IPCC underestimates the Sun's role in Climate Change

Bas van Geel[1], Peter A. Ziegler†[2]

Reprinted from Energy & Environment, Vol. 24, No. 3 & 4, 2013, pp. 431–453. We highly appreciate permission for reproduction.

Abstract

For the understanding of current and future climate change it is a basic pre requisite to properly understand the mechanisms, which controlled climate change after the Last Ice Age. According to the IPCC 5th assessment report the Sun has not been a major driver of climate change during the post-Little Ice Age slow warming, and particularly not during the last 40 years. This statement requires critical review as the IPCC neglects strong paleo-climatologic evidence for the high sensitivity of the climate system to changes in solar activity. This high climate sensitivity is not alone due to variations in total solar irradiance-related direct solar forcing, but also due to additional, so-called indirect solar forcings. These include solar-related chemical-based UV irradiance-related variations in stratospheric temperatures and galactic cosmic ray-related changes in cloud cover and surface temperatures, as well as ocean oscillations, such as the Pacific Decadal Oscillation and the North Atlantic Oscillation that significant affect the climate. As it is still difficult to quantify the relative contribution of combined direct and indirect solar forcing and of increased atmospheric CO_2 concentrations to the slow warming of the last 40 years, predictions about future global warming based exclusively on anthropogenic CO_2 emission scenarios are premature. Nevertheless, the cyclical temperature increase of the 20th century coincided with the buildup and culmination of the Grand Solar Maximum that commenced in 1924 and ended in 2008. The anticipated phase of declining solar activity of the coming decades will be a welcome «natural laboratory» to clarify and quantify the present and future role of solar variation in climate change.

[1] Institute for Biodiversity and Ecosystem Dynamics, University of Amsterdam, Science Park 904, P.O. Box 94248, 1090 GE Amsterdam, The Netherlands [B.vanGeel@uva.nl]

[2] formerly at Geological-Paleontological Institute, University of Basel, Bernoullistrasse 32, CH-4056 Basel, Switzerland

1 Introduction

Future climate change, whether cooling or warming, will probably have considerable consequences for sea level, food production, world economy, biodiversity and health. The natural climate system varies on long as well as on short time-scales, neither of which is properly understood. How much of the 20th century warming was induced by natural, rather than by anthropogenic forcing remains a major open and hotly debated question. In order to explain global warming during the last century it is necessary to understand the contribution of natural processes and particularly of solar forcing to climate change and its retention time, versus that of the so-called enhanced greenhouse effect, commonly referred to as Anthropogenic Global Warming. In addition to historical documents recording weather and climate change observations, nature itself provides valuable information stored in various archives, such as the ice sheets of Greenland and Antarctic, lacustrine and marine sediments, peat deposits and tree rings. Based on so-called paleodata (climate proxy data) an increasingly clear picture of past climate changes is emerging, though we are still a long way from understanding all processes involved. Any primary cause of climate change may trigger a chain of secondary reactions, some of which amplify the primary change. The problem is to identify all relevant processes and to quantify their climate forcing factors, including numerous interlinked components of the climate system in the atmosphere, biosphere, cryosphere and hydrosphere.

This paper discusses: (1) one of the most abrupt solar-forced climate changes since the end of the Last Ice Age (ca. 11,500 years ago) that occurred between the Minoan and Roman warm times, around 850 years BC; (2) general evidence for significant solar forcing of climate change after the Last Ice Age and during the Modern Warm Period; (3) IPCC views on the very minor climate forcing role of the Sun that contradict evidence discussed in (1) and (2).

2 A Late Holocene Climate Change - the 850 BC Cooling Event

Climate changes during Holocene times (11,500 years ago to present) can be reconstructed in temperate zones, such as NW-Europe, on the base of the natural archives provided by peat sequences which formed in rainwater-fed raised bogs (wetlands). In peat deposits plant remains can be readily identified. Using information on the ecological habitat of peat forming plant species permits to assess vegetation changes in temporal peat sample sequences, which can be interpreted in terms of local hydrological changes in response to climate changes. The degree of decomposition of peat-forming plants is also related to climatic conditions: more decomposed peat is formed under drier conditions, and well preserved plant remains represent periods of wetter conditions.

Based on the analysis of Scandinavian peat profiles, Blytt and Sernander [1] subdivided the Holocene into alternating periods interpreted as representing relatively dry and warm, respectively cool and wet climatic conditions. Later this subdivision appeared to be too simplistic, although the so-called Subboreal-Subatlantic transition of the Blytt-Sernander scheme, that occurred around 850 BC, is still recognized as an abrupt and intense global climate change. Peat profiles of NW-Europe document that this climatic crisis involved a rapid change from relatively dry and warm to cool, wetter conditions that can be attributed to a major decline in solar activity [2, 3]. After 850 BC increased windiness persisted for about 200 years [4].

2.1 Radiocarbon, the Sun and climate change

The radiocarbon (^{14}C) method is commonly used for dating Holocene climate-induced shifts as recorded in peat deposits and lacustrine sediments. Radiocarbon delivers, however, more than only the possibility of dating organic material. Past changes in the atmospheric radiocarbon level are a proxy for solar activity and there are strong links between ^{14}C fluctuations and climate shifts. The period between 850 BC and 760 BC is characterized by a steep increase in the atmospheric radiocarbon content (arrow in fig. 1) and corresponds in temperate zones to an extremely cool and wet period [2, 3, 4, 5, 6].

In order to further explain the link between variations in past solar activity and climate change, some aspects of the production and decay of the radioactive carbon isotope ^{14}C need to be discussed. The carbon isotope ^{14}C is produced in the upper layers of the troposphere and the stratosphere by spallation of nitrogen atoms with thermal ions derived from cosmic rays. Therefore ^{14}C is referred to as a cosmogenic isotope. The intensity of the cosmic ray flux reaching the Earth depends on the strength of the solar interplanetary magnetic field, the solar wind, a proton-electron gas emitted by the Sun, and the geomagnetic field, which together shield the Earth from galactic cosmic rays (GCR). As the flux of GCR reaching the Earth anti-correlates with solar activity, it is a proxy for solar activity. When formed by the action of GCR, ^{14}C is oxidized to $^{14}CO_2$, becomes part of the carbon cycle and is taken up by plants and animals. When these die, their carbon uptake ceases and the decay of radiocarbon with a half-life of 5730 ± 40 years commences and thus can be used for dating purposes. Radiocarbon ages are expressed in years BP (Before Present) as radiocarbon «years» relative to 1950 AD. Radiocarbon «years» differ from calendar years because through time the production of ^{14}C is not constant, mainly due to changes in the intensity of solar activity and the GCR flux. The ^{14}C scale is calibrated to a calendar time scale by measuring the ^{14}C content of tree rings, which can be exactly dated by means of dendrochronology.

Past fluctuations in solar activity caused the so-called «wiggles» of the ^{14}C calibration curve. Closely spaced sequences of ^{14}C dates obtained from peat deposits display wiggles that can be correlated with the wiggles of the radiocarbon calibration curve. The method of dating peat sequences using ^{14}C «wiggle-match dating» has greatly improved the precision of radiocarbon chronologies [7] since it was first applied by van Geel and Mook [8]. By now, high precision calendar age chronologies can be obtained by ^{14}C wiggle-matching of peat sequences that show evidence for temporary increases in mire surface wetness during the early Holocene, at the Subboreal/Subatlantic transition and during the Little Ice Age (1650–1850), which coincided with periods of suddenly increasing atmospheric ^{14}C production, reflecting low solar activity. Peat records showing such phenomena are available from the Netherlands [3, 9, 10], the Czech Republic [11], the UK and Denmark [12]. Since production of radiocarbon is regulated by solar activity, periods of increased mire surface wetness have been interpreted as evidence for solar forced climate change (effects of sharply declining solar activity). In ice cores, variations in the occurrence of the cosmogenic radioisotope ^{10}Be, which has a half-life of ± 1.36 million years [13], provide an independent record of changes in solar activity that reaches back into the Pleistocene.

2.2 Evidence for solar-forced climate change over longer time spans

Magny [14, 15, 16] published a long record of Holocene climate-related water table changes for lakes in southeastern France

