lengths of descending branches for reliable cycles 10th –24th							6.3	6.9	7.4	7.2
Difference between lengths of descending and ascending branches for reliable cycles 10th –24th							2.4	3.2	3.2	2.9

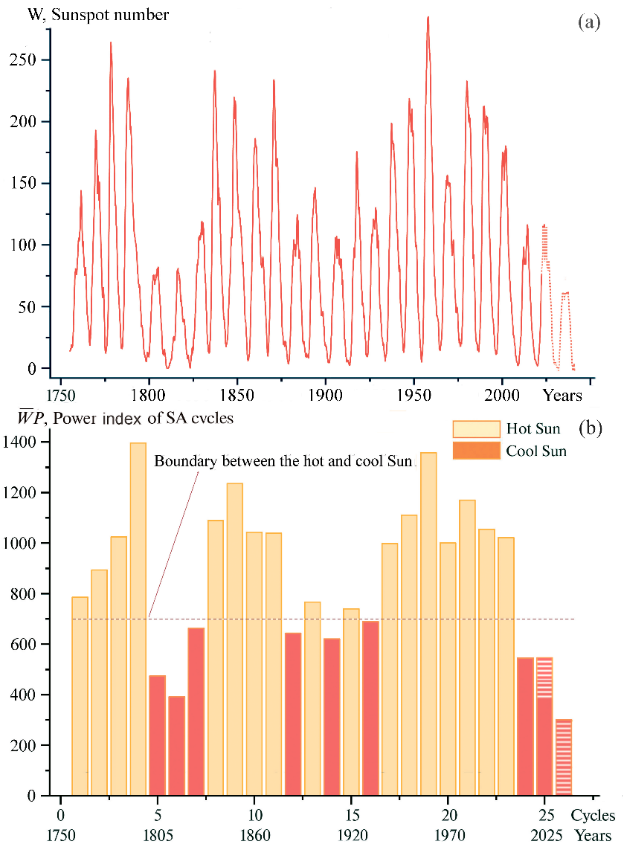

Figure 3. General title. (**a**) Oscillations of the index of sunspot number W [42]; (**b**) A new index of relative energetic power of a cycle SA $\overline{W}P$ for all cycles from 1st to 24th; the forecast of these parameters for subsequent 25th and 26th cycles is also shown; the hot Sun is marked by yellow, but the cool is marked by red.

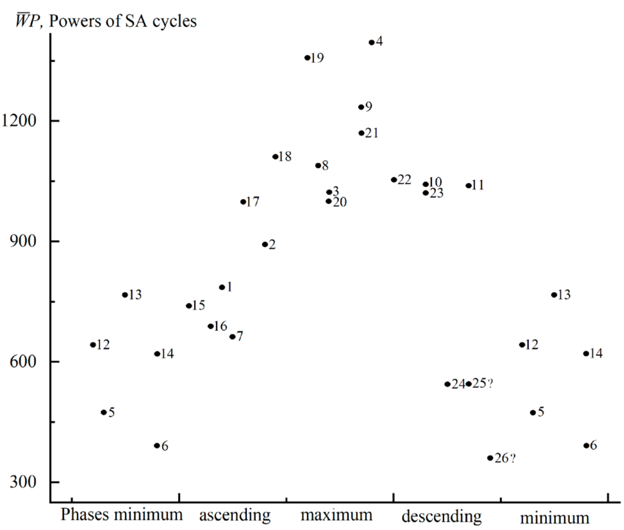

Figure 4. Relative integral energetic powers of 11-year cycles depend on the bicentennial cycle phases. Numerals indicate the numbers of all cycles from 1st to 26th.

The study of consequent variations in the amplitude of the most reliable new index of the relative integral energetic power $\overline{W}P$ for all 24 cycles as a function of the BCC phase makes it possible to conclude that:

- there exists a quantitative dependence of the duration P of 11-year SA cycles on the phase of BCC oscillations: in the growth phase, the duration of 11-year cycles is smaller with a simultaneous consistent increase in the amplitude of the oscillations of the index of their relative integral energetic power, while in the decline phase, the opposite variations occur, which is a result of direct manifestations and the determining role of a powerful BCC of the global solar activity;
- in the decline phase of the BCC, the index of the relative integral energetic power for each subsequent 11-year cycle is lower than it was in the previous cycle, while the opposite dependence is seen in the BCC growth phase. On the other hand, consistent variations of relative integral energetic power of cycles in the stages of BCC decline and growth, naturally, cannot always depend on the evenness or oddity of their number [43].

Consequently, in all parameters, short and weak 11-year cycles virtually depend on the phase of oscillations of the powerful BCC and are physically related to it, while the BCC modulates the amplitude of their fluctuations. BCC represents the basic parent cycle that governs 11-year variations of SA and TSI [6,39,44]. The abovementioned differences between opposite variations of the duration and generating capacity of 11-year cycles in the BCC's growth and decline phases indicate the forthcoming corresponding climate variations within these phases. These differences can also help explain why a consistent variation of the duration of 11-year cycles can indicate the corresponding climate variations only within the BCC's growth or decline phase, considering the Ocean's thermal inertia [45]. The consistent decline of a relative integral energetic power of 11-year cycles with the simultaneous growth of their duration also indicates the onset of the decline phase of a quasi-bicentennial variation of the power of the energy generated by the Sun and thereby is a precursor of a subsequent cooling of the climate considering the thermal inertia of the Ocean. These facts also prove that 11-year cycles are genetically related to BCC, which controls their development and the variation of the power of subsidiary 11-year cycles depending on its (BCC's) phase [46]. More objectively and quantitatively, the index of the absolute generating capacity of an 11-year cycle and its total combined physical characteristics should be determined from the absolute value of the TSI $S_{\odot}$ weighted average for the entire 11-year cycle using the equation (4),

