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Climate change and solar variability: What's new under the sun?

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Abstract

The Sun has an obvious effect on climate since its radiation is the main energy source for the outer envelopes of our planet. Nevertheless, there is a long-standing controversy on whether solar variability can significantly generate climate change, and how this might occur. This is a crucial issue not only in the field of paleoclimatology, but also for predicting the future of the Earth's climate, which will be subject to perturbations by anthropogenic greenhouse gases. Indeed, if climate changes due to the Sun were large and rapid, this would make it more difficult to extract the anthropogenic effects from precise records of instrumental data over the past century. Hence, Sun–climate relationships have never been so controversial as today, forming a debate that often escapes the scientific arena.

Here, we provide a review of this problem by considering changes on different time scales, from the last million years up to recent decades. In doing so, we also critically assess recent claims that the variability of the Sun has had a significant impact on global climate. The different studied records also illustrate the multi-disciplinary nature of this difficult problem, requiring knowledge in several fields such as astronomy and astrophysics, atmospheric dynamics and microphysics, isotope geochemistry and geochronology, as well as geophysics, paleoceanography and glaciology.

Overall, the role of solar activity in climate changes — such as the Quaternary glaciations or the present global warming — remains unproven and most probably represents a second-order effect. Although we still require even more and better data, the weight of evidence suggests that solar changes have contributed to small climate oscillations occurring on time scales of a few centuries, similar in type to the fluctuations classically described for the last millennium: The so-called Medieval Warm Period (900–1400 A.D.) followed on by the Little Ice Age (1500–1800 A.D.).

Keywords: solar activity; climate forcing; cosmogenic isotopes; geomagnetic field

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1. Introduction

Does the Sun have an influence on climate? This question may seem absurd in relation to our own star, which is at the origin of essentially all phenomena affecting the atmosphere and the ocean and whose output radiation represents the main source for the radiative budget of the Earth [1]. Nevertheless, it has been known for many centuries that the Sun is variable. The most obvious evidence for its variable activity is the occurrence and disappearance of sunspots. These solar features began to be studied in detail as soon as the first telescopes were developed. From 1610 onwards, astronomers were turning their instruments towards the Sun and were describing and counting sunspots. Harriot in

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England was the first to mention them in his notebooks. The following year, Fabricius in Germany was the first to actually publish his own observations and interpretations. In 1612 and 1613, Scheiner in Germany and Galileo in Italy became famous for their debate about the real nature of sunspots and their dispute over priority for the discovery.

Until the beginning of the 1980s, the relation between the Sun and climate change were still viewed with suspicion by the wider climate community and often remained a "taboo" subject in the solar astrophysics community. The main reason was a fundamental lack of knowledge about the causal link between the activity of the Sun and its irradiance, i.e. the amount of energy received per surface unit at the average distance between the Earth and the Sun. For many years, the energy radiated by the Sun was even assumed invariable. This led to the use of the term "solar constant", a concept formalized in 1838 by Pouillet [2] who first measured it in a quantitative manner.

Nevertheless, some authors doubted this assumed stability of the solar radiative output. Their arguments were based on apparent, but poorly explained, correlations between fluctuations of solar activity and atmospheric phenomena. One of these early pioneers was certainly de Mairan [3], who suggested a link between solar activity, based on the abundance of sunspots, and the frequency of aurorae observed at mid-latitudes (see the original plate in Fig. 1). de Mairan even described the concomitant decrease of both phenomena around 1645 and their subsequent increase around 1715. This seventy-year period of anomalous solar behavior was studied again more than a century later by Maunder [4] whose name would ultimately be associated with this period [5].

Herschel was another important pioneer in the study of solar-terrestrial relations [6]. Most famous for his discovery of the planet Uranus and the existence of infrared radiation, he also attempted to correlate the presence of sunspots with the price of wheat in England,