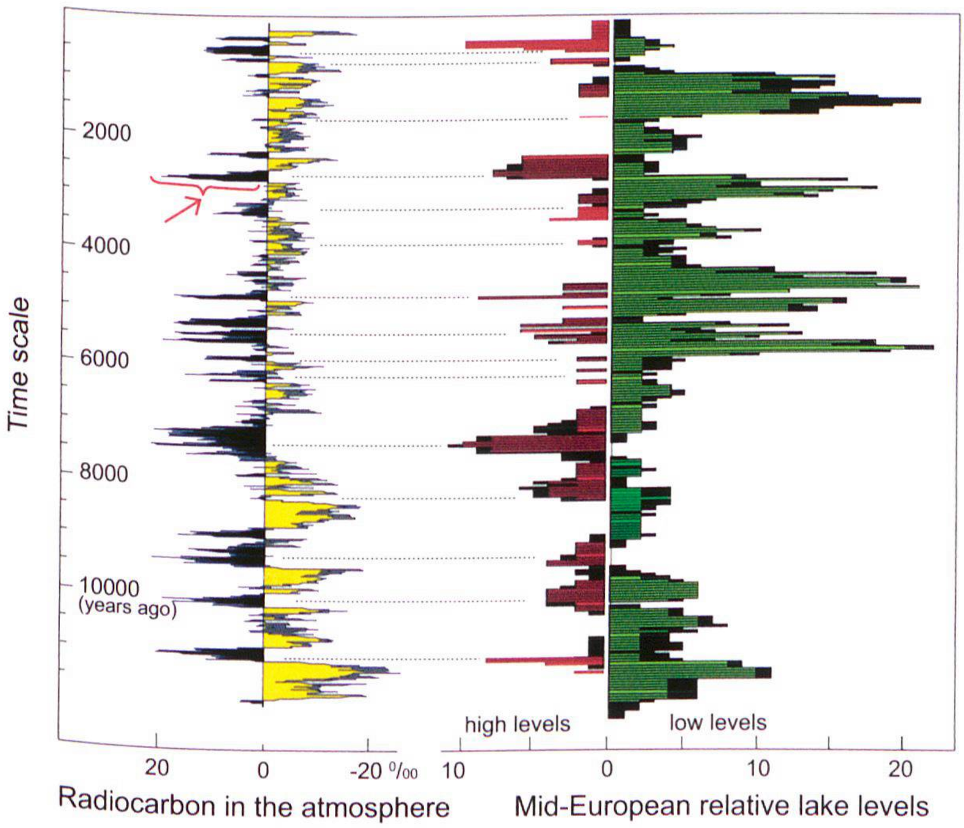

Fig. 1: Mid-European lake level changes and atmospheric radioarbon fluctuations during the last 11,500 years (after Magny 2007) [16]. Periods of low solar activity (high radiocarbon values) are linked with high lake levels, while low lake levels occurred during periods of high solar activity (low radiocarbon values). The arrow points to the 850 BC event.

and adjacent Switzerland (fig. 1). Lake level fluctuations correspond closely to atmospheric ^{14}C fluctuations with low lake levels occurring during periods of high solar activity and low atmospheric ^{14}C, while high lake levels correspond to periods of low solar activity and high atmospheric ^{14}C. Moreover, there is increasing evidence for solar climate forcing coming from studies of marine sediments, stalagmites and ice cores. Bond et al. [17] showed that in the North Atlantic ice-rafted debris was transported further southward during periods of relatively low solar activity. The temporal correlation of fluctuations in the cosmogenic isotopes ^{14}C and ^{10}Be and ice rafted debris points to a dominant control of North Atlantic climate changes by variations in solar activity. Sejrup et al. [18] provided evidence for solar forcing of the Norwegian Sea temperature during the last millennium. Neff et al. [19] studying the climate archive of stalagmites in Oman, showed that their oxygen isotope record can be interpreted as a proxy for fluctuations in monsoonal rainfall and is linked to the delta ^{14}C record, thus suggesting that changing monsoon intensity was driven by changes in solar activity. Marchitto et al. [20] recorded a response of the tropical Pacific Ocean to solar forcing during the early Holocene. Muscheler et al. [21] compared fluctuations of ^{14}C and ^{10}Be with oxygen isotope changes in ice cores of Greenland and showed that early Holocene climate shifts – as reflected by the oxygen isotope record – correlate with changes in the production of the cosmogenic isotopes and thus with changes in solar activity. Haltia-Hovi et al. [22] established a link between variations in solar activity and the spacing of annual laminae of lacustrine sediments in Finland. In the same vein Kokfelt and Muscheler [23] concluded from lake sediments in northern Sweden that the Sun was an important climate driver during the last 1000 years and that summer precipitation may have been affected by variations in solar activity. Holzhauser et al. [24] compared glacier and lake level fluctuations in west-central Europe during the last 3500 years and found that advances of glaciers, periods of higher lake levels and fluctuations in atmospheric ^{14}C were synchronous. Moreover, the record of lake sediments and peat deposits yields evidence for the relationship between solar forced changes to cooler, wetter climatic conditions and the economy of prehistoric people. In a special issue of Quaternary International [25], several papers give further support to the concept that climatic conditions had a strong impact on the cultural developments of human societies [26, 27, 28]. Sirocko et al. [29] showed that freezing of the river Rhine during strong winters of the last 230 years coincided with temporary minima in solar activity. Based on climate proxy data, there is increasing evidence that variations in solar irradiance are a very important driving force of climate variations not only at longer but also at short time scales. Van Geel et al. [30], Beer and van Geel [31] and Engels and van Geel [32] presented overviews of solar forced climate shifts based on paleo-data. For an up to date overview of peer-reviewed papers addressing solar forcing of climate change readers are referred to http://chrono.qub.ac.uk/blaauw/ («Club de Soleil»).

2.3 Socio-Economic effects of the 850 BC cooling event

The solar-forced climate deterioration around 850 BC was one of the most intense and abrupt climate changes during the second half of the Holocene. It had a strong socio- economic impact in areas that were already marginal from a hydrological point of view (high ground water table). In the northern Netherlands increased rainfall and lower temperatures caused a sudden rise of the ground water table that transformed arable land to wetland, fostering the growth of peat. Farming communities living in such areas were forced to migrate because they could no longer subsist on local food production [2]. One of the best examples of the impact of this climate shift comes from West-Friesland in the northern Netherlands, which was inhabited by Bronze Age farmers between ca. 1600 and 800 BC. Extensive archeological investigations on settlement sites, including detailed archeobotanical and archeozoological studies, yielded information on husbandry and environment. Between about 850 and 800 BC, people adapted to the suddenly increasing wetness of the region by building their houses on dwelling mounds. Around 800 BC the area had become so wet that no further adaptation was possible. The loss of cultivated land in West-Friesland and in many other parts of the northern Netherlands forced farming communities to move to the newly emerging salt marsh area along the northern coast of the Netherlands. Van Geel et al. [2] postulated that this change to a cooler climate caused a stagnation of the Holocene sea level rise in response to thermal contraction of the upper layer of the ocean and/or a reduced velocity and pressure on the coast by the Gulf Stream. For the first time extensive salt marshes developed, providing a new habitat for the farmers, who had lost their arable land and homesteads owing to a rising water table. In the Alpine domain the climate shift around 850 BC marked the beginning of major glacier advances, culminating around 600 BC [24].

In south-central Siberia archeological evidence suggests that after 850 BC the population density and cultural development of the nomadic Scythian population increased. Pollen studies showed a decline of xerophytic taxa, while tree birches and moisture demanding Cyperaceae replaced shrub birches. Van Geel et al. [33] suggested that this vegetation change reflects an abrupt climatic shift towards increased humidity owing to an equator-ward displacement of mid-latitude storm tracks. Areas that initially were hostile semi-deserts changed into attractive steppes with a high biomass production and carrying capacity. These newly available steppes provided an ideal habitat for herbivores, making them very attractive to nomadic tribes. The Central Asian equestrian Scythian culture expanded, and an increasing population density stimulated westward migration towards southeastern Europe.

The climate shift of about 850 BC was apparently of a worldwide nature. For instance, massive glacier advances in the south-central Andes of Chile were probably induced by an equator-ward shift of mid-latitude storm tracks, as also indicated for the northern hemisphere [5]. There is also strong evidence for a climate change around 850 BC in the Central African rain forest belt [3]. Pollen studies point to a drastic change in the vegetation cover (from rain forest to a more open savannah landscape) reflecting an aridity crisis. This climate and vegetation change induced Bantu farmers to migrate from the south into the Central African rainforests. Moreover, a dryness crisis in northwest India [6] speaks for a period of weak monsoons after the climate shift of 850 BC.

This change to dryness in central West Africa and India, and the contemporary increase of precipitation in temperate zones is compatible with the hypothesis that – after a decline in solar activity – there was a decrease in the latitudinal extent of the Hadley Cell circulation, probably slowing down the monsoon, while the mid-latitude storm tracks of the temperate zones were enhanced and shifted equator-ward [34].

Evidence from paleo-data indicates that in some areas the climate shift of 850 BC had a positive effect on cultural and economic development, such as for the Scythian culture and Bantu farmers whilst in other areas, such as the northern Netherlands, it was a severe crisis that triggered migration and new technological and cultural developments [31, 35].

3 Direct Solar Forcing and Amplifications Mechanisms

The Sun has since long been recognized as the dominant driver of the Earth's climate. The amount of solar energy reaching the Earth varies with the Earth's orbit around the Sun, as well as with the activity of the Sun that changes over time scales from minutes to millennia.

Satellite-based direct measurements of the Total Solar Irradiance (TSI) and Solar Spectral Irradiance (SSI) are only available since 1978. For pre-space age times, TSI estimates are derived from various proxies, such as the number of sunspots (since 1610), the solar open magnetic field (since 1963), the galactic cosmic ray flux (neutron monitor data since 1964) and the density of the cosmic isotopes ^{14}C in tree rings and ^{10}Be in ice and deep-sea sediment cores [13, 36, 37, 38, 39]. Since TSI estimates based on proxies are relatively poorly constrained, they vary considerably between authors, such as Wang et al. [40] and Hoyt and Schatten [41]. There is also considerable disagreement in the interpretation of satellite-derived TSI data between the ACRIM and PMOD groups [42, 43]. Assessment of the Sun's role in climate change depends largely on which model is adopted for the evolution of TSI during the last 100 years [44, 45, 46].