$$\overline{S}_{\odot(cycle)} = \frac{\sum S_{\odot} \cdot \Delta t}{\sum \Delta t} \quad (4)$$

multiplied by the duration of cycle *P* over the years. Due to the thermal inertia of the Ocean, the variation index of the absolute generating capacity of a cycle $\overline{S}_{\odot}P$ taken about for three or more consecutive 11-year cycles will make it possible to reliably forecast an insignificant direct effect on subsequent geophysical processes at the Sun-Earth system. Thus, we observe a consistent increase in the amplitude of the oscillations of the absolute values of the cycle-averaged TSI level $\overline{S}_{\odot}$ and in the absolute integral generating capacity of 11-year cycles $\overline{S}_{\odot}P$, along with a simultaneous decrease in the cycle duration in the BCC growth phase. The opposite variations are seen in its decline phase, which also reveals the BCC's pivotal role in such consistent interdependent variations in 11-year cycles during the entire BCC. These variations result from the influence of the powerful bicentennial cycle of the global SA and TSI. The onset of the growth and decline phases of the bicentennial cycle provides an optimal physically justified indication to forecast corresponding variations of both the duration and the integral generating capacity of SA and TSI in the forthcoming 11-year cycles [7]. In the current 25th and in the following 26th cycles, which are formed in the decline phase of the bicentennial cycle, the trend that we forecasted as long ago as in 2007, long before the onset of the 24th cycle will remain: the index of the relative integral energetic power and also the height of the maximum of the activity level will consistently fall to about 120 ± 25 and 60 ± 35 sunspot number units, respectively [7]. The consistent variation of the maximum activity level in the 24th cycle completely justified our forecast and confirmed the onset of the phase of BCC decline.

In the 20th century, in the growth phase of the current bicentennial cycle, 11-year cycles SA naturally displayed a shorter duration, well below the average for all 24 cycles. At the same time, the height of their maximum level and the index of the cycle-averaged relative energetic power consistently increased (**Figure 3a** and **Table 1**). Besides, the maximum phase of the current BCC with an exceptionally high level of TSI was also anomalously extended, which inevitably caused the warming of the 20th century. As a result, the Earth consistently absorbs more and more solar energy and radiates less intrinsic thermal energy to space (than it absorbs). Because it was heated with the climate's characteristic thermal time-response, which is a large delay of 32 ± 8 years, determined by the thermal inertia of the active layer of the Ocean using the equation (5) [47,48]

$$t = 0.095(1 + 0.42 \cdot h)\text{years} \quad (5)$$

where *h* is the depth of the active layer of the Ocean, equal to 800 ± 200 m. The surplus of the incoming solar energy thereby accumulated in the Ocean's active layer during the BCC's growth phase, without considering the effect of all the other factors, resulted in only an insignificant (~0.25 K) increase in the planet's temperature. However, the latter triggered a significant change in the physical, optical (the albedo), and radiation characteristics (degrees of emissivity, as well as the transmission of thermal radiation of the Earth's surface into space by the atmosphere) of the Earth's surface and atmosphere and the content of water vapor and carbon dioxide. This also triggered the long-term substantial impact of the long chain of an important secondary feedback mechanism:

- a substantial decrease around snow-ice covers, variation in the physical parameters of the

Earth's surface and atmosphere, and, consequently, a substantial decrease in the loss by Earth fraction of the incoming solar energy due to increased absorbed radiation.

- a natural increase in the concentration of the basic greenhouse gas, water vapor, and other greenhouse gases in the atmosphere, with the warming according to Clausius-Clapeyron relation and Henry law, which substantially enhanced the occurred warming due to the noticeable growth in the greenhouse effect.
- a decrease in atmospheric transmission of the thermal radiation of the Earth's surface to space due to the narrowing of its transparency windows caused by the increase in the concentrations of greenhouse gases in the atmosphere.
- an increase in the "dark" surface of the Ocean, caused by the increase in the water level, due to deglaciation on land and the thermal expansion of water by warming, which results in a growth in the fraction of the absorbed solar energy.

They led to a further significant increase in warming. The increase of this heating, in turn, has caused additional changes in the physical and optical characteristics of the Earth's surface and atmosphere, forming a re-intensification of temperature change. Increased heating, in turn, has caused additional changes in the physical and optical characteristics of the Earth's surface and atmosphere, which has formed a chain of repeated multiple self-intensification of temperature changes. The natural substantial self-amplification of the warming in the 20th century by long chains of those mentioned above secondary cause-and-effect climatic feedback effects additionally continued anomalously for more than 60 years in the very extended phase of the BCC maximum, when the amplitude of the SA and TSI oscillations quasi-stabilized around the maximum level during five 11-year cycles (**Figures 3a,b**). The natural substantial self-amplification of the warming by long chains of the above-mentioned secondary feedback effects also continued at the beginning of 21st century, an approximately 30-year initial period of the BCC's decline phase. This is precisely the effect of very extended chains of feedback that resulted in the observed natural additional substantial self-amplification of climate warming at the end of the 20th and the beginning of the 21st century. In general, it is known that the Bond albedo increases to the maximum level with deep cooling and decreases to the minimum level with global warming. This is why climatic variations on the planet in the fourth quarter of the 20th century accelerated under the influences of feedback effects, which imminently led to substantial multiple additional self-amplification of the started warming. No such anomalously long duration and high TSI level, as in the 20th century, had been seen at least for the past 700 years. In this case, an extended minor TSI growth (up to 0.3%) is sufficient for starting the insignificant heating and triggering a chain of consistent events of secondary cause-and-effect feedback effects, mutually enhancing each other and resulting in substantial climate variations.