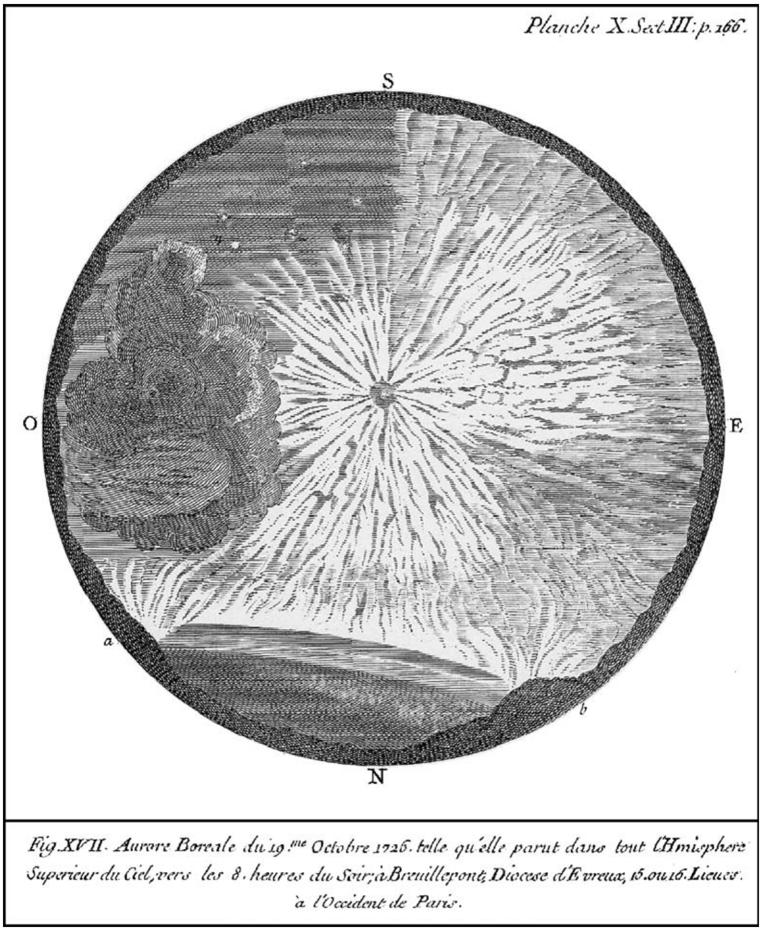

Fig. 1. Plate representing the Aurora Borealis seen in 1726 by De Mairan in the vicinity of Paris [3]. Naked-eye observations of aurorae at mid-latitudes can be used as a qualitative solar activity proxy back to the year 1500 [41].

which was ultimately linked to climate variability [6]. Following this early work, many studies reported similar apparent correlations, notably with Asian monsoon precipitations (e.g. [7,8] published more than a century ago and numerous subsequent papers). It is beyond the scope of our review to make an exhaustive list of these studies. Moreover, most of them remained elusive and qualitative on the actual physical processes generating the observed correlations.

Research on the mechanisms of solar effects on climate and their magnitude is currently benefiting from a tremendous renewal of interest. A large amount of high resolution data is now available from archives such as ice cores, speleothems, corals, marine and lacustrine sediments. However, the matter remains controversial because most of these records are influenced by other factors in addition to solar activity. Moreover, we still lack a fundamental understanding of all causal relationships between solar activity and climate.

We review here some of the more controversial issues, pointing out that this important field of climate research not only needs more reliable datasets, but also a deeper mechanistic understanding of the processes involved (see also Veizer [9] for a review with a different perspective). This is essential for reliable interpretations of the present or future impact of solar activity on global climate.

2. Has the warming observed during the past decades been partly linked to solar variability?

We can be certain of one thing: solar activity has varied on recent time scales. Evidence for these fluctuations is provided by the variation in the number of sunspots, which is following an 11-yr cycle (Fig. 2). Owing to measurements carried out by satellites, it is now clear that the “solar constant” also fluctuates on short time scales from weeks to years. The 11-yr cycle is characterized by a variation of about 0.1% in total solar irradiance (Fig. 3). Paradoxically, the irradiance increases with the number of sunspots: although spots darken the Sun’s surface, their effect is overcompensated by the faculae, which are more brilliant zones associated with the spots [10,11].

In addition, the irradiance variations are not spectrally homogeneous and the amplitude of the UV variability is, in relative terms, an order of magnitude larger than the variability of total solar irradiance [10,11]. This enhances stratospheric ozone formation through photochemical reactions [12,13] leading to further heating of the stratosphere through absorption of the excess UV radiation by