The ACRIM TSI satellite composite shows that during the last 30 years TSI averaged at 1361 Wm^{-2}, varied during solar cycles 21 to 23 by about 0.9 Wm^{-2}, had increased by 0.45 Wm^{-2} during cycle 21 to 22 to decline again during cycle 23 and the current cycle 24 [47]. By contrast, the PMOD TSI satellite composite suggests for the last 30 years an average TSI of 1366, varying between 1365.2 and 1367.0 Wm^{-2} that declined steadily since 1980 by 0.3 Wm^{-2}. On centennial and longer time scales, differences between TSI estimates become increasingly larger. Wang et al. [40] and Kopp and Lean [48] estimate that between 1900 and 1960 TSI increased by about 0.5 Wm^{-2} and thereafter remained essentially stable, whilst Hoyt and Schatten [41] combined with the ACRIM data and suggest that TSI increased between 1900 and 2000 by about 3 Wm^{-2} and was subject to major fluctuations in 1950–1980 [46, 49]. Similarly, it is variably estimated that during the Maunder Solar Minimum (1645–1715) of the Little Ice Age TSI may have been only 1.25 Wm^{-2} lower than at present [40, 50, 51, 52] or by as much as 6 ± 3 Wm^{-2} lower than at present [39,41], reflecting a TSI increase ranging between 0.09% and 0.5%, respectively (fig. 2).

If a small centennial-scale TSI fluctuation [40, 52] is assumed, the cyclical increase in global surface temperatures of about 1.1 °C between the Maunder Minimum of the Little Ice Age and the Modern Warm Period cannot be fully explained. Indeed, TSI- related direct solar forcing is thought to account for only about 40% of this temperature increase [36, 50, 53]. Therefore, a substantial amplification of TSI-related direct solar climate forcing is required to explain the post-Maunder temperature increase that culminated in the late 1990s and early 2000s towards the end of the uniquely long-lived Grand Modern Solar Maximum that apparently had commenced in 1924 and ended in 2008 [39, 54, 55].

Similarly, strong paleo-evidence for solar forcing of Holocene climate changes, involving temperature fluctuations of 1–2 °C [18, 56], requires powerful amplification effects if small TSI fluctuations of around 2 Wm^{-2} are assumed [13, 37, 48], though considerably less if TSI fluctuations of up to 10 Wm^{-2} as proposed by Shapiro et al. [39] are considered.

Since climate forcing by anthropogenic CO_2 emissions, as postulated by the IPCC, can be excluded for pre-industrial times, three mechanisms of indirect solar climate forcing, amplifying direct solar climate forcing, have been proposed; these probably play an important role also in recent climate fluctuations: 1) changes in solar UV radiation-related stratospheric ozone production underlying changes in atmospheric circulation, 2) the cosmic ray control on cloud formation and Albedo, and 3) solar and lunar tidal forcing of oceanic and atmospheric oscillations (PDO: Pacific Decadal Oscillation; AMO: Atlantic Multidecadal Oscillation; North Atlantic/Arctic Oscillation (NAO/AO).

3.1 Solar UV radiation, stratospheric ozone and atmospheric circulation

Solar radiation variability is strongly wavelength-dependent, with higher variability in the UV domain. Moreover, variations in UV radiation and TSI are not fully synchronized. Measurements show that during on average 11-year solar cycles variations in UV radiation are with 2–6% considerably larger than those of TSI (about 0.1%). Therefore, similar and probably even larger discrepancies between TSI and UV radiation than the observed variations may have occurred during longer time frames [39, 51, 52, 57].

Variations in UV radiation affect particularly the stratosphere in which UV-C radiation is totally and UV-B partially absorbed by oxygen molecules, producing ozone, causing warming of the stratosphere and affecting its dynamics [52, 58, 59]. As the warm stratosphere emits infrared radiation it can warm the much colder upper troposphere [50, 57]. Moreover, as the stratosphere and troposphere are dynamically coupled across the temperature inversion of the tropopause, warmer stratospheric air masses can be inserted into the troposphere at the polar jet front [60] (fig. 3). By this mechanism, variations in UV radiation, ozone production and the stratospheric temperature may have a direct bearing on the Earth's climate.

A chemical-atmospheric model indicates that during the peak of solar cycles a 1% increase in UV radiation causes a 1–2% increase of the stratospheric ozone concentration [58, 59]. Moreover, satellite measurements suggest that during the maximum of solar cycles the temperature of the upper stratosphere (40–50 km) increases by about 1 K [50, 61]. Climate models indicate that warming of the stratosphere, particularly in low latitudes where the incidence of solar irradiation is nearly vertical, strengthens stratospheric winds while the tropospheric jet streams are displaced pole-ward. Since the position of the jets determines the latitudinal extent of the Hadley Cell circulation, their pole-ward shift

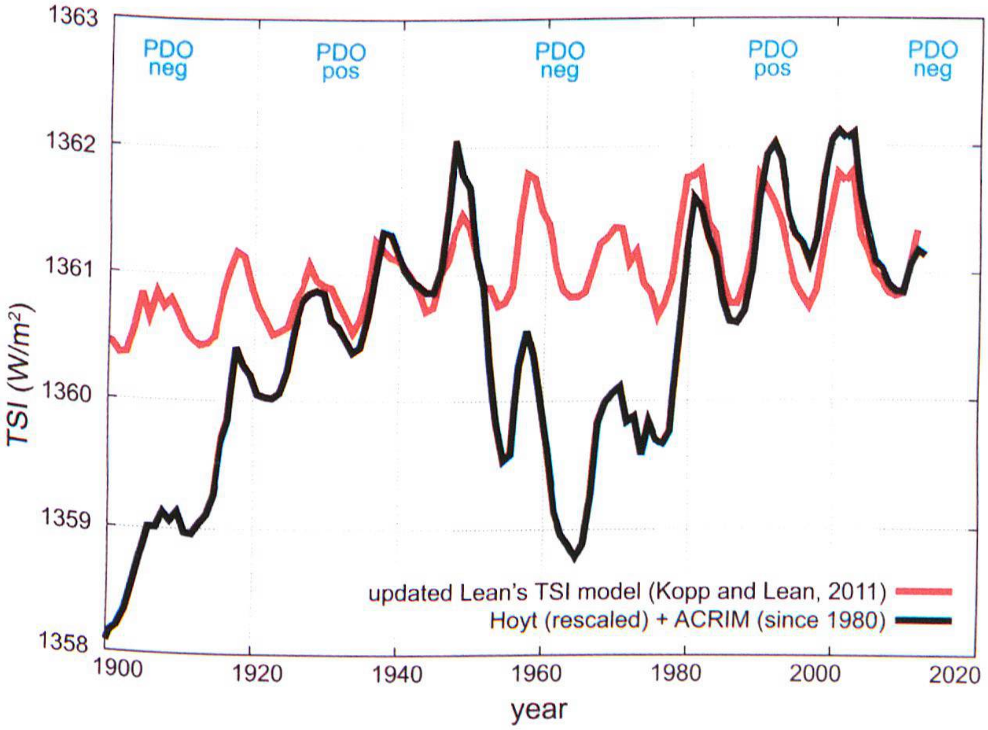

Fig. 2: Phases of the Pacific Decadal Oscillation compared with the TSI reconstruction by Hoyt & Schatten - ACRIM and the TSI reconstruction by Kopp and Lean, 2011-PMOD, as used by the GCMs (modified after Scafetta 2013) [46].

causes also a pole-ward displacement of the mid-latitude storm tracks [50, 61]. This concept is compatible with the results of a coupled atmosphere-ocean general circulation model and marine sediment core data, which indicate that solar-induced stratospheric ozone variations strongly influence mid-latitude troposphere dynamics [62].

Since with decreasing solar UV-irradiance and an increasing GCR flux the ozone content of the stratosphere decreases [51, 63], the stratosphere begins to cool and, by cooling the upper troposphere, affects the climate. Prolonged low solar UV-irradiance may therefore foster climate deterioration in the northern hemisphere and an increase in extreme weather events due to greater temperature differences between the oceans and the upper atmosphere [64].

The climate deterioration that occurred around 850 BC involved not only a decrease in TSI and but also an increase in the GCR flux, as indicated by the observed strong increase in atmospheric ^{14}C and ^{10}Be. Simultaneously a decline of solar UV irradiance caused a decrease in stratospheric ozone concentrations and a cooling of the lower stratosphere. Consequently the latitudinal extent of the Hadley Cell circulation decreased and mid-latitude storm tracks were displaced equator-ward [3].

3.2 Solar activity, Galactic Cosmic Ray flux, cloud cover and Albedo

TSI and the open solar magnetic flux (solar wind) anti-correlate with the GCR flux, which varies by up to 20% during the 11-year solar cycles [51]. According to Dickinson [65], Pudovkin and Raspopov [66], and Raspopov et al. [67], ionization of the troposphere by GCR positively affects aerosol formation and thus cloud- nucleation. Svensmark and Friis-Christensen found support for this potentially important indirect solar climate-forcing mechanism [68].

