Grand Minimum of the Total Solar Irradiance Leads to the Little Ice Age

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GRAND MINIMUM OF THE TOTAL SOLAR IRRADIANCE LEADS TO THE LITTLE ICE AGE

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SUMMARY FOR POLICY MAKERS

Significant climate variations during the past 7.5 millennia indicate that bicentennial quasi-periodic TSI variations define a corresponding cyclic mechanism of climatic changes from global warmings to Little Ice Ages and set the timescales of practically all physical processes taking place in the Sun-Earth system. Quasi-bicentennial cyclic variations of the TSI entering the Earth's upper atmosphere are the main fundamental cause of corresponding alternations of climate variations. At the same time, more long-term variations of the annual average of the TSI due to changes in the shape of the Earth's orbit, inclination of the Earth's axis relative to its orbital plane, and precession, known as the astronomical Milankovitch cycles, together with the subsequent feedback effects, lead to the Big Glacial Periods (with the period of about 100,000 years).

The annual average difference between the solar radiation energy coming into the Earth's outer atmosphere, and the reflected solar radiation and longwave radiation energy outgoing into space determine the balance of the energy budget of the Earth-atmosphere system. Difference between the incoming E_{in} and outgoing E_{out} radiation is described by the following equation:

$$E = (S_\odot + \Delta S_\odot)/4 - (A + \Delta A)(S_\odot + \Delta S_\odot)/4 - \varepsilon\sigma(T_p + \Delta T_p)^4. \quad (1)$$

Here $S_\odot$ is the TSI, $\Delta S_\odot$ the increment of the TSI, A is the albedo of the Earth as a planet (Bond albedo), ΔA is the increment of the Bond albedo, ε is the emissivity of the Earth-atmosphere system, σ is the Stefan-Boltzmann constant, T_p is the planetary thermodynamic temperature, E is the specific power of the enthalpy change of the active oceanic and atmospheric layer [W m^{-2}], which can be considered as the energy balance of the annual average budget in the debit and credit of the thermal power of the planet.

Quasi-bicentennial variation of the solar radiation absorbed by the Earth remains uncompensated by the energy emission to space over the interval of time that is determined by the thermal inertia of the World ocean (20±8 year). That is why the debit and credit parts of the average annual energy budget of the terrestrial globe with its air and water envelope are always in an unbalanced state (E≠0), which is the basic state of the climatic system. The average annual balance of the thermal budget of the Earth-atmosphere system during long time periods will reliably determine the course and value of both the energy excess accumulated by the Earth or the energy deficit in the thermal budget, which, with account for the data of the

forecasted variations of the TSI in the future, can define and predict well in advance the direction and amplitude of the forthcoming climate changes. If the TSI increases over long time scales, the annual mean change in the Earth-atmosphere enthalpy proves to be positive (E>0); conversely if the TSI decreases over long time scales, this change is negative (E<0). As a result, the planet will gradually warm up or cool down respectively. The formula for the increment of the Earth's effective temperature due to the increments of the TSI and Bond albedo can be obtained from:

$$\Delta T_{ef} = [\Delta S_{\odot}(1 - A - \Delta A) - \Delta A S_{\odot}]/(16\sigma T^3_{ef}). \qquad (2)$$

The quasibicentennial changes in the TSI are relatively small (maximum value approximately to 6.3 Wm^{-2}, or less than 0.5% (from the latest reconstructed data *Shapiro A.I. et al. A new approach to the long-term reconstruction of the solar irradiance leads to large historical solar forcing. Astron. Astrophys. 2011; 529: A67*). However, the direct impact of changes in TSI on the observed global climate change will always be additionally (with some time-lag) further enhanced due to the secondary feedback effects: natural non-linear changes in global albedo of the Earth as a planet (additional changes of the TSI fraction being absorbed) and changes in the concentration of greenhouse gases in the atmosphere (water vapor as well as carbon dioxide and other gases) – additional variations of the greenhouse effect influence. The Bond albedo increases up to the maximum level during a deep cooling and decreases to the minimum in a warming, while the concentration of greenhouse gases in the atmosphere varies inversely since it depends mostly on the temperature of the World Ocean. Variations in the parameters of the Earth's surface and atmosphere, which are due to the quasi-bicentennial cyclic variations in the TSI, generate successive further changes in temperature due to multiple repetitions of such causal cycle of the secondary feedback effects, even if the TSI will subsequently remain unchanged over a certain period of time. Thus quasi-bicentennial variation of the TSI always leads to the unbalance of the annual average energy budget of the Earth-atmosphere system, while upcoming Grand minimum of the TSI leads to deficit of the annual average energy budget of the Earth and the Little Ice Age.