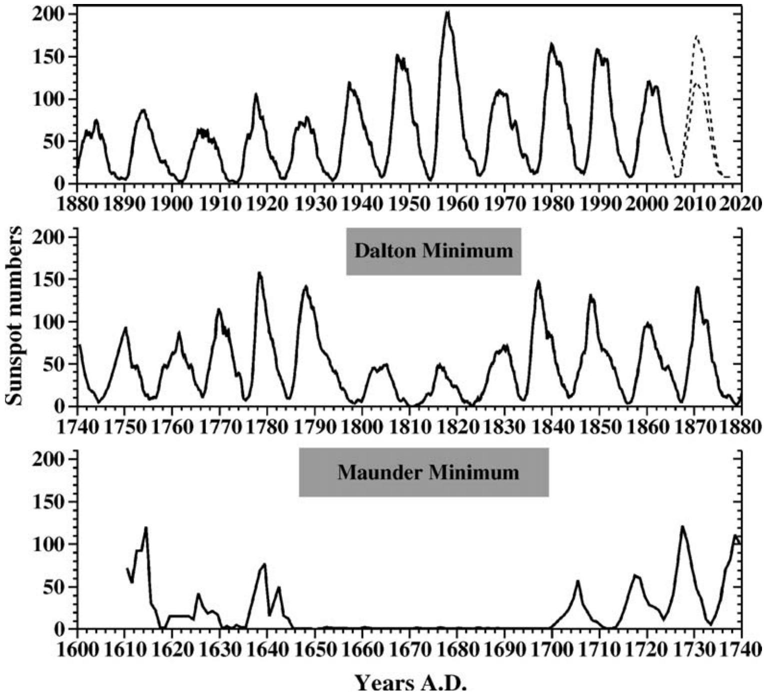

Fig. 2. Time series of the sunspot numbers since 1610. Since 1750 monthly averages have been available (reproduced from R.A.M. Van der Linden and the SIDC team, World Data Center for the Sunspot Index, Royal Observatory of Belgium, http://sidc.oma.be/html/sunspot.html). Beyond 1750, there are fewer observations and the displayed curve is based on yearly averages [5,30]. Previsions for solar cycle 24 are based on the 10.7 cm radio flux precursor technique [92] and a calibrated flux-transport dynamo model (upper curve from [93]).

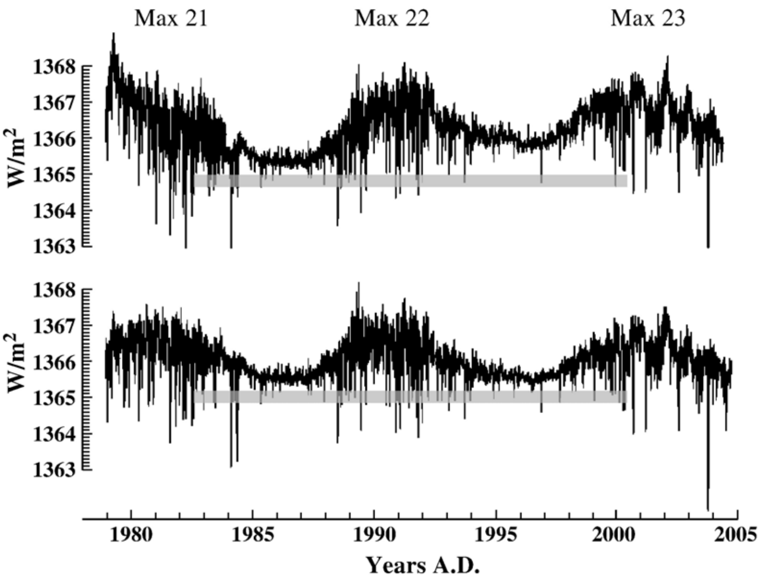

Fig. 3. Variations of solar irradiance recorded by satellites since 1978. These curves are compiled from raw measurements carried out by various instruments and do not cover all of the three cycles. Before compilation, the data are corrected for several factors, some of them being subject of debate. As a result, two groups arrive at somewhat different reconstructions: one [17], on the top panel, showing a slow increase in irradiance, and the other [18], on the bottom panel, without any long-term trend.

ozone. Modeling studies [14,15] indicate that this mechanism amplifies the global average warming due to the increase in irradiance by about 15–20%.

Several scientists have proposed that part of the global warming of about 0.8 °C since the mid 19th century has been related to a slow increase in solar irradiation from 1750 up to the present-day. According to Willson [16,17], solar irradiance also appears to have increased over the past 20 yrs. However, this trend is currently weakly constrained and subject to debate. To obtain a reliable estimate, we need to compare irradiance values obtained during the minima of the 11-yr solar cycle. This is because the activity maxima are characterized by a pronounced high-frequency variability related to the presence of numerous spots scattered across the face of the rotating Sun (Fig. 3). So far, the analysis of Willson is based solely on a comparison of the two minima of 1986 and 1997. We should also note that the various available databases are rather fragmentary and that they need to be homogenized and corrected for several biases, some of which are related to the deterioration of the sensors in space. Currently, there are essentially two reconstructions: one suggests an annual increase of 0.005% in irradiance since the mid 1980s [17], while another study indicates that there has been no long-term trend [18]. We will have to wait a few more years for the next minimum to be fully documented before being able to decide between these two interpretations.