Clouds play a very important role in the Earth's energy budget by (a) impeding solar

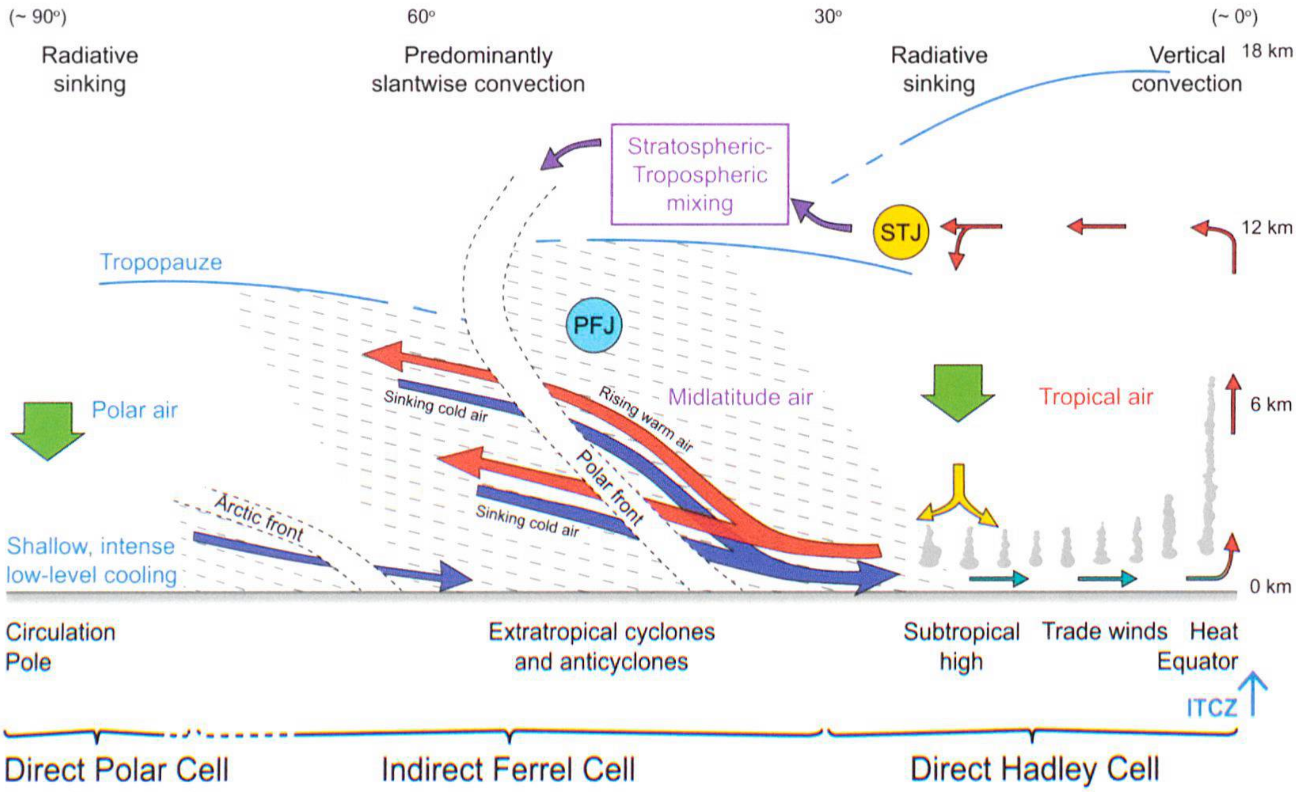

Fig. 3: Troposphere-Stratosphere interaction after Geerts and Linacre (1997) [60]. http://www-das.uwyo.edu/~geerts/cwx/notes/chap01/tropo.html Abbreviations: PFJ: Polar Front Jet, STJ: Sub-Tropical Jet, ITCZ: Inter-Tropical Convergence Zone.

shortwave radiation from reaching the Earth's surface (cooling effect), (b) reflecting solar shortwave radiation back to space (cooling effect), and (c) impeding long-wave infrared radiation emanating from the Earth's surface to escape to space and reflecting it back to the surface (warming effect) [69]. By contrast to IPCC models [70], observations show, however, that the cooling effect of clouds exceeds considerably their warming effect [71, 72]. The cooling effect of clouds is furthermore documented by a statistical analysis of global cloud cover versus global surface air temperatures, which indicate that a 1% increase in cloud cover corresponds to a 0.07 °C decrease in surface temperatures (http://www.climate4you.com/ClimateAndClouds.htm#LowCloudCoverVersusGlobalSurfaceTemperature).

Based on satellite records Marsh and Svensmark [73, 74] and Svensmark et al. [75] established a close correlation between variations of the GCR flux and the global low cloud cover during 1984 to 2006, spanning solar cycles 21 to 23. Laken et al. [76] confirmed their findings. The CLOUD experiment of CERN shows how cosmic rays promote the formation of clusters of molecules («particles») that in the real atmosphere can grow and seed clouds [77, 78], thus confirming the results of the Danish National Space Institute experiment on the cloud/cosmic ray relationship [79].

Measurements show that between 1964 and the 1990s the total magnetic flux leaving the Sun (solar wind) increased by a factor of 1.4 (fig. 4) with surrogate measurements indicating that it increased since the Little Ice Age by 350%, while the GCR flux decreased by about 50% to reach a low in the 1990s [13, 80, 81]. Earthshine data show that the Earth's Albedo, reflecting changes in cloud-cover, decreased between 1985 and 2000 by almost 10% and thereafter remained stable [82, 83]. The observed decrease in Albedo (cloud cover) and the GCR flux (see Oulu Cosmic Ray Station http://cosmicrays.oulu.fi/) is compatible with the concept of the GCR/cloud relationship and its contribution to the 20th century warming.

At geological time scales variations in the GCR flux are an order of magnitude greater than those caused by changes in the solar magnetic flux and solar wind in response to variations in solar activity, owing to the solar system passing through spiral arms of the Milky Way galaxy. This is compatible with the proxy record of tropical sea-surface temperatures, glacial deposits and meteorites of the last 520 million years [84, 85, 86].

The concept of «more GCR, more clouds and cooling, respectively less GCR, less clouds and warming» is, however, still hotly disputed since the observed variability in low cloud cover correlates equally well with the GCR flux, TSI and solar UV irradiances and thus should not be ascribed to a single mechanism [51, 87, 88].

3.3 Solar forcing of Pacific Decadal Oscillation (PDO)

The PDO, with a cyclicity of about 60 years, is characterized by two different oceanic and atmospheric circulation patterns that alternate every 20–30 years and give rise to changes in areas of warm and cold surface waters [89]. During positive PDO phases, TSI-induced warming of global surface temperatures is enhanced, while during negative PDO phases TSI-induced warming is dampened up to net cooling. El Niños are more frequent and stronger during positive PDO phases while La Niñas are more frequent and stronger during the negative PDO phases, indicating interaction between the essentially independent PDO and ENSO phenomena. The PDO, which affects the entire Pacific Ocean, is essentially in phase with the Atlantic Multidecadal Oscillation (AMO) but leads it by 10–15 years. On the other hand, the phase of the North Atlantic/Arctic Oscillation (NAO/AO) ante-correlates with the phase of the AMO and the PDO [90, 91, 92]. The PDO, partly reinforced by the AMO, involves large-scale variations in atmospheric and oceanic flow patterns and sea surface temperatures, which, in combination with TSI fluctuations (fig. 2), apparently influence global surface temperatures (fig. 5).

The warming and cooling trends of the 20th century global surface temperature curve closely coincide with positive, respectively negative phases of the PDO. The cooling phase of 1882–1914 reflects a negative PDO phase; 1914–1947 warming coincided with a positive PDO phase; slight cooling between 1947 and the late 1970s coincided with a negative PDO phase; subsequent warming coincided with a positive PDO phase; around 2005 the PDO switched again to a negative phase, contributing to the recent stagnation and slow decrease of surface temperatures (fig. 5).

The driving mechanism of the PDO may be of an astronomical-physical type, involving gravitational interaction of Jupiter and Saturn with the Sun that affects solar activity as well as the Earth's rotation rate [49, 93, 94, 95, 96]. Moreover, multidecadal repeating patterns in the soli-lunar tidal dynamics may also be important in regulating ocean oscillations because, when in alignment with the Moon, the Sun adds an extra 46% to the Moon's gravitational «pull» on Earth. The gravitational interaction of the Sun and its planets with the Earth is strongest when Venus, Mars and Jupiter are halfway between perihelion and aphelion (line of nodes) and are in alignment with the Earth and Moon at line of nodes. This happens rarely, though various degrees of alignments occur approximately every 30–35 years. These cause greater than average changes in the Earth's rotational speed and a phase-change of the PDO [64, 96]. Under such a scenario a PDO-type effect may have contributed to the rapid climate deterioration around 850 BC that coincides with a marked decrease in TSI [13].