3. An energy imbalance between the Earth and the cosmic space

Disbalancing the energy system of the underlying surface and the atmosphere can result only from consistent variations of the yearly average EEI for 30 years or more, whatever their reasons. Therefore, this parameter is of fundamental significance for establishing the patterns of climatic variations and forecasting future climate variations. To study the physical mechanisms of climate formation and variations, it is primarily necessary to determine the reasons for long-term variations in the yearly average EEI. In the decline (or growth) phase of the TSI bicentennial cycle within a period of ~35–65 years, the Earth always radiates to space more (or less) energy than it absorbs. Due to the thermal inertia of the Ocean, the planet does not have enough time to cool down (or heat up) respectively. Naturally, this mechanism provides a negative (or positive) long-term yearly-average EEI, respectively, due to 11-year and quasi-bicentennial TSI variations caused by the Ocean's thermal inertia. An imbalanced state in the income and outcome of the entering solar energy in the underlying surface-atmosphere system on the atmosphere's outer border is the climate system's natural state [8,9]. Therefore, the quasi-bicentennial and 11-year TSI variations and the variations of the physical conditions on the surface and in the Earth's atmosphere related to the long-term effect of TSI variations (primarily the variations of the Bond albedo and the water vapor concentration), considering the thermal inertia, are the basic sources of the energy instability and violation of the Earth's thermal balance. The EEI is determined by the difference between the values of the specific power of the solar radiation obtained by the outer layers of the atmosphere on the area of the cross-section of the globe πr^2 (r is the radius of the planet) and the fractions of its reflected and scattered energy outgoing to the space, determined by the Bond albedo of the Earth and also by the intrinsic thermal radiation outgoing from the atmosphere to the space in all directions from the entire surface of the Earth's sphere with the area $4\pi r^2$, i.e., by the difference between the TSI fraction absorbed by the planet and the energy of the intrinsic thermal radiation emitted to the space by the Earth using equation (6) [8,9]:

$$E = \frac{(S_{\odot} + \Delta S_{\odot})}{4} - \frac{(A_{BE} + \Delta A_{BE})(S_{\odot} + \Delta S_{\odot})}{4} - \varepsilon\sigma(T_p + \Delta T_p)^4 \tag{6}$$

where E is the specific power of the enthalpy (heat content) change of the active oceanic and atmospheric layer (W/m^2), which can be considered the energy disbalance of the annual average budget in the debit and credit of the thermal power of our planet, $S_{\odot}$ is the TSI, $\Delta S_{\odot}$ is the TSI increment, A_{BE} is the Bond albedo of the Earth, ΔA_{BE} is the increment of the Bond albedo of the Earth, ε is the emissivity (blackness degree) of the underlying surface-atmosphere system, σ is the Stefan-Boltzmann constant, T_{p} is the thermodynamical planetary temperature, and ΔT_{p} is its increment. The planetary thermodynamical temperature is the mean temperature over the entire planet (the Earth's surface and the atmosphere). Long-term increments of the TSI and the Bond albedo of the Earth determine the temperature increment using equation (7):

$$\Delta T = \frac{\Delta S_{\odot}(1 - A_{\mathrm{BE}} - \Delta A_{\mathrm{BE}}) - \Delta A_{\mathrm{BE}} S_{\odot}}{16\varepsilon\sigma T^3} \tag{7}$$

A natural temperature gradient in BCC determined by the TSI difference for the period from the Maunder minimum phase to the current maximum phase, equal to $\Delta S_{\odot} \approx 4$ W/m^2 [35–38], without considering all other contributions for $\Delta A_{\mathrm{BE}} = 0$, can only be reached using equation (8):

$$\Delta T \approx 0.25\ ℃ \tag{8}$$

It is possible to estimate the correspondence between relative contributions of the increments of the TSI ($\Delta S_{\odot}$) and the Bond albedo (ΔA_{BE}) into EEI if we accept the condition of their mutual compensation in equation (7) under the conservation of the energy equilibrium [4,8,9]:

$$\Delta S_{\odot}(1 - A_{BE} - \Delta A_{BE}) - \Delta A_{BE} S_{\odot} = 0 \tag{9}$$

Equation (9) makes it possible to determine the correspondence between relative contributions of the increments of the TSI and the Bond albedo to EEI using equation (10):

$$\frac{\Delta S_{\odot}}{S_{\odot}} = \frac{\Delta A_{BE}}{1 - A_{BE} - \Delta A_{BE}} \tag{10}$$