According to another hypothesis, the warming of the last few decades could be an indirect effect of solar activity because the primary irradiance forcing is much too weak to cause major climatic changes. In particular, Svensmark and colleagues [19,20] have given new life to an old hypothesis about the influence of cosmic radiation on cloud formation [21]. This can be viewed as a rather simplistic analogue to the principle of the “cloud chamber”, a type of particle detector formerly used in physics. In this device, interactions between ionizing particles and gas molecules produce ions that serve as condensation nuclei along the trajectories of the particles.

The hypothesis put forward by Svensmark and colleagues depends on the magnetic field of the solar wind modulating the incoming cosmic rays: a minimum of activity of the Sun goes hand in hand with an increase in the cosmic radiation on Earth and would raise the number of condensation nuclei and ultimately increase cloud cover. This theory received a lot of attention in 1997 [19], when a positive correlation was first presented linking cloudiness with the intensity of cosmic radiation modulated by the Sun over the period 1984–1991.

It should be emphasized that the hypothesis is still very poorly quantified on several levels, such as the relationship between cosmic rays and clouds, as well as the temporal and spatial variations of the solar modulation [22]. Moreover, subsequent studies have failed to confirm the relationship [23,24]. Regional data from the United

States even appear to show an opposite correlation to that proposed by Svensmark [25]. Thus, despite the fact that the cosmic ray hypothesis stimulated numerous research initiatives in this field, it was premature to suggest it could possibly explain all global temperature variations between 1970 and 1990 [19]. Indeed, even the original correlation reported by Svensmark and colleagues did not show a long-term trend over several decades.

It also needs to be stressed here that the climatic impact of clouds depends strongly on their radiative properties, and thus also on their altitude. Indeed, the actual overall radiative effect of a cloud comprises the competing influences of its reflection properties, its absorption of visible and IR, and its emission of IR towards the Earth and into outer space. During periods of strong solar activity, the initially considered solar modulation should induce a reduction in high-altitude clouds at high latitudes. However, these high-altitude clouds actually have an overall tendency to warm the climate, rather than to cool it, as low-altitude clouds do. Therefore, the initial hypothesis does not appear to be compatible with the apparent correlation between solar activity and global warming.

The hypothesis was subsequently modified by the same group [26], who proposed a solar influence limited to low-altitude clouds. Indeed, variations in low cloud cover seem to match better with the solar fluctuations over the period between 1983 and 1995. Although these authors presented a number of working hypotheses, this new proposal seems somewhat paradoxical: We would expect a maximum solar effect in the upper parts of the atmosphere rather than in its lowest part, which contains abundant condensation nuclei. In addition, cosmic rays and low cloud cover have not remained correlated after 1995 [23]. Other sources of variability in cloudiness, such as volcanic aerosols and ENSO, could have obscured the signal over interannual and decadal time scales [27].

Pallé [28] recently performed a precise reanalysis of these correlations by considering spatial patterns in addition to temporal relationships. He concluded that the solar-like variability in low cloud cover might be an artifact induced by the satellite observing perspective. A possible explanation would be a redistribution of clouds at high-altitude, rather than changing amounts of clouds through cosmic ray forcing. Indeed, if there are any significant changes in the atmospheric circulation modulated by the irradiance (total and UV), one could expect them to change cloud cover as well. Therefore, even if a correlation between clouds and cosmic ray flux exists, it does not constitute a final proof for a direct causal relationship.

A major difficulty is that the noise, particularly in the cloud data, continues to obscure the identification of possible signals. Data for the next solar cycles will ultimately allow checking if there is any link between solar activity and cloudiness. For the moment, the exact mechanisms by which cosmic radiation and solar forcing may affect cloud formation remain very poorly understood and clearly require future research efforts [29].