Based on global circulation models (GCMs), which assume only very small secular TSI variability simulating the Wang/Lean proxy model [38, 40, 48], the IPCC acknowledges that prior to the 1950s climate variations were controlled by the Sun but that since then anthropogenic CO_2 emissions must be held responsible for the increase in global surface temperatures. The GCMs adopted by the IPCC are based on the combined TSI models of Wang et al. [40] and the PMOD group [43], which do not reflect the 1882–1914, 1947–1977 and post-2005 PDO-related cooling phases. This implies that the PDO phenomenon cannot be related to TSI fluctuations and thus ought to be regarded as an internal climate oscillation of unknown

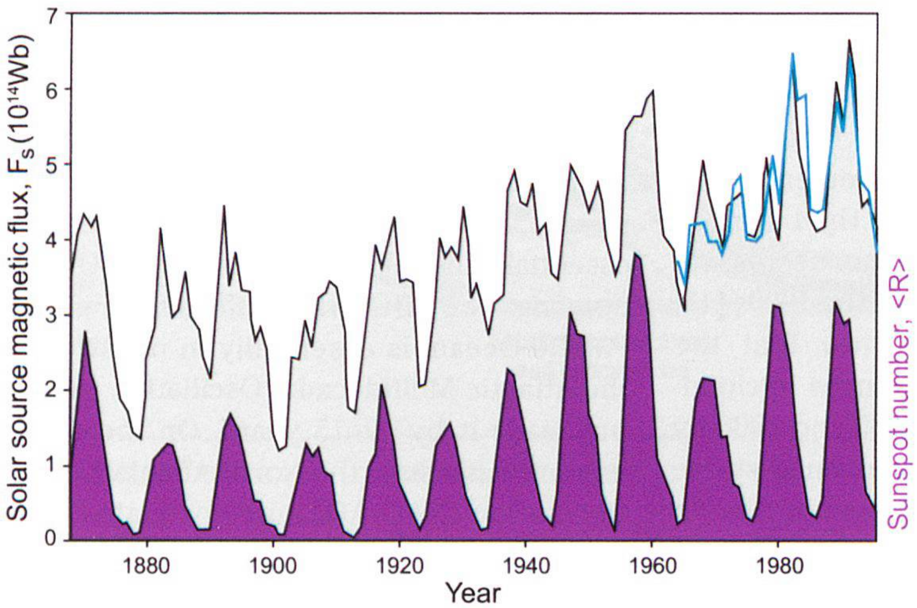

Fig. 4: Total solar magnetic flux derived from geomagnetic aa data for 1868–1996 (black line bounding grey shading) and from interplanetary observations for 1964–1996 (blue line). Variation of annual mean sunspot number (purple shaded area). The solar magnetic flux has increased by 40% since 1964 and by a factor of 2.3 since 1901 (after Lockwood et al., 1999) [81].

origin. On the other hand, the combined TSI models of Hoyt and Schatten [41] and the ACRIM team [42, 47] clearly indicate that these PDO-related cooling phases coincide with periods of decreased TSI [46] (fig. 2), suggesting that the PDO is dominated by variations in solar activity with changes in ocean currents playing a subordinate role in its climatic effects. As such, the PDO phenomenon would not qualify as an indirect solar forcing mechanism and therefore ought to be attributed to planetary-solar oscillations [46, 49, 94, 97].
Variations in solar activity, UV radiation and the GCR flux are genetically linked [51]. Decreasing/increasing UV radiation and an increasing/decreasing GCR flux reinforce each other's climatic effects by reducing/increasing the energy that reaches the Earth's surface and thus amplify the effect of the accompanying TSI changes. The response to such a change in the Earth's energy balance and rotation rate is a reorganization of the Earth's atmospheric and oceanic circulation systems, the climatic effects of which are overprinted by the PDO-AMO [46, 96].

4 Discussion and Conclusion

In Chapter 5 of the draft IPCC 5th Assessment Report the «Information from Paleoclimate Archives» gives a valuable overview of indications for climate change derived from the various paleoclimate archives. Essential information and an interpretation concerning the sensitivity of the climate system to

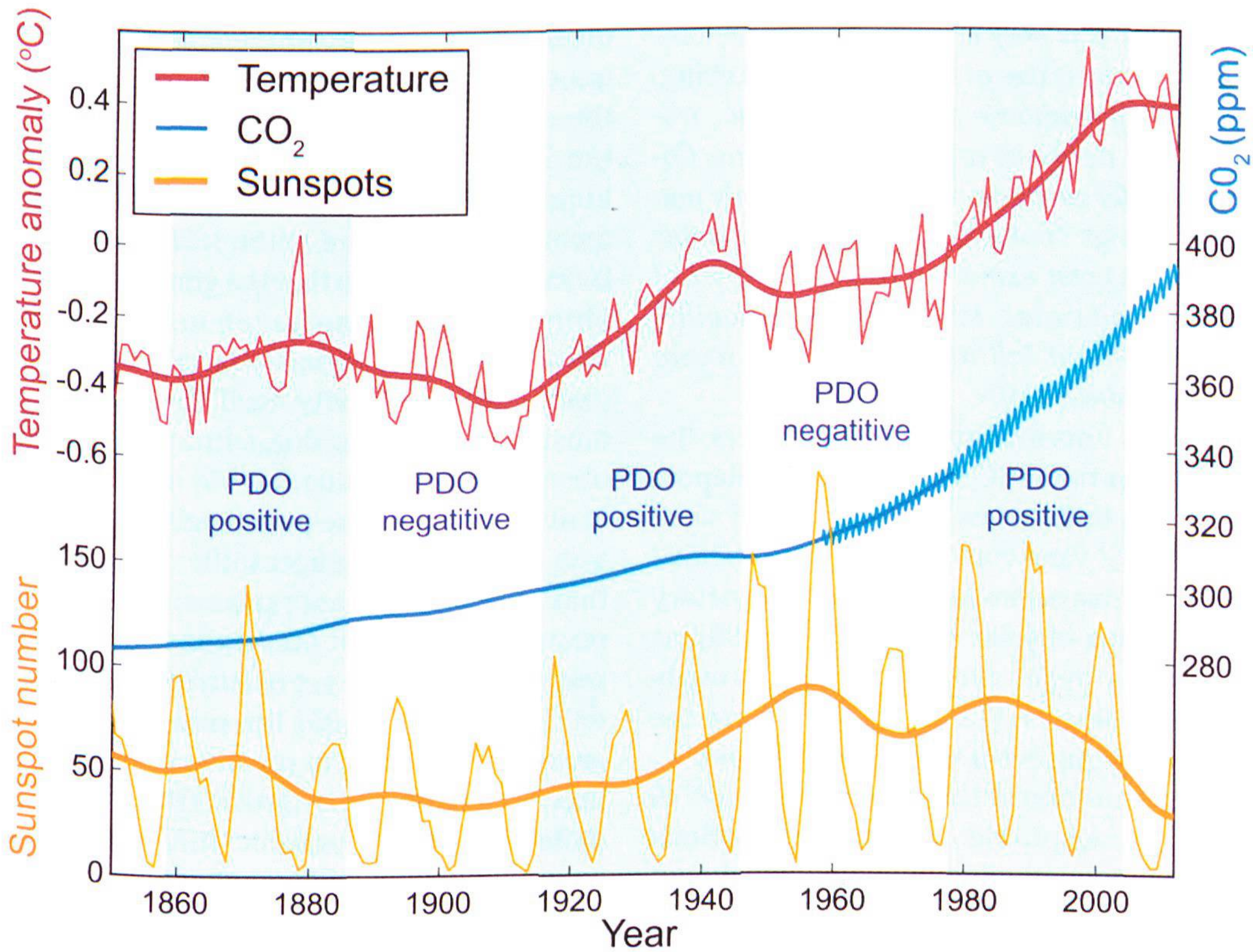

Fig. 5: Phases of Pacific Decadal Oscillation compared with global surface temperatures, atmospheric CO_2 concentrations (smooth line: Antarctic ice core data; serrated line: Mauna Loa observatory) and the sunspot number. Thick lines for temperatures and sunspots represent a 25 year moving average smoothing of the raw data. Modified after L. McInnes, 2009, http://en.wikipedia.org/wiki/Solar_variation.

relatively small changes in solar activity are, however, missing. The role of the Sun is presented in an answer to a Frequently Asked Question: «Is the Sun a major driver of climate changes?» The relevant part of the answer provided by the IPCC is quoted here: *«The Sun is not a major driver of the climate changes over the past 40 years because instrumental TSI and SSI records contain no significant trend; whereas records of global mean temperature and greenhouse gas concentrations contain significant trends of increasing values. This lack of agreement in trends demonstrates that the Sun did not play a role during this period.»*

In the draft of the IPCC Summary for Policymakers, CO_2 is mentioned as *«the strongest driver of climate change. Its relative contribution has further increased since the 1980s and by far outweighs the contributions from natural drivers. It is very likely that early 20th century warming is due in part to external forcing, including greenhouse gas concentrations, tropospheric aerosols, and solar variations. Climate model simulations that include only natural forcings (volcanic eruptions and solar variations) can explain a substantial part of the pre-industrial temperature variability since 1400 but fail to explain more recent warming since 1950».*

With this information to policymakers the authors of the IPCC 5th Assessment Report may soon find themselves disqualified since TSI and SSI vary considerably at centennial and millennia scales in response to planetary tidal forcing of solar activity [94, 98, 99], as evident by major climate changes throughout the Holocene [13, 37, 100]. Of these the 850 BC cooling event is just one example.

There is no doubt that during the past 40 years atmospheric CO_2 concentrations increased, partly owing to fossil fuel consumption. During the second half of the 20th century solar activity has, however, also reached a very high level [101], with TSI increasing considerably more than what the GCMs allow for [49,102]. Indeed, the long-lived Grand Modern Solar Maximum that had commenced in 1924, culminated in the second half of the 20th century in 2008 [55, 103, 104] involved TSI fluctuations of up to 3 Wm^{-2} [46]. Moreover, the GCMs conveniently overlook the fact that the 20th century temperature increase involved, apart from an important TSI increase, also an increase in solar UV radiation and a decrease in the GCR flux, as well as their fluctuation during the different PDO phases. In the 5th Assessment report of the IPCC, models assuming natural climate forcing only, indicate no temperature increase during the 20th century. By contrast, Holocene paleo-climatologic data indicate that the Earth's climate is very sensitive to even small fluctuations in solar radiation. In view of the observed TSI increase during the 20th century [46], it is therefore highly unlikely that temperatures would have remained stable during this time, provided greenhouse gas emissions had remained stable. Indeed, the observed cyclical temperature rise of the 20th century can be explained by the buildup of the modern Grand Solar Maximum that culminated in the 1990s and early 2000s. This suggests that the climate models of the IPCC, as presented in its 5th Assessment Report (high sensitivity to greenhouse gases, low sensitivity to TSI variations), must be erroneous due to neglect of the observed TSI variation.