Since the early 1990s one has observed a decrease in both the TSI and hence the portion of energy absorbed by the Earth (Figure 1). Since the Sun is in the phase of decline of the quasi-bicentennial variation, an average annual decrease of the smoothed absolute value of TSI from the 22nd cycle to the 23rd and 24th cycles is increasing: an average annual decrease rate in the 22nd cycle was ~0.007 Wm^{-2}/yr, while in the 23rd cycle it already became ~0.02 Wm^{-2}/yr. The mean TSI was lower by ~0.15 Wm^{-2} in the 23rd cycle than in the 22nd cycle. The value of TSI at the minimum between 23rd and 24th cycles was lower by ~0.23 and ~0.30 Wm^{-2} than at the minimum between 22/23 and 21/22 cycles, respectively. The current increasing rate of an average annual TSI decline (with account for abrupt drop of its 11-year component) is almost 0.1 Wm^{-2}/yr (Figure 1) and will continue its increase in the 25th cycle. The observed trend of the increasing rate of an average annual decline in the absolute value of TSI allows us to suggest that this decline as a whole will correspond to the analogous TSI decline in the period of Maunder minimum according to its most reliable reconstruction (*Shapiro A.I. et al. A new approach to the long-term reconstruction of the solar irradiance leads to large historical solar forcing. Astron. Astrophys. 2011; 529: A67*). Let us note that the level of maximum of the 11-year component of TSI has decreased within five years of the 24th cycle by ~0.7 Wm^{-2} with respect to the maximum level of the 23rd cycle. The Earth as a planet will have also a negative

balance in the energy budget in the future, because the Sun has entered the decline phase of the quasibicentennial cycle of the TSI variations. This will lead to a drop in the temperature and to the beginning of the epoch of the Little Ice Age approximately after the maximum of solar cycle 24 since the year 2014. The increase in the Bond albedo and the decrease in the greenhouse gases concentration in the atmosphere by cooling will lead to an additional reduction of the absorbed solar energy and reduce the greenhouse effect influence. The influence of the consecutive chain of the secondary feedback effects will lead to additional drop in temperature, which can surpass the influence of the effect of the quasibicentennial TSI decrease. The start of Grand Maunder-type Minimum of the TSI of the quasibicentennial cycle is anticipated in solar cycle 27±1 about the year 2043±11 and the beginning of the phase of deep cooling of the 19th Little Ice Age in the past 7,500 years in the year 2060±11 (Figure 1, 2). Now we witness the transitional period from warming to deep cooling characterized by unstable climate changes when the global temperature will oscillate (approximately until 2014) around the maximum achieved in 1998-2005. These prognoses are confirmed by the Sun itself and the course of global temperature changes and the level of the World Ocean for the past 16 years.

In general, by analogy with the seasons on Earth there is also a similar alternation of climatic conditions in the Solar System, dictated by the quasi-bicentennial cycle variation of the TSI. From this point of view, now the whole of our Solar System after season of the "solar summer" is moving to the season of the "solar autumn" and then will move to the season of the "solar winter" of the quasibicentennial solar cycle. There is simultaneous warming on the Earth, Mars and the whole Solar System. Which has a natural solar origin and confirms the action of "solar summer" throughout the Solar system and alternation of climate conditions in it.

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The content of greenhouse gases in the atmosphere largely depends on the World Ocean, and the content of dust depends on volcanic activity and on the rise of aerosols from land. The amounts of natural flows (carbon dioxide, water vapour, and dust) from the Ocean and land to the atmosphere (M_{in}) and from the atmosphere (M_{out}) to the Ocean and land exceed many times the anthropogenic discharges of these substances into the atmosphere (M_{ant}) (*Nigmatulin R.I. The Ocean: climate, resources, and natural disasters. Herald of the Russian Academy of Sciences. 2010; 80(4): 338-349*). The overall content of carbon dioxide in the Ocean is 50 times

higher than in the atmosphere, and even a weak "breath" of the Ocean can change dramatically the carbon dioxide level in the atmosphere. Natural causes play the most important role in climate variations rather than human activity since natural factors are substantially more powerful. Antarctic ice cores provide clear evidence of a close coupling between variations of temperature and the atmospheric concentration of carbon dioxide during the glacial/interglacial cycles of at least the past 800-thousand years. Analysis of ice cores shows that the concentration of carbon dioxide in the atmosphere follows the rise temperatures very closely and lagged warmings by 800±400 years. During the glacial/interglacial cycles the peaks of carbon dioxide concentration have never preceded the warmings. Therefore there is no evidence that carbon dioxide is a major factor in the warming of the Earth now. Considerable changes of the atmospheric concentration of carbon dioxide always determined by corresponding temperature fluctuations of the World Ocean.