3. Has solar forcing been the main cause of climate change over the past few centuries?

Prior to the last two decades, there are no direct and reliable measurements of solar irradiance. The main source of information on solar variability is provided by sunspot observations, which have become systematic from the 17th century onwards (see [5,30] for compilations of early studies). As shown on Fig. 2, the yearly average sunspot number displays a prominent 11-yr cyclicity. Minimum values are all similar and thus a simple linear correlation between sunspot number and total solar irradiance would not account for variations larger than 0.1% in the long-term. This is particularly important since the recent minima of the solar cycle and the Maunder Minimum are both characterized by a near absence of sunspots, which, following this simplistic rule, would result in the same irradiance.

Studies of the Sun [10] and of other solar-type stars [31,32] indicate that the magnetic activity is positively correlated with brightness. Using this linkage, it is possible to infer long-term trends of irradiance by taking account of the magnetic activity records. In particular, Lean et al. [10] explicitly proposed that the irradiance record is composed of two components: a slowly varying base line and an 11-yr cycle. This periodic component is calculated by modeling the darkening and brightening effects of sunspots and faculae, respectively [10]. These principles have led to reconstructions of the total solar irradiance based on the available sunspot observations [10,33]. Recently, Lean et al. [34] reassessed previous results and provided arguments suggesting that previous studies overestimated the variation of the base line, generally expressed by estimating the irradiance decrease during the Maunder Minimum.

Nevertheless, long-term changes have been identified in the record of geomagnetic perturbations [35], which have been linked to the magnetic field of the solar corona. The amplitude antipodal activity index (the so-called *aa* index), which goes back to the year 1868, exhibits an 11-yr cycle superimposed on a long-term background [36]. This latter component exhibits a distinct rise during the first half of the 20th century, a limited decrease during the 60s and 70s, followed by a re-increase until the end of the last century [36]. The overall shape of this curve is similar to the irradiance curves derived from sunspots [10,33]. Cliver et al. [36] also showed that the *aa* base line is broadly similar in shape to the global surface air temperature curve, suggesting that the Sun is responsible for part of the global warming. The *aa* index was further used in a quantitative manner to derive a time series of the solar magnetic flux, which exhibits more than a two-fold increase over the last century [37]. Lockwood et al. [37] further showed that this heliomagnetic increase was accompanied by a 0.1% increase of the total solar irradiance.

However, it has been shown that the original *aa* index is affected by instrumental problems and new proxies of geomagnetic activity were developed for investigating the long-term variability of the solar wind–magnetosphere system [38,39]. Mursula et al. [40] for example showed that the centennial increase in global geomagnetic activity was considerably smaller than depicted by the original *aa* index.

Other solar proxies shall be used for periods beyond the past few centuries covered with geomagnetic measurements and telescopic observations of sunspots. This is achieved by considering other effects of the solar magnetic field on Earth (as pictured in Fig. 4). Compilations of naked-eye observations of aurorae at mid-latitudes clearly show secular changes back to the year 1500, in particular the prominent solar minima found in the sunspot record [41]. However, the number and quality of observations decreases exponentially with age making it impossible to use this record to quantify changes of past solar activity.

As a proxy for the solar magnetic variability, we can use the high-frequency component of variations in the production of cosmogenic nuclides such as ^{14}C, ^{10}Be and ^{36}Cl. These cosmogenic nuclides are formed by the interaction of cosmic radiation (mainly galactic protons) with the molecules of the atmosphere and their production is modulated by the intensity of the magnetic field of the solar wind [42].

Geochemists measure the abundance of cosmogenic nuclides in natural archives such as polar ice (for ^{10}Be and ^{36}Cl), marine sediments (for ^{10}Be), or tree-rings and corals (for ^{14}C). Over the past four centuries, we find a clear link between the production rates of cosmogenic nuclides and solar activity, i.e. solar activity minima correspond to maxima in cosmogenic nuclide production [43,44]. After appropriate scaling, the variations of cosmogenic isotopes can be converted into irradiance fluctuations, which are in good agreement with estimates based on sunspot numbers (Fig. 5 from [45]).

However, cosmogenic nuclides are also subject to other processes until they are finally deposited in ice or sediments. These nuclides are mainly produced in the stratosphere, where production rates are maximal at high latitudes, but stratospheric residence times on the order of a year tend to homogenize them. The main exchange, however, between stratosphere and troposphere occurs at mid-latitudes. When combined with the effects of atmospheric transport and the hydrological cycle, this intense exchange is reflected by the mid-latitude