Consequently, the Bond albedo of the Earth is also a highly important physical parameter in the EEI, as its increment $\Delta A = 0.003$ (1.0%) is equivalent to a lowering of the TSI by $\Delta S_{\odot} = -5.88$ W/m^2 (0.435%). A variation of the EEI, independent of reasons for variations of its constituents for the time of the order of 30 years and more, is a basic measure of subsequent climate variations. Such a long-term consistent drop in the Earth's temperature in the decline phase of the bicentennial cycle generates secondary causal feedback effects: an increase in the Bond albedo of the Earth, a substantial decrease in the concentrations of greenhouse gases in the atmosphere, according to Clausius-Clapeyron relation and Henry law, an increase in the atmosphere transmission of the thermal radiation of the Earth's surface to the space, and a decrease in the area of the "dark" surface of the Ocean. These effects will result in an additional reduction in the planet's temperature; in turn, this will lead to a long chain of such cycles, which will also retain within the entire phase of the extended Grand minimum of the TSI bicentennial cycle when $\Delta S_\odot \approx 0$. Therefore, at the end of the Grand minimum phase, the cooling will reach its maximum.

Even in the periods of virtually constant TSI ($\Delta S_\odot \approx 0$) during extended maximum and minimum phases of the bicentennial cycle, due to multiple repeated feedback effects, the EEI variation, determined from the equation (6) will persist,

$$E = \frac{S_\odot(1 - A_{BE} - \Delta A_{BE})}{4} - \varepsilon\sigma(T_p + \Delta T_p)^4 \tag{11}$$

and the same is true for the temperature increment determined from the equation (7):

$$\Delta T = -\frac{\Delta A_{\mathrm{BE}} S_\odot}{16\varepsilon\sigma T^3} \tag{12}$$

Thus, during extended maximum and minimum phases of a bicentennial solar cycle, temperature and EEI variations result from continued secondary cause-and-effect feedback effects under virtually constant TSI. Depending on the long-term trend of variations of the absolute value of yearly-average EEI and its sign, one can reliably estimate the excess of the accumulated entered energy (with the positive sign) or its accumulated deficit (with the negative sign) in the Ocean, and, consequently, a corresponding direction and the depth of the forthcoming climate variations taking into account the thermal inertia of the Ocean and the forecast of the forthcoming TSI variations of the quasi-bicentennial cycle. Note that the combined radiation energy outgoing from the upper part of the atmosphere into space is one of the critically important parameters in studies of climate variations and the most reliable forecasting of future variations. In this case, of course, in the climatic system, the role of natural inter-system reasons for short-term temperature variations up to ± 0.2 °C must also be considered. They are due to the distinction between fluctuations of regional oceanic and atmospheric flows, cloudiness, the surface area of snow and ice covers, etc., and due to their substantial difference in the North and South hemispheres, taking into account primarily the non-uniform distribution of land on their surfaces (~39% and ~19%, respectively).

4. The study of climate variations of the distant past as a key to corresponding global TSI variations and the truth

A full understanding of how the climate has changed in the distant past will give us much greater power to study and deal with future change. Especially when there was no anthropogenic influence on nature, we see how quasi-periodic changes in the Sun's output can lead to significant changes in the Earth's climate, i.e., the variability of the Sun has driven much of the observed climate change, which is due to space forces beyond our control. Truly understanding the complex natural influences of solar variability, we may better understand past climate changes and be able to predict and prepare for future changes. This will help us make sensible decisions about where to focus our efforts to ensure that future generations are well-prepared for whatever nature throws at us next. During the last 150 years, an increase in the carbon dioxide concentration in the atmosphere has been observed, with an almost simultaneous trend of moderate growth in the level of the Earth's temperature. Both trends are far from coincidence, while the statistically significant correlation between the two data sets does not prove their cause-and-effect relationship. Therefore, the data on the climate of the Earth in the past deserve a detailed and thorough analysis and study. Deep climate variations during past centuries and millennia, when no industrial impact on nature was possible, could have resulted only from substantial long-term variations in the power of the entering flux of solar radiation. Studies of the natural variability of the climatic system in the distant past make it possible to estimate corresponding TSI variations in that time and thereby understand possible climate variations in the future. Paleoclimatic reconstructions provide reliable information concerning variations of the solar energy influx in the past. As a result, it has been found that it is one hundred-thousand-year TSI oscillations caused by variations of the shape of the Earth's orbit according to Milankovitch cycles [10] that result in the Big Glacial Period and substantial variations in the abundance of greenhouse gases in the atmosphere with corresponding cyclicity (**Figure 5**).

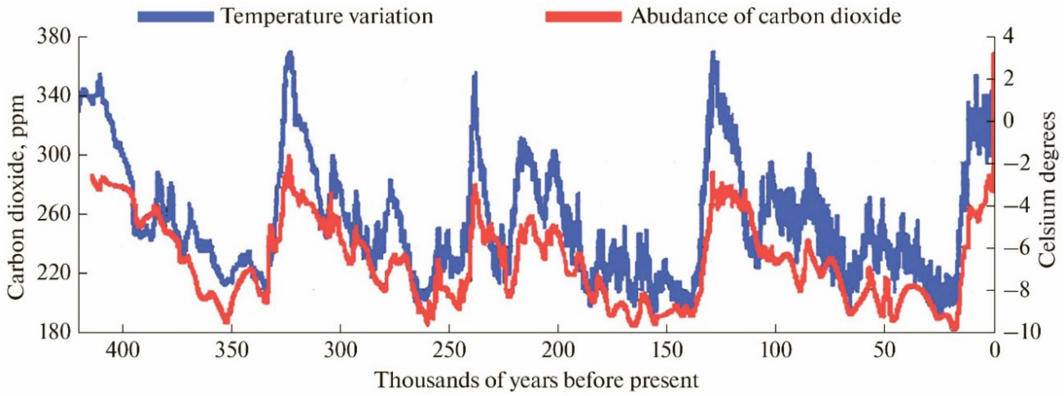

Figure 5. Variations in the Earth's climate and volumetric carbon dioxide concentrations for 420,000 years (according to the ice core data near Vostok, Antarctica) [11].