In discussions on the postulated role of CO_2 as a climate-forcing agent it is often stated that the full temperature increase in response to current atmospheric CO_2 concentrations has not yet occurred. According to Hansen et al. [105] the planet is out of energy balance due to positive climate forcings. Hansen et al. estimate that owing to increasing anthropogenic emissions the time required for 60% of the equilibrium response (global warming) to be achieved is in the range of 25 to 50 years («warming in the pipeline»).

The postulated time lag between an initial disturbance of the climate system and the re-establishment of its energy balance is generally attributed to the thermal inertia of the oceans. However, since it is difficult to quantify the rate at which the warm upper ocean layers mix with the cooler deeper ones, climate lag estimates vary significantly. A delayed response of the climate system may be expected for all climate-forcing mechanisms. The fact that the observed temperature increase of the 20th century coincided with the Grand Modern Solar Maximum that involved not only an increase in TSI, but also an increase in solar UV irradiance and a decrease in the GCR flux, both of which amplify the effects of TSI, as well as the overprinting effects of the PDO, is inexplicably ignored by IPCC.

Climate change is a natural phenomenon; the climate has never been and will never be stable. To understand the extent of the human influence on climate, the causes of natural changes must be fully understood first. The IPCC, claiming to understand natural climate forcing factors, concludes that their contribution to climate change is minor, and asserts that only anthropogenic global warming forced by CO_2 emissions can explain the discrepancy between the observed global average surface temperature and GCMs that do not include CO_2 forcing. The IPCC dismisses the important role of the Sun in natural climate change as evidenced by the climate history and blames mankind for climate change without presenting convincing physical evidence that increasing atmospheric CO_2 concentrations are indeed the cause of global warming, a highly controversial subject [106, 107]. The important decline in solar activity that commenced with the end of the Grand Modern Solar Maximum in 2008 [55, 101, 104, 108, 109, 110, 111] will provide the opportunity to clarify the dispute about natural, directly and indirectly solar forced climate change and its relative importance to as yet unproven anthropogenic climate warming [112, 113].

Acknowledgement

The authors thank Nicola Scafetta, Madhav Khandekar and an anonymous reviewer for critical and constructive comments. Jan van Arkel kindly prepared illustrations.

References

1. Sernander, R., *Die schwedischen Torfmoore als Zeugen postglazialer Klimaschwankungen. Die Veränderungen des Klimas seit dem Maximum der Letzten Eiszeit*, Herausgegeben von dem Exekutivkomitee des 11. internationalen Geologenkongresses Stockholm, 1910, 197-246.
2. van Geel, B., Buurman, J. and Waterbolk, H. T., Archeological and paleoecological indications for an abrupt climate change in The Netherlands and evidence for climatological teleconnections around 2650 BP, *Journal of Quaternary Science*, 1996, 11, 451-460.
3. van Geel, B., van der Plicht, J., Kilian, M. R., Klaver, E. R., Kouwenberg, J. H. M., Renssen, H., Reynaud-Farrera I. and Waterbolk, H. T., The sharp rise of $\Delta^{14}C$ ca. 800 cal BC: possible causes, related climatic teleconnections and the impact on human environments, *Radiocarbon*, 1998, 40, 535-550.
4. Martin-Puertas, C., Matthes, K., Brauer, A., Muscheler, R., Hansen, F., Petrick, C., Aldahan, A., Possnert, G. and van Geel, B., Regional atmosferic circulation shifts induced by a grand solar minimum. *Nature Geoscience*, 2012, 5, 397-401.
5. van Geel, B., Heusser, C. J., Renssen, H. and Schuurmans, C. J. E., Climate change in Chile at around 2700 BP and global evidence for solar forcing: a hypothesis, *The Holocene*, 2000, 10, 659-664.
6. van Geel, B., Shinde, V. and Yasuda, Y., Solar forcing of climate change and a monsoon-related cultural shift in western India around 800 cal BC, in: Yasuda, Y. and V. Shinde, V., eds, *Monsoon and Civilization*, 2001, 35-39.
7. Blaauw, M., Heuvelink, G. B. M., Mauquoy, D., van der Plicht, J. and van Geel, B., A numerical approach to ^{14}C wiggle-match dating of organic deposits: best fits and confidence intervals, *Quaternary Science Reviews*, 2003, 22, 1485-1500.
8. van Geel, B. and Mook, W. G., High-resolution ^{14}C dating of organic deposits using natural atmospheric ^{14}C variations, *Radiocarbon*, 1989, 31, 151-156.
9. van der Plicht, J., van Geel, B., Bohncke, S. J. P., Bos, J. A. A., Blaauw, M., Speranza, A. O. M., Muscheler, R. and Björck, S., Early Holocene solar forcing of climate change in Europe, *Journal of Quaternary Science*, 2004, 19, 263-269.
10. Kilian, M. R., van der Plicht, J. and van Geel, B., Dating raised bogs: new aspects of AMS ^{14}C wiggle matching, a reservoir effect and climatic change, *Quaternary Science Reviews*, 1995, 14, 959-966.
11. Speranza, A., van Geel, B. and van der Plicht, J., Evidence for solar forcing of climate change at ca. 850 cal BC from a Czech peat sequence, *Global and Planetary Change*, 2002, 35, 51-65.
12. Mauquoy, D., van Geel, B., Blaauw, M. and van der Plicht, J., Evidence from northwest European bogs shows «Little Ice Age» climatic changes driven by variations in solar activity, *The Holocene*, 2002, 12, 1-6.
13. Steinhilber, F., Abreu, J. A., Beer, J., Brunner, I., Christl, M., Fischer, H., Heikkilä, U., Kubik, P. W., Mann, M., McCracken, K. G., Miller, H., Miyahara, H., Oerter, H. and Wilhelms, F., 9,400 years of cosmic radiation and solar activity from ice cores and tree rings, *PNAS*, 2012, 109(16), 5967-5971.
14. Magny, M., Solar influences on Holocene climatic changes illustrated by correlations between past lake level fluctuations and the atmospheric ^{14}C record, *Quaternary Research*, 1993, 40, 1-9.
15. Magny, M., Holocene climate variability as reflected by mid-European lake level fluctuations, and its probable impact on prehistoric human settlements, *Quaternary International*, 2004, 113, 65-79.
16. Magny, M., Lake level studies - West-Central Europe, in: *Encyclopedia of Quaternary Studies*, Vol. 2, Elsevier, Amsterdam, 2007, 1389-1399.
17. Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M. N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I. and Bonani, G., Persistent solar influence on North Atlantic climate during the Holocene, *Science*, 2001, 294, 2130-2136.
18. Sejrup, H. P., Lehman, S. J., Haflidason, H., Noone, D., Muscheler, R., Berstad, I. M. and Andrews, J. T., 2010. Response of Norwegian sea temperature to solar forcing since 1000 AD. *Journal of Geophysical Research*, 2010, 115, C12034.
19. Neff U., Burns S., Mangini A., Mudelsee M., Fleitmann D. and Matter A., Strong coherence between solar variability and the monsoon in Oman between 9 and 6 kyr ago, *Nature*, 2001, 411, 290-293.
20. Marchitto, T. M., Muscheler, R., Ortiz, J. D., Carriquiry, J. D. and van Geen, A., Dynamical response of the tropical Pacific Ocean to solar forcing during the Early Holocene, *Science*, 2010, 330, 1378-1381.
21. Muscheler, R., Beer, J. and Kubik, P. W., Long-term solar variability and climate change based on radionuclide data from ice cores, *Geophysical Monograph*, 2004, 141, 221-235.
22. Haltia-Hovi E., Saarinen T. and Kukkonen M., A 2000-year record of solar forcing on varved lake sediment in eastern Finland. *Quaternary Science Reviews*, 2007, 26, 678-689.
23. Kokfelt, U. and Muscheler, R., Solar forcing of climate during the last millennium recorded in lake sediments from northern Sweden. *The Holocene*, published online 18 October 2012, DOI: 10.1177/0959683612460781.