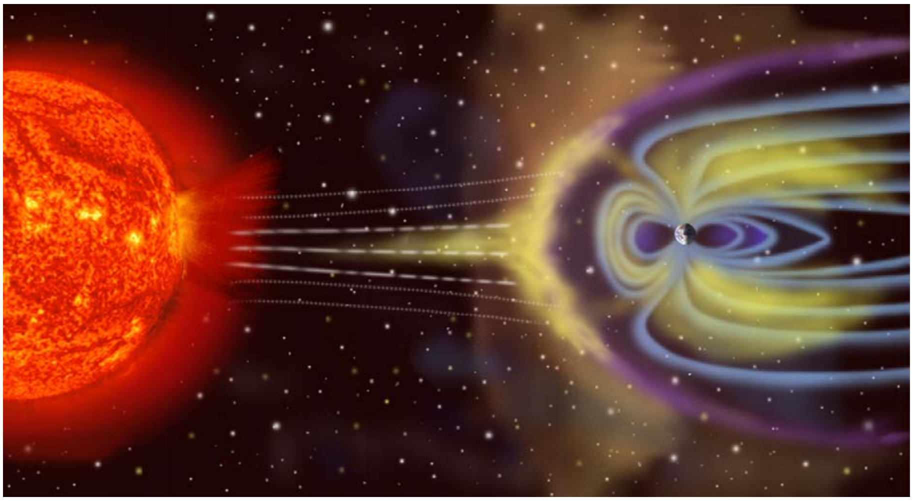

Fig. 4. Artistic view of the Sun–Earth system (NASA http://sec.gsfc.nasa.gov/popscise.jpg). Matter and energy stream radially from the Sun at high speed. The charged particles and the solar magnetic field, which constitute the solar wind, interact with the Earth and confine its magnetic field lines into an elongated cavity known as the magnetosphere (compressed on the day side due to the force of the arriving particles, and extended on the night side). Several phenomena observed on Earth are modulated by the magnetic properties of the solar wind: geomagnetic variability, aurorae and production of cosmogenic isotopes such as ^{14}C, ^{10}Be and ^{36}Cl.

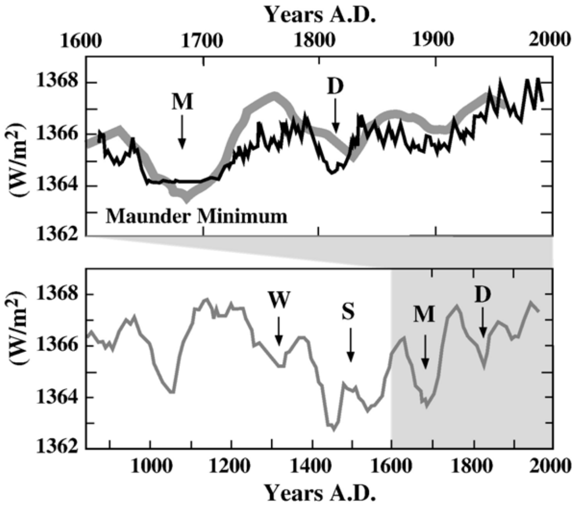

Fig. 5. Reconstructions of the total solar irradiance based on data related to the solar variability. The black line is based on sunspots [10] and the grey line on cosmogenic nuclides [45]. Letters correspond to solar activity minima named after pioneers in solar research (Dalton, Maunder, Spörer, Wolf).

maximum in ^{10}Be flux arriving at the Earth's surface [42,46,47] (Fig. 6). Hence, there are considerable uncertainties concerning records from single locations due to atmospheric transport and the relative efficiency of wet and dry deposition of ^{10}Be. These processes may have varied along with climate changes, which complicates the interpretations.

Overall, studies of cosmogenic isotopes indicate that solar minima have been numerous and that the Sun has spent much of the last millennium in calm phases, conceivably exhibiting an irradiance several ‰ weaker than at present. Solar fluctuations appear to have been involved in causing widespread climatic changes, such as the Medieval Warm Period (900–1400 A.D.) or the subsequent Little Ice Age (1500–1800 A.D.) [5,45,48].

Climate models give results for the solar forcing that are in line with their sensitivity to CO_2 increases. For a forcing corresponding to an activity minimum, the models indicate coolings of a few tenths of a degree [49]. However, these drops are not evenly distributed across regions, seasons and altitudes. Results from the GISS GCM indicate that intense cooling (1–2 °C) would be concentrated in Europe and North America, especially during winter, in a pattern resembling the low index state of the Arctic Oscillation/North Atlantic Oscillation [14]. In contrast, similar modeling performed with a GCM from the Hadley Centre suggests regional patterns different from that of the AO/NAO [15].