A study of the longest ice core, 3769 meters long, extracted from the borehole drilled over the relic Vostok Lake in the central part of Antarctica (next to the Russian Vostok station) yielded a time series of the temperature of the surface air layer as well as that of the carbon dioxide and methane concentration in the atmosphere for four of the latest Big glacial/interglacial cycles—for 420 thousand years [11]. During this time interval, the Earth has made it through four big climatic glacial/interglacial cycles (with a period of about 100 thousand years) with extended ice ages and relatively short seasons of five high-temperature phases, with temperature oscillations of about 10 °C. Note that the minimum temperatures in all four climatic cycles differ by 1 °C. European scientists drilled another deep borehole in Central Antarctica, which embraces eight climatic cycles (over 800 thousand years) [12]. The analysis of ice cores has revealed that, for at least the last 800 thousand years, variations in the Earth's orbital shape have been crucially important for determining the climate, specifically, the occurrence of one-hundred-thousand-year cycles of TSI variations. The studies of substantial climate oscillations during at least the latest 800 thousand years show that bicentennial (at least for a period of the latest 7500 years [3]) and one hundred thousand-year cyclical TSI variations are the pivotal and basic reasons for climate alternations from warmings to the Little Ice Age and the Big Glacial Period. The studies of ice cores from Antarctica indicate that for the last 800 thousand years, substantial periodical increases in CO_2 abundance in the atmosphere have never preceded climate warming and have never been a reason for warming. On the contrary, increases in carbon dioxide concentration have always followed temperature increases driven by an extended influx of solar radiation with enhanced energy (**Figure 5**), with a delay of approximately 800 ± 400 years [11,49,50], i.e., they have always naturally followed a temperature growth, according to Henry law. According to this law, as warming occurs, more CO_2 is released from the Ocean and land into the atmosphere, but the warming Ocean will absorb only less. The remaining parts of excess CO_2 will accumulate in the atmosphere. Therefore, the increase in the carbon dioxide concentration in the atmosphere with the warming was only a secondary phenomenon. Every time, the natural growth in the concentration of greenhouse gases started after the onset of the warming. The temperature also began to fall after reaching a very high value, even though the concentration of greenhouse gases continued to grow [11,34,49,50]. In current times, for a short period from January 1980 to December 2011, the phase relation (advancing—lagging) was studied using some data on the abundance of CO_2 in the atmosphere and on the global temperature [51]. It was found that even for a short period, the maximum positive correlation between the carbon dioxide concentration in the atmosphere and the temperature was observed. Nigmatulin (former director of the Shirshov Institute of Oceanology of the Russian Academy of Sciences) established that natural flows of carbon dioxide from the Ocean and the land into the atmosphere and from the atmosphere to the Ocean and the land multiply exceed emissions of these matters resulting from human activity [52,53]. The Ocean waters contain 50 times more dissolved CO_2 than the atmosphere. The observed climate variations primarily result from the bicentennial cyclicity of TSI variations and the influence of subsequent strong feedback. Due to the upcoming Grand solar minimum, the trend of global climate change is currently directed towards cooling. It already happened systematically for at least 7500 years [3], after a modern warming will inevitably begin a regular 19-the global cooling.