24. Holzhauser, H., Magny, M. and Zumbühl, H. J., Glacier and lake-level variations in west- central Europe over the last 3500 years, *The Holocene*, 2005, 15, 789-801.
25. Galop, D., Magny, M. and Guilaine, J., Rhythms and causalities of the anthropisation dynamics in Europe between 8500 and 2500 cal BP: socioocultural and/or climate assumptions, *Quaternary International*, 2009, 200, 1-3.
26. Magny, M., Peyron, O., Gauthier, E., Rouèche, Y., Bordon, A., Billaud, Y., Chapron, E., Marguet, A., Pétrequin, P. and Vanniére, B., Quantitative reconstruction of climatic variations during the Bronze and early Iron ages based on pollen and lake-level data in the NW Alps, France, *Quaternary International*, 2009, 200, 102-110.
27. Gauthier, E. and Richard, H., Bronze Age at Lake Bourget (NW Alps, France): vegetation, human impact and climate change, *Quaternary International*, 2009, 200, 111- 119.
28. López-Sáez, J. A., Blanco-González, A., López-Merino, L., Ruiz-Zapata, M. B., Dorado-Valiño, M., Pérez-Díaz, S., Valdeolmillos, A. and Burjachs, F., Landscape and climatic changes during the end of the Late Prehistory in the Amblés Valley (Ávila, central Spain), from 1200 to 400 cal BC, *Quaternary International*, 2009, 200, 90-101.
29. Sirocko, F., Brunck, H. and Pfahl, S., Solar influence on winter severity in central Europe. *Geophysical Research Letters*, 2012, 39, L16704, doi: 10.1029/2012GL052412.
30. van Geel, B., Raspopov, O. M., Renssen, H., van der Plicht, J., Dergachev, V. A. and Meijer, H. A. J., The role of solar forcing upon climate change, *Quaternary Science Reviews*, 1999, 18, 331-338.
31. Beer, J. and van Geel, B., Holocene climate change and the evidence for solar and other forcings, in: Battarbee, R. W. and Binney, H. A., eds, *Natural climate variability and global warming: a Holocene perspective*, Wiley-Blackwell, 2008, 138-162.
32. Engels, S. and van Geel, B., The effects of changing solar activity on climate: contributions from palaeoclimatological studies, *Journal of Space Weather and Space Climate*, 2012, 2, A09.
33. van Geel, B., Bokovenko, N. A., Burova, N. D., Chugunov, K. V., Dergachev, V. A., Dirksen, V. G., Kulkova, M., Nagler, A., Parzinger, H., van der Plicht, J., Vasiliev, S. S. and Zaitseva, G. I., Climate change and the expansion of the Scythian culture after 850 BC, a hypothesis. *Journal of Archaeological Science*, 2004, 31, 1735-1742.
34. van Geel, B. and Renssen, H., Abrupt climate change around 2,650 BP in North-West Europe: evidence for climatic teleconnections and a tentative explanation, in: Issar, A. S. and Brown, N., eds, *Water, Environment and Society in Times of Climatic Change*, Kluwer, Dordrecht, 1998, 21-41.
35. van Geel, B. and Berglund, B. E., A causal link between a climatic deterioration around 850 cal BC and a subsequent rise in human population density in NW-Europe?, *Terra Nostra*, 2000, 7, 126-130.
36. Beer, J., Mendel, W. and Stellmacher, R., The role of the sun in climate forcing. *Quaternary Science Reviews*, 2000, 19, 403-415.
37. Steinhilber, F., Beer, J. and Fröhlich, C., Total solar irradiance during the Holocene. *Geophysical Research Letters*, 2009, 36, L19704. doi:10.1029/2009GL04040142.
38. Lean, J., Cycles and trends in solar irradiance and climate, *Climate Change*, 2010, 1, 111-122.
39. Shapiro, A. I., Schmutz, W., Rozanov, E., Schoell, M., Shapiro, V. and Nyeki, S., A new approach to long-term reconstruction of the solar irradiance leads to larger historical solar forcing. Astronomy and Astrophysics, 2010, 529, A67.
40. Wang, Y. M., Lean, J. L. and Sheeley, N. R., Jr., Modeling the Sun's Magnetic Field and Irradiance since 1713. *The Astrophysical Journal*, 2005, 625 (1), 522-538.
41. Hoyt, D. V. and Schatten, K. H., The Role of the Sun in Climate Change. Oxford University Press, New York, 1997, pp 279.
42. Willson, R. C. and Mordvinov, A. V., Secular total solar irradiance trend during solar cycles 21-23. *Geophysical Research Letters*, 2003, 30, 5, 1199, doi:10.1029/2002GL016038.
43. Fröhlich, C., Observational evidence of a long-term trend in total solar irradiance. *Astronomy and Astrophysics*, 2009, 501(3): L27-L30.
44. Scafetta, N. and West, B. J., Phenomenological reconstructions of the solar signature in the Northern Hemisphere surface temperature records since 1600, *Journal of Geophysical Research*, 2007, 112, D24S03, doi:10.1029/2007JD008437.
45. Scafetta, N., Empirical analysis of the solar contribution to global mean air surface temperature change. *Journal of Atmospheric and Solar-Terrestrial Physics*, 2009, 71, 1916-1923.
46. Scafetta, N., Solar/planetary oscillation control on climate change: hind-cast, forecast and a comparison with the CMIP5 GCMs. In: Rörsch, A., Ziegler, P. A., (eds), Mechanisms of climate change and the AGW concept: a critical review. *Energy and Environment* (this volume).
47. Scafetta, N. and Willson, R. C., ACRIM-gap and TSI trend issue resolved using a surface magnetic flux TSI proxy model. *Geophysical Research Letters*, 2009, 36, L05701, doi:10.1029/2008GL036307.
48. Kopp, G. and Lean, J. L., A new, lower value of total solar irradiance: evidence and climate significance. *Geophysical Research Letters*, 2011, 38, L01706.

49. Scafetta, N., Testing an astronomically based decadal-scale empirical harmonic climate model versus the IPCC (2007) general circulation climate models. *Journal of Atmospheric and Solar-Terrestrial Physics*, 2012b, 80, 124-132.
50. Haig, J. D., The effect of Solar variability on the Earth's climate. *Philosophical Transactions Royal Society London A*, 2003, 361, 95-110.
51. Gray, L. J., Beer, J., Geller, M., Haigh, J. D., Lockwood, M., Matthes, K., Cubasch, U., Fleitmann, D., Harrison, G., Hood, L., Luterbacher, J., Meehl, G. A., Shindell, D., van Geel, B. and White, W., Solar Influence on Climate. *Reviews in Geophysics*, 2010, 48, RG4001, 53 pp., doi:10.1029/2009RG000282.
52. Krivova, N. A., Vieira, L. E. A. and Solanki, S. K., Reconstruction of solar spectral irradiance since the Maunder minimum, *Journal of Geophysical Research*, 2010, 115, A12112, doi:10.1029/2010JA015431.
53. de Jager, C., Duhau, S. and van Geel, B., Quantifying and specifying the solar influence on terrestrial surface temperature, *Journal of Atmospheric and Solar-Terrestrial Physics*, 2010, 72, 926-937.
54. Lockwood, M., Owens, M. J., Barnard, L., Davis, C. J. and Steinhilber, F., The persistence of solar activity indicators and the descent of the Sun into Maunder Minimum conditions. *Geophysical Research Letters* 38, 2011, L22105, doi: 10.1029/2011GL049811.
55. de Jager, C. and Duhau S., Sudden transitions and grand variations in the solar dynamo, past and future, *Journal of Space Weather and Space Climate*, 2012, 2, A07 DOI: 10.1051/swsc/2012008.
56. Renssen, H., Seppä, H., Heiri, O., Roche, D. M., Goosse, H. and Fichefet, T., The spatial and temporal complexity of the Holocene thermal maximum, *Nature Geoscience*, 2009, 2, 411-414.
57. Haig, J. D., Winning, A. R, Toumi, R. and Harder, J. W., An influence of solar spectral variations on radiative forcing of climate. *Nature*, 2010, 167, 696-699.
58. Haigh, J. D., The role of stratospheric ozone in modulating the solar radiative forcing of climate, *Nature*, 1994, 370, 544–546.
59. Haigh, J. D., The impact of solar variability on climate, *Science*, 1996, 272, 981-984.
60. Geerts, G. and Linacre, E., Climate and Weather explained, chapter 11: The height of the Troposphere, 1997, http://www-das.uwyo.edu/~geerts/cwx/notes/chap01/tropo.html.
61. Simpson, R., Blackburn, M and J. D. Haigh, J. D., The role of eddies in driving the tropospheric response to stratospheric heating perturbations. *Journal of the Atmospheric Sciences*, 2009, 66, 1347-1365.
62. Varma, V., Prange, M., Spangehl, T., Lamy, F. Cubasch, U. and Schulz, M., Impact of solar-induced stratospheric ozone decline on Southern Hemisphere westerlies during the Late Maunder Minimum, *Geophysical Research Letters*, 2012, 39, L20704, doi:10.1029/2012GL053403.
63. Lu, Q.-B., Correlation between cosmic rays an ozone depletion. *Physical Review Letters*, 2009, 102, 118501, 1-5.
64. Walker, B., Extra-terrestrial influences on nature's risks. Joint IACA, IAAHS and PBSS Colloquium in Hong Kong, 2012. http://www.actuaries.org/HongKong2012/Presentations/WBR9_Walker.pdf.
65. Dickinson, R. E., Solar variability and the lower atmosphere. *Bulletin of the American Meteorological Society*, 1975, 56, 1240-1248.
66. Pudovkin, M. I. and Raspopov, O. M., The mechanism of action of solar activity on the state of the lower atmosphere and meteorological parameters (a review). *Geomagnetism and Aeronomy*, 1992, 32, 593-608.
67. Raspopov, O. M., Shumilov, O. I., Kasatkina, E. A., Dergachev, V. A. and Creer, K. M., Impact of cosmic ray flux variations caused by changes in geomagnetic dipole moment on climate variability. *Russian Academy of Sciences IOFFE Physical-Technical Institute, Preprint 1693*, 1997, pp. 1–41.
68. Svensmark, H. and Friis-Christensen, E., Variation of cosmic ray flux and global cloud coverage – a missing link in solar-climate relationships, *Journal of Atmospheric and Solar-Terrestrial Physics*, 1997, 59, 1225-1232.
69. Trenberth, K. E., Fasullo, J. T. and Kiehl, J., Earth's Global Energy Budget. *Bulletin of the American Meteorological Society*, 2009, 90, 311–323.
70. Bony, S., Colman, R., Kattsov, V. M., Allan, R. P., Bretherton, C. S., Defresne, J.-L., Hall, A., Hallegatte, S., Holland, M. M., Ingram, W., Randall, D. A., Soden, B. J., Tselioudis, G. and Webb, M. J., How well do we understand and evaluate climate change feedback processes? *Journal of Climate*, 2006, 19, 3445-3482.
71. Gray, W. M. and Schwartz, B., The association of albedo and OLR radiation with variations of precipitation – Implications for AGW. Science and Public Policy Institute Reprint Series, March 2011.
72. Lindzen, R. S. and Choi, Y. S., On the observational determination of climate sensitivity and it is implications. Asia-Pacific Journal of Atmospheric Science, 2011, 47 (4), 377-390.
73. Marsh, N. and Svensmark, H., Cosmic rays, clouds and climate. *Space Science Reviews*, 2000, 94, 215-230.
74. Svensmark, H., Cosmoclimatology: a new theory emerges. *Astronomy and Geophysics*, Royal Astronomical Society, London, 2007, 48(1), 1.18-1.24.