4. Was there any solar modulation of climate during the Holocene period?

Several authors have studied various archives to identify climate variability associated with changes in solar activity. Beyond the last millennium, the usual technique involves comparing the records of cosmogenic nuclides, mainly ^{14}C and ^{10}Be, with time series based on climate proxies measured in archives such as tree-rings, sediments or stalagmites.

The usefulness of these comparisons relies on the accuracy and precision of the time scales of the different records. The best chronological constraints are given by tree-rings that allow us to study ^{14}C production over the past twelve millennia [50]. The ^{10}Be content in polar ice cores is another proxy that can be used to track past solar changes [43,44,51,52]. Both ^{14}C and ^{10}Be records are tightly coupled, exhibiting prominent cycles, e.g. 90 and 210 yr, that are probably linked to intrinsic solar variations similar to the 11-yr sunspot cycle.

Bond et al. [53,54] followed by Hu et al. [55], proposed that variations of solar activity are responsible for quasi-periodic climatic and oceanographic fluctuations that follow cycles of about one to two millennia.

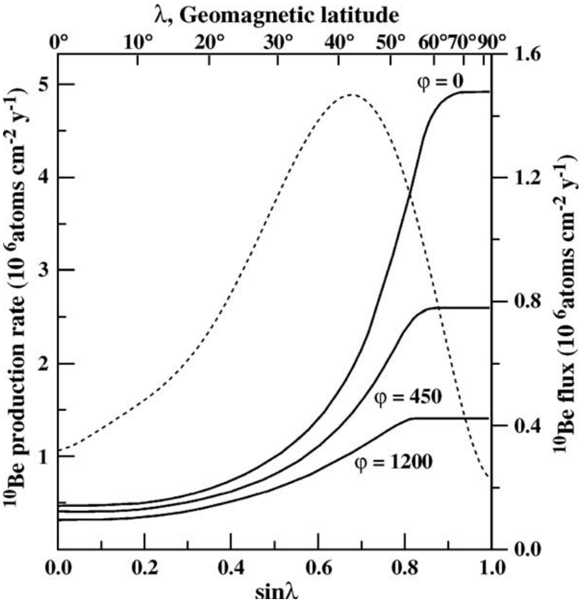

Fig. 6. Relationship between the atmospheric ^{10}Be production rate and geomagnetic latitude, for different values of the solar modulation parameter phi [90]. Typical solar-minimum and -maximum phi values are 300 and 900, respectively. The average effective value is about 450 during a typical 11-yr solar cycle. The dashed line provides a best fit to measurements of ^{10}Be deposition rate at the Earth's surface [42], which is controlled by the maximum in stratospheric/tropospheric exchange at mid-latitudes (see [47] for recent estimates based on a general circulation model).

The succession from the Medieval Warm Period to the Little Ice Age would thus represent the last cycle [54]. According to this hypothesis, our present climate is in an ascending phase on its way to attaining a new warm optimum in a few centuries.

Climate scientists remain cautious because these hypotheses really are founded solely on an apparent correlation between paleoenvironmental records and variations of solar activity. In addition, even if the millennium cycle is present, it appears to have a nonstationary character. For example, the 1500-year cyclicity observed in the Greenland ice core temperature profile during the last glacial period (based on $^{18}O/^{16}O$) is essentially dominated by the presence of three maxima in the record [56], which contrasts with the hypothesis of a regular solar cycle.

More fundamentally, there is actually no evidence for a significant millennium cycle in the ^{14}C record measured from well-dated tree-rings [57]. As a working hypothesis, a recent modeling study suggests that an apparent 1500-yr cycle could arise from the superimposed influence of the 90 and 210 yr solar cycles on the climate system, which is characterized by both nonlinear dynamics and long time scale memory effects [58].

The search for solar variability in climate records spanning the Holocene has been revived recently by analyzing $^{18}O/^{16}O$ fluctuations, a proxy for rainfall, in well-dated speleothems from the Asian monsoon area [59–61]. After subtracting a long-term decrease attributed to orbital forcing, these authors suggested that the centennial variability of the monsoon has been, at least partly, linked to solar forcing. Based on statistical consideration of the comparison of climate and solar records, it appears that a solar effect can explain, at best, only part of the observed climate variability over the Holocene period (see [62] for a recent review). Other mechanisms and forcings are superimposed on each other, making it particularly difficult to detect them or to attribute their different effects to a particular forcing.