5. The forthcoming Grand solar minimum

Variations in the flux of the intrinsic long-wavelength radiation to the space in the surface-atmosphere system always lag behind variations of the fraction of the flux of short-wavelength TSI absorbed by the Earth, which varies with the 11-year and bicentennial cycles by the term of the order of 30 years, due to a large heat capacity and the thermal inertia of the active layer of the Ocean, with the depth of 600–1000 m [47,48]. In so doing, we are headed for a Grand solar minimum, only virtually continually lowering the TSI to 4.0 W/m^2 [35–38]. During the entire phase of BCC decline (without considering all other factors), taking into account the Ocean's thermal inertia will result in a gradually insignificant decrease in the temperature of the Earth by ~0.25 K (equations 7 and 8). However, if we consider the naturally important influences of secondary feedback effects, the climatic sensitivity to them can significantly differ from the climatic sensitivity to significantly reduced direct radiative forcings. Most long-term effects of solar radiation on the climate may not be induced by insignificant direct TSI forcing alone but rather by other Sun-climate processes, which must be thoroughly investigated and physically understood. This can explain why empirical studies found that the solar contribution to climate changes throughout the Holocene has been significant [16–22], whereas TSI-based studies, which only adopt direct radiative forcings, suggest that the Sun plays a relatively modest role. Such a long-term insignificant consistent decrease in the temperature will cause a corresponding subsequent increase in the Bond albedo of the Earth, a reduction in the concentration of water vapor and other greenhouse gases in the atmosphere, according to Clausius-Clapeyron relation and Henry law, an increase in the atmospheric transmission of the thermal radiation of the Earth's surface to the space, and a decrease in the area of "dark" surface of the Ocean. This will lead to a second decrease in the TSI fraction absorbed by the planet and in the influence of the greenhouse effect, as well as the growth in the fraction of the thermal radiation of the surface outgoing to space through transparent windows of the atmosphere. This additionally lowers the temperature of the Earth as a planet, which in turn gives rise to the next turn of such cooling and the formation of a long chain of such cycles, also including due to the thermal inertia, the subsequent phase of the extended Grand minimum of the TSI, when $\Delta S_{\odot} \approx 0$, as well as the period of the beginning of slow growth of TSI (for the order of 30 years) of the phase BCC. Secondary feedback mechanisms are important distinctive self-amplifiers of corresponding variations of the thermal regime of our planet, multiplying the amplitude of temperature variations caused only by the direct impact of TSI BCC variations. A long series of feedback cycles results in multiple additional self-amplifications of the cooling occurring up to the Little Ice Age. Thus, the bicentennial cyclicity of the energy released by the Sun, without considering all other factors, dictates and determines the corresponding insignificant oscillations of temperature on the Earth. However, long-term trigger changes of the Bond albedo and water vapor as a response to the TSI forcing can strongly amplify its initial input. In this case, subsequent secondary causal feedback effects multiply and amplify the arrived climatic change by analogy with the Milankovitch cycle. However, due to the non-linear nature of feedback mechanisms' impact on relevant temperature and climate changes, the precise quantitative characteristics of their impacts are difficult to assess. This is, first, due to the variations between fluctuations of regional oceanic and atmospheric flows, cloudiness, the surface area of snow and ice covers, etc., and due to their substantial difference in the North and South hemispheres, taking into the non-uniform distribution of land on their surfaces (~39% and ~19%, respectively). However, it is known that if we exclude the influence of the climatic feedback in the 100-thousand-year oscillations of the TSI of the Milankovitch cycle, then the planetary temperature oscillations may be changed by no more than 1.5 °C instead of the observed change of about 10 °C [13–15].

For this reason, the debit and credit parts of the EEI always deviate from the equilibrium state ($E \neq 0$), which is a natural state of the climatic system. Note that in the growth phase of the bicentennial cycle, the 11-year cycles display shorter duration, while their height of the maximum and the absolute generating capacity consistently increase; due to the thermal inertia of the Ocean, during 35–65 years, the Earth absorbs more solar energy than it radiates to the space. Because in the growth phase of the bicentennial cycle, the EEI will always become durably positive ($E > 0$). As a result of such extended absorption and the accumulation of additional solar energy entering during the entire growth phase of the bicentennial cycle by the Ocean, the planet can gradually warm up. Inversely, in the decline phase of the bicentennial cycle, during about 35–65 years, the EEI will, similarly, become durably negative ($E < 0$). The EEI will also remain negative in the subsequent 26th–30th solar cycles, as the Sun is heading to its next Grand minimum [6–8,33]. The extended deficit of the entering solar energy results in the subsequent cooling of the planet. The total saved (accumulated) additional solar energy (ΣE) (or its deficit) in the Ocean during the entire growth (or decline) phase of the bicentennial cycle may determine the corresponding depth of the forthcoming warming (or cooling). Following our forecast for 2006 [39], the XXIV and XXV cycles have displayed low SA and TSI levels for the latest century, and the next weakening XXVI and XXVII cycles of the further lowering of SA and TSI are yet to occur until their sufficiently deep Maunder-type minimum is reached in 2042 or 2053. Since the 1990s, the fraction of solar energy absorbed by the Earth has decreased virtually in proportion to the lowering of the TSI.

6. Variations of the galactic cosmic rays and cloud cover practically do not affect the climate

In the period of the bicentennial cycle minimum, when the effect of the Sun's magnetic field substantially weakens, the flux of galactic cosmic rays penetrating the lower layers of the Earth's atmosphere increases. They supposedly may result in an increase in the rate of formation of clouds and the cloudiness area there. Such a possible growth in the optical density and the cloudiness area increases the fraction of the entering TSI reflected into space, thereby weakening the flux of solar radiation reaching the Earth's surface. However, simultaneously, increased cloudiness causes an increase in the reflection and absorption of the thermal radiation of the surface, and solar radiation reflected from the surface outgoing into space. It also narrows the atmosphere's transparency windows, lowering the fraction of the energy thermal radiation of the surface outgoing into space. Besides, the growth in the area and the optical density of clouds strengthens the greenhouse effect, which will also heat the atmosphere and the entire planet. These processes present an important source of accumulation of supplementary heating energy, which virtually may well compensate for the cooling caused by the impact of the increase in the reflected fraction of the entering TSI outgoing back into the space. We have carried out a combined estimate of the entire process, including the opposite aspects of the energy impact of a possible increase in the area and optical density of the cloud cover simultaneously on climate warming [54,55]. The quantitatively estimated potential variation in the current value of the yearly average EEI E_o, if the area of the cloud cover in the lower atmosphere of the Earth will gradually increase by 2% due to the supposed impact of the growth in the flux of galactic cosmic rays in the period of a Grand minimum of SA. From calculations obtained, the yearly average EEI difference after the growth in the cloudiness area in the lower atmosphere by 2% is approximately zero, as calculated using equation (13):

$$\Delta E = E_1 - E_o \approx 0 \tag{13}$$

i.e., the difference between EEI before E_o and after the growth in the cloudiness area E_1 is virtually equal to zero since an increase around cloud cover in the lower atmosphere simultaneously can both decrease and increase temperature in approximately equal amounts, virtually compensating each other, without practically disturbing the stability of the energy balance [54,55]. As a result, the impact of long-term increase in the area and optical density of the cloud cover, caused by the presumed influence of the growth of the flux of galactic cosmic rays in the period of the minimum of the bicentennial cycle, on the EEI and climate is virtually nonexistent.