75. Svensmark, H., Bondo, T. and Svensmark, J., Cosmic ray decreases affect atmospheric aerosols and clouds. *Geophysical Research Letters*, 2009, 36, L15101, doi 10.1029/2009GL038429.
76. Laken, B. A., Kniveton, D. B. and Frogley, M. R., Cosmic rays linked to rapid mid-latitude cloud change. *Atmospheric Chemistry and Physics*, 2010, 10, 10941-10948.
77. Kirkby, J., The Cloud Project: climate research with accelerators. Proceedings IPAC 10, Kyoto, Japan, 03 Special Presentation, 2010, 4774-4778.
78. Kirkby, J. et al., Role of sulphuric acid, ammonia and galactic cosmic rays in atmospheric aerosol nucleation. *Nature*, 2011, 476-433.
79. Enghoff, M. B., Pedersen, J. O. P., Uggerhøj, U. I., Paling, S. M. and Svensmark, H., Aerosol nucleation induced by a high energy particle beam, *Geophysical Research Letters*, 2011, 38, L09805, doi:10.1029/2011GL047036.
80. Beer, J., Baumgartner, S., Dittrich-Hannen, B., Hauenstein, J., Kubik, P., Lukasczyk, Ch., Mende, W., Stellmacher, R. and Suter, M., Solar variability traced by cosmogenic isotopes. in: Pap, J. M., Fröhlich, C., Hudson, H. S. and Solanki, S. K., eds., *The Sun as a variable star: solar and stellar irradiance variations*. Cambridge University Press, 1994, 291-300.
81. Lockwood, M., Stamper, R. and Wild, M. N., 1999. A doubling of the Sun's coronal magnetic field during the last 100 years. *Nature* 399, 437-439.
82. Pallé, E., Goode, P. R., Montañés-Rodriguez, P. and Koonin, S. E., Changes in Earth's reflectance over the past two decades, 2004, *Science*, 304, 1299-1301.
83. Pallé, E., Goode, P. R. and Montañés-Rodriguez, P., 2009. Interannual variations in Earth's reflectance 1999–2007. *Journal of Geophysical Research*, 2009, 114, D00D03, doi:10.1029/2008JD010734.
84. Shaviv N. J. and Veizer. J., Celestial driver of Phanerozoic climate. GSA Today July 2003.
85. Veizer, J., Celestial climate driver: a perspective from four billion years of the carbon cycle, *Geoscience Canada*, 2005, 32, 13-28.
86. Gies, D. R. and Helsel, J. W., Ice Age Epochs and the Sun's path through the Galaxy. *Astrophysical Journal*, 2005, 626, 844-848.
87. Agee, E. M., Kiefer, K. and Cornett, E., Relationship of lower-troposphere cloud cover and cosmic rays: an updated perspective. *Journal of Climate*, 2012, 25, 1057-1060.
88. Voiculescu, M. and Usoskin, I., Persistent solar signatures in cloud cover: spatial and temporal analysis. *Environment Research Letters*, 2012, 7, 1-11.
89. Mantua, N. J. and Hare, S. A., The Pacific Decadal Oscillation. *Journal of Oceanography*, 2002, 58 (1), 35-44.
90. d'Aleo, J. and Easterbrook, D., Multi-decadal tendencies in ENSO and global temperatures related to multi-decadal oscillations. *Energy & Environment*, 2010, 21 (5), 437-460.
91. Knudsen, M. F., Seidenkrantz, M.-S., Jacobsen, B. H. and Kuijper, A., Tracking the Atlantic Multidecadal Oscillation through the last 8,000 years, *Nature Communications*, 2011, February 2011.
92. Kodera, K., Solar influence on the spatial structure of the NAO during the winter 1900–1999, *Geophysical Research Letters*, 2003, 30, 4, doi:10.1029/2002GL016584.
93. Scaffetta, N., Empirical evidence for a celestial origin of the climate oscillations and its implications. *Journal of Atmospheric and Solar-Terrestrial Physics*, 2010, 80, 296-31.
94. Scafetta N., Multi-scale harmonic model for solar and climate cyclical variation throughout the Holocene based on Jupiter–Saturn tidal frequencies plus the 11-year solar dynamo cycle. *Journal of Atmospheric and Solar-Terrestrial Physics*, 2012a, 80, 296-311.
95. Wilson, I. R. G., Do Periodic Peaks in the Planetary Tidal Forces Acting Upon the Sun Influence the Sunspot Cycle? *General Science Journal*, 2011a, December 2011, 1-25.
96. Wilson, I. R. G., Are changes in the Earth's rotation rate externally driven and do they affect climate? *General Science Journal*, 2011b, December 2011, 1-31.
97. Soon, W., Variable solar irradiance as a plausible agent for multidecadal variations in the Arctic-wide surface air temperature record of the past 130 years. *Geophysical Research Letters*, 2005, 32, L16712.
98. Scafetta, N., Does the Sun work as a nuclear fusion amplifier of planetary tidal forcing? A proposal for a physical mechanism based on the mass-luminosity relation. *Journal of Atmospheric and Solar-Terrestrial Physics*, 2012c, 81–82, 27–40.
99. Abreu, J. A., Beer, J., Ferriz-Mas, A., McCracken, K. G. and Steinhilber, F., Is there a planetary influence on solar activity? *Astronomy and Astrophysics*, Volume 548, no. A88, December 2012. http://dx.doi.org/10.1051/0004-6361/201219997.
100. Schönwiese, C.-D., Klimaänderung: Daten, Analyse, Prognose. Springer Verlag, 1995.
101. Duhau, S., Solar dynamo transitions as drivers of sudden climate changes, in: B. R. Sing, ed., *Global Warming - Impacts and Future Perspectives*, INTECH Open Science/Open Minds, 2012, 185-204, http://dx.doi.org/10.5772/51814.
102. Soon, W. and Legate, D. R., Solar irradiance modulation of Equator-to-Pole (Arctic) temperature gradients: Empirical evidence for climate variation on multi-decadal timescales. *Journal of Atmospheric and Solar-Terrestrial Physics*, 2013, 93, 45-56.

103. Lockwood, M., Solar influence on global and regional climates, *Surveys in Geophysics*, 2012, 1-32. 10.1007/s10712-012-9181-3.
104. Clette, F. and Lefèvre, L., Are the sunspots really vanishing? Anomalies in solar cycle 23 and implications for long-term models and proxies, *Journal of Space Weather and Space Climate*, 2012, 2, A06, DOI: 10.1051/swsc/2012007.
105. Hansen, J., Nazarenko, L., Ruedy, R., Sato, M., Willis, J., Del Genio, A., Koch, D., Lacis, A., Lo, K., Menon, S., Novakov, T., Perlwitz, J., Russell, G., Schmidt, G. A. and Tausnev, N., Earth's energy imbalance: confirmation and implications, *Science*, 2005, 308 (5727), 1431-1435.
106. Clark, R., A coupled thermal reservoir description of surface temperature and climate. *Energy & Environment*, 2013, (this volume).
107. Priem, H. N. A., Climate Change and Carbon Dioxide: Geological Perspective, In: Rörsch, A., Ziegler, P. A., (eds.), Mechanisms of climate change and the AGW concept: a critical review. *Energy and Environment* (this volume).
108. Solheim, J.-E., Stordahl, K. and Humlum, O., The long sunspot cycle 23 predicts a significant temperature decrease in cycle 24. *Journal of Atmospheric and Solar-Terrestrial Physics*, 2012, 80, 267-284.
109. Abdussamatov, H. I., On long-term variations of the total irradiance and on probable changes of temperature in the Sun's core. *Kinematics and Physics of Celestial Bodies*, 2005, 21 (6), 471-477.
110. Abdussamatov, H. I., Bicentennial decrease of the Total Solar Irradiance leads to unbalanced thermal budget of the Earth and the Little Ice Age. *Applied Physics Research*, 2012, 4 (1), 178-184.
111. de Jager, C. and Duhau S., The variable solar dynamo and the forecast of solar activity; influence on terrestrial surface temperature, in: Cosia, J. M, Global warming in the 21th century, Nova Science Publishers, New York, 2011, 77-106.
112. Feulner, G. and Rahmstorf, S., On the effect of a new grand minimum of solar activity on the future climate on Earth, *Geophysical Research Letters*, 2010, 37, L05707, doi: 10.1029/2010GL042710.
113. Akasofu, S. I., On the recovery from the Little Ice Age, *Natural Science*, 2010, 2 (11), 1211-1224.