In addition, these recent statistical analyses are merely qualitative because the $^{18}O/^{16}O$ variations in speleothems can only be taken as a crude proxy for rainfall, which is not easy to scale quantitatively with regard to climate. In addition, the cosmogenic nuclide records are also used qualitatively: ^{14}C and ^{10}Be records are simply detrended for slow changes occurring over several millennia [50]. The long-term trends are usually ascribed to variations of the geomagnetic dipolar field that effectively deflects cosmic protons colliding with the upper atmosphere at low and mid-latitudes (Fig. 6). Some authors have recently invoked the possibility of shorter-term archeomagnetic “jerks” [63]. However, it is unclear whether such events were synchronous with ^{14}C and ^{10}Be excursions, in particular the most recent ones, which do correspond to well-identified sunspot minima.

In order to achieve a more detailed interpretation, several authors have tried to extract the solar component by subtracting the nuclide production component linked to geomagnetic variations as modeled from paleomagnetic data. This is a rather difficult task, even for the well-dated tree-ring ^{14}C record spanning the past twelve millennia. Indeed, the short-term wiggles linked to solar changes are an order of magnitude smaller than the long-term trend ascribed to the geomagnetic modulation. This means that detrending is problematic, especially when studying the still hypothetical slow changes of solar activity.

Based on such an approach, Solanki et al. [64] have claimed that the Sun’s activity was much more intense during the past century when compared to the previous eleven millennia. These authors converted the numerous ^{14}C excursions observed during the Holocene into changes of sunspot numbers on the basis of a model: A typical 20–30‰ increase of $\Delta^{14}C$, similar to the one corresponding to the Maunder Minimum, would correspond to a drop of the sunspot number by 30–50 [64]. In addition to this variability, Solanki et al. make the case that the sunspot number was significantly higher (by about 20) over the past century than during the rest of the Holocene period.

As pointed out in a subsequent criticism [65], a problem arises in bridging the ^{14}C-based reconstruction with the recent variability based on counting sunspots. Furthermore, the raw ^{14}C data are detrended by modeling the geomagnetic modulation with a record of the virtual dipole moment (VDM), as reconstructed using archeomagnetic intensity data that are both spatially and temporally scattered (i.e. [66]). As shown by Korte and Constable [67], it is possible to separate the dipolar field variations from nondipole contributions to the geomagnetic field. The bias linked to the use of VDM instead of DM has been calculated for the past seven millennia [68]. These new calculations suggest that two century-long periods around 4000 BP exhibited solar activity levels comparable to those observed over the past century.

Other sources of variations could have operated during the Holocene: for example atmospheric CO_2 levels have slowly risen by about 20 ppm [69] which somehow affected atmospheric $\Delta^{14}C$. In a box-diffusion model at steady state, this CO_2 change leads to a systematic $\Delta^{14}C$ shift of about 5‰ [70]. Relatively small variations of ocean circulation may also have changed the atmospheric $\Delta^{14}C$ by altering air–sea exchange and ^{14}C transfer to the deep-sea. By using the same box-diffusion model, it has been shown [70] that varying the eddy diffusivity by 20% leads to atmospheric $\Delta^{14}C$ changes on the order of 20‰ (equivalent to a change of the sunspot number by ca. 30, according to [64]). Such an oceanic change would be difficult to detect with paleoceanographic proxies as it would shift by only 200 yr the apparent ^{14}C age of the deep-ocean (ca. 1600 yr on average). Other climate parameters, such as sea–ice distribution and wind strength may have changed slightly over the Holocene as well and may have had a significant impact on the long-term trend of atmospheric $\Delta^{14}C$.

It is clear that, besides uncertainties of past geomagnetic intensity, other systematic biases may have been involved in the ^{14}C-based reconstruction of sunspot numbers [64]. Therefore, the hypothesis of a distinctly unusual Sun over the past century remains an unresolved issue.

5. Solar variability and climate on orbital time scales

In 1968, Suess proposed that the last glaciation might have been driven by variations of solar activity [71]. To reach this conclusion, he extrapolated the observed trends of ^{14}C content measured in tree-rings and scaled them in terms of solar changes. Less than a decade after the solar hypothesis of Suess, paleoclimatic data [72] and theoretical considerations [73] provided convincing evidence in favor of the Milankovitch theory, which explains glaciations by periodic changes in the Earth's orbital parameters and not by solar irradiance changes.

It is now recognized that cosmogenic nuclide production is mainly modulated on time scales of 10^4 to 10^5 yrs by changes in the geomagnetic