7. Quasi-bicentennial seasons in the Solar system

All planets in the Solar system tend to undergo natural periodical cycles of warming and cooling that have occurred over many millennia due to the bicentennial cyclicity of solar radiation entering the planets. Mars was also experiencing a warming phenomenon like ours in the last quarter of the 20th century, driven by a substantial and extended increase in the incoming solar energy flux. NASA researchers [56,57], having followed variations on the surface of the neighboring planet in 1999–2005, found climate warming and consistent growth in thawing ice on the Southern Pole during this period three Martian years in a row. These parallel events of global warming, observed simultaneously on Mars and the Earth, may only be a direct consequence of the action of the same factor: the long-term significant increase in the power of entering solar radiation, which subsequently resulted in a substantial enhancement of this process and a decrease of the Bond albedo of Mars [58–60].

Warming events similar to that on Mars and the Earth were observed simultaneously on Jupiter, Triton (Neptune's moon), Pluto, and several other Solar system bodies [61–66]. Can there be any factor common to all the planets in the Solar system, the action of which could result in their virtually simultaneous heating in the same period? If these processes correlate, their only real causal source may be a concurrent increase in the solar energy flux entering all these planets. The common factor acting simultaneously on all Solar system bodies was the extended extremely high level of the energy radiated by the Sun virtually during the entire 20th century. This means that our climate and our neighbors in the Solar system are affected exceptionally by the variation of the entering solar energy flux. Therefore, the simultaneous climate warming events observed on the Earth, Mars, and the planets virtually in the entire Solar system in the last quarter of the 20th century were of the natural solar nature and were determined precisely by the natural cosmic patterns [57,59,60]. The basic reason for all these simultaneous warming events was the increase in the power of the entering solar energy flux in the growth phase of the bicentennial cycle. In the interview for National Geographic News, in the paper *Mars Melt Hints at Solar, Not Human, Cause for Warming, Scientist Says*, Abdussamatov [57] noted that both the Earth and Mars are heated simultaneously and that the culprit of this heating is the long-term increase in the power of the solar radiation. This paper was named among the 7 best scientific stories of the year 2007 published in this magazine. The data on the global warming on Mars and the consistent thawing of its ice polar cap during three Martian years in a row present additional evidence that the cyclicity in variations of the solar radiation power is the key factor of climate variations in the entire Solar system and that the observed warming on the Earth was to a large extent a natural phenomenon. We should particularly note that the warming on Mars was not a result of variations in the shape of its orbit and of the inclination of the axis of its rotation (as it is often incorrectly suggested by some authors [57]), which allegedly could for such a short-term result in a substantial increase in the entering solar energy. The period of variations in the shape of the orbit of Mars, as well as that of the Earth, is of the order of a hundred thousand years, and for such an insignificant time interval (six Earth years!), this factor virtually could in no way significantly affect the solar energy entering Mars and result in a substantial variation of its climate. The parallel warming events observed in the last quarter of the 20th century virtually in the entire Solar system confirm that, also by the analogy with terrestrial seasons (with the seasonal change on different hemispheres), the Solar system undergoes cyclical quasi-bicentennial alternations of climatic conditions (seasons), specified by corresponding long-term variations in the power of entering solar radiation [34]. From this point of view, "the solar summer" has been over in the Solar system, and "the solar autumn" has begun. Then, approximately in 2070 or 2080, "the solar winter" will come. The "solar spring" in the Solar system will only tentatively begin in 2120 ± 20.

8. Conclusions

The study of significant climate oscillations for the last 800 thousand years indicates that bicentennial (at least for a period of the latest 7500 years) and 100-thousand-year cyclical variations of TSI are the primary reasons for alternating all corresponding warmings and cooling [2–4,9–15,67]. Around 1990, the Sun entered the decline phase of its bicentennial cycle, in which the intensity of both TSI and SA in each subsequent 11-year cycle practically becomes smaller than in the previous one while the duration of the cycles increases [40]. We have developed and introduced new physically based indexes for 11-year cycles independent of the duration of the cycle: the integral relative energetic power of the solar activity and TSI, as well as the cycle-weighted mean value of both TSI and sunspot number. The onset of the Grand minimum phase of TSI and SA of the Maunder-type bicentennial cycle is expected in the 27th or 28th cycle in 2042 or 2053. In the decline phase of quasi-bicentennial variation of TSI from ~1990 to approximately 2042 or 2053, our planet will absorb the fraction of the resulting decreasing average energy level radiated by the Sun. However, due to the Ocean's thermal inertia, the Earth will not cool down and, consequently, during this entire period, will radiate significantly larger energy into space than it will absorb. As a result, a negative energy imbalance between the Earth and the cosmic space is present during the entire decline phase of the bicentennial cycle. This long-term negative energy imbalance in the absence of powerful repeated El Niño phenomenon and submarine volcanic eruptions with heating properties [68] results in a natural insignificant (≈ 0.25 K) lowering of the temperature and a corresponding variation in the global physical, optical, and radiative parameters of the underlying surface and the atmosphere. These variations will generate a long chain of sustained and repetitive causal feedback effects: an increase in the value of Bond albedo of the Earth, a decrease in the concentration of greenhouse gases in the atmosphere according to Clausius-Clapeyron relation and Henri law, an increase in transmission of the thermal radiation of the Earth's surface into the space by the atmosphere, and also a decrease in the area of the "dark" surface of seas and oceans. These variations also result in a significant lowering of the absorption of the fraction of TSI by the planet and in a growth of negative EEI, which will enhance the arrived insignificant cooling by the factor of a few by analogy with the significant influence of feedback effects in Milankovitch cycles [14,15]. Perhaps this will lead to a deep cooling phase around 2070 or 2080.