Thus, the quasi-bicentennial variations of the TSI (allowing for their direct and secondary impacts, with the latter being due to the secondary feedback effects) are the major and essential cause of climate changes. The Sun is the main factor controlling the climatic system and even non-significant long-term TSI variations may have serious consequences for the climate of the Earth and other planets of the Solar system. Quasi-bicentennial solar cycles are the key to understanding cyclic changes in both the nature and the society. The sign and value of the energy imbalance in the Earth-atmosphere system over a long time span (excess of incoming TSI accumulated by the Ocean, or its deficiency) determine a corresponding change of the energy state of the system and, hence, a forthcoming climate variation and its amplitude. That is why the Earth's climate will change every 200±70 years; and it is the result of bicentennial cyclic TSI variation. The observed long-term decline of TSI and forthcoming deep cooling will, first of all, essentially affect climate-dependent natural resources and, hence, influence, in the first place, economic closely connected with state of the climate. The most reasonable way to fight against the coming Little Ice Age is a complex of special steps aimed at support of economic growth and energy-saving production in order to adapt mankind to forthcoming period of deep cooling which will last approximately until the beginning of the XXII century. Early understanding of reality of the forthcoming global cooling and physical mechanisms responsible for it directly determines a choice of adequate and reliable measures which will allow the mankind, in particular, population of countries situated far from the equator, to adapt to the future global cooling.

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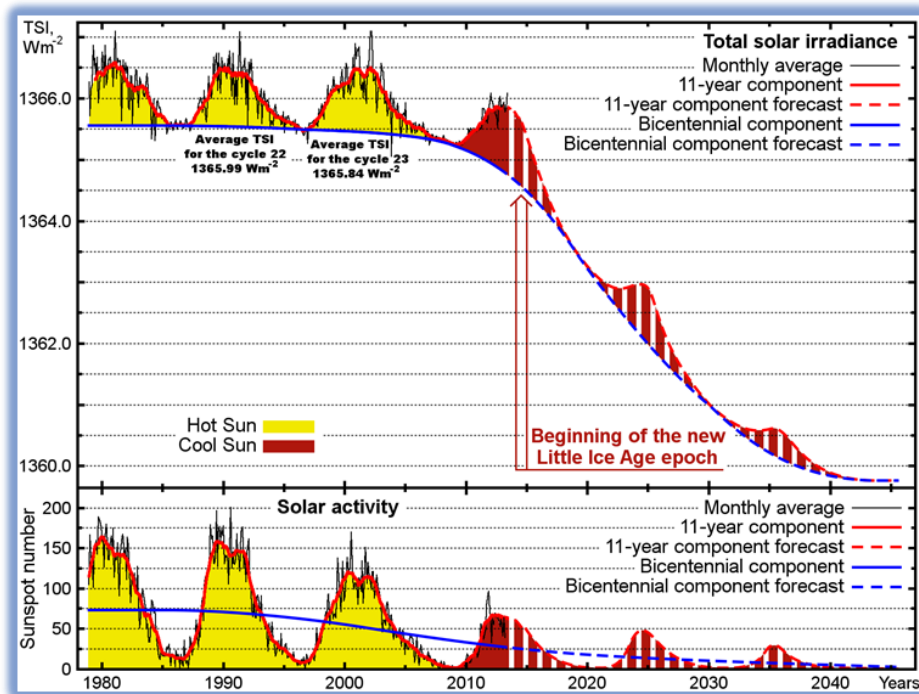
Figure 1. Variations of both the TSI and solar activity in 1978-2013 and prognoses of these variations to cycles 24-27 until 2045. The arrow indicates the beginning of the new Little Ice Age epoch after the maximum of cycle 24.
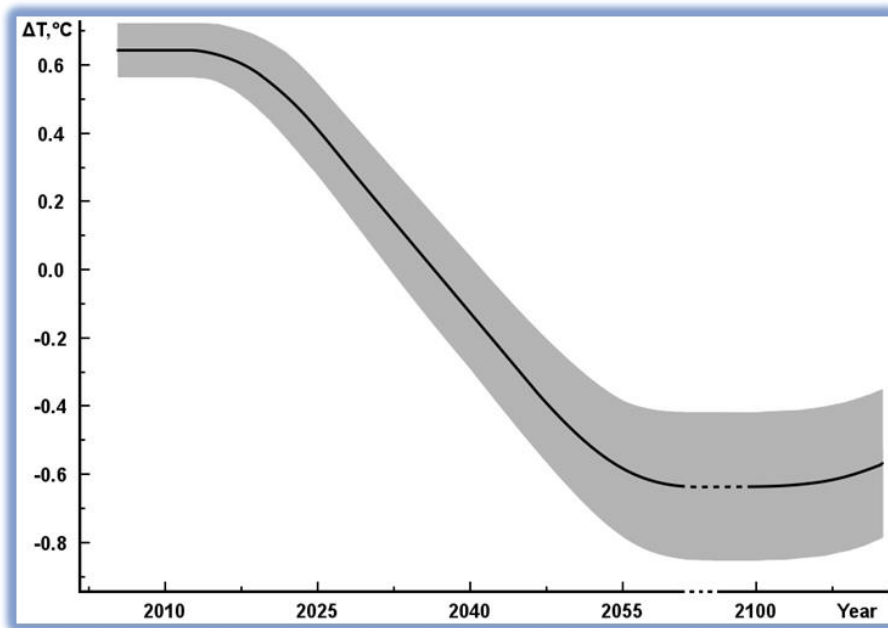

Figure 2. The prognosis of natural climate changes for the next hundred years.

*Cover photo of view from underwater looking up at the sun
provided by Microsoft.*

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