It should be noted here that the self-enhancement of climate change by corresponding impacts of the secondary feedback effects, which continuously acted in the growth and decline phases of the bicentennial cycle, will continue due to the thermal inertia during the entire period of maximum and minimum phases when the average TSI value in general virtually does not vary ($\Delta S_{\odot} \approx 0$), as well as during short periods of exposure at the beginning of slow growth and decline in BCC (about 30 years). This will provide further self-enhancement corresponding to temperature variations within these BCC periods. The depth of climate change in total depends on the duration of the growth branch (the growth and maximum phase) and the decline branch (the decline and minimum phase) of the bicentennial cycle. The longer the duration of the growth and decline branches of the bicentennial cycle, the more powerful the amplitude of corresponding variations of the EEI and the temperature. That's why the natural substantial self-amplification of the warming by long chains of those mentioned above, secondary cause-and-effect climatic feedback effects, additionally continued also at the beginning of 21st century in the period exposure to thermal inertia in the about 30 years, in the period of the beginning BCC decrease phase; taking into account powerful eruptions of submarine volcanoes similar to the Hunga Tonga—Hunga Ha'apai volcano, which was also accompanied by the eruption, 146 million tons of water vapor from the South Pacific Ocean to a height up to 55 km [68]. By acting as a main and excellent greenhouse gas, this water vapor curtailing heat energy from leaving the Earth, overrode the aerosol effect, and dominated the top-of-the-atmosphere radiative forcing, leading to a net warming of the climate system. In so doing, powerful volcanic eruptions on land lead to short-term cooling periods [9]. Such volcanic eruptions increase the number of solid particles and gases in the lower stratosphere. Their scattering, screening, and partial absorption of the incident solar radiation decreases the portion of TSI reaching the surface, which can result in short-term climate cooling. However, these changes are not long-term because of the limited lifetime of volcanic particles in the atmosphere. The atmosphere can self-clean and gradually increase its transparency to its previous level, from 6 months to a few years. The role of volcanic eruptions in climate variations cannot be long-term and determinant. Thus, the powerful volcanic eruptions on land lead to short-term cooling, and their submarine eruptions—to warming.

The combined value of EEI accumulated in the Ocean for 30 years and more determines the corresponding variations of the thermal state of the surface-atmosphere system and, consequently, forthcoming climate change and its amplitude. The long-term positive or negative EEI results, respectively, in the warming or cooling since the climate change on the Earth is a function of TSI and EEI variations for the time of the order 30 years and more. The bicentennial and 100-thousand-year (caused by variations of the shape of the Earth's orbit) cyclicities of TSI variations are the basic factors that control the Earth's climate system, and even the most insignificant long-term TSI variations may seriously affect the climate of the Earth, as the case in Milankovitch cycles [10]. The long-term cyclical TSI variations are the key to understanding the subsequent corresponding environmental and societal changes. The heating of virtually all the Solar system planets in the last quarter of the 20th century [61–66] indicates that natural causes led to this process, with the growth phase of the TSI bicentennial cycle being its fundamental factor. An extended lowering in the incoming flux of the solar radiation in the decline phase of the TSI bicentennial cycle and continuous action of the secondary feedback effects, while insignificantly lowering the temperature of the tropical surface of the Ocean, will weaken the power of the outgoing oceanic currents, including the Gulf stream, which continually carrying heat to high latitudes. In this period, the total meridional heat transfer from the tropical zone to high latitudes carried out by the atmosphere and oceanic currents will appreciably decrease. The bicentennial cyclicity of TSI and EEI, along with the very important self-enhanced continuous action of the secondary feedback effects, is the basic fundamental reason for corresponding cyclical alternations of the climate from warming to cooling and the main factor that controls the climate system. Long-term minor direct TSI forcing is the primary solar trigger driving Earth's climate change by launching and triggering a chain of consistent events of secondary cause-and-effect climatic feedback, mutually enhancing each other. Therefore, long-term changes in the solar radiation influence have a much stronger overall impact on the Earth's climate than the TSI direct forcing alone. In so doing, it should be noted that the impact of long-term increase in the area and optical density of the cloud cover, caused by the possible influence of the growth of the flux of galactic cosmic rays in the period of the bicentennial minimum of the BCC, on the EEI and climate is virtually nonexistent.

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

Data will be available on request from the author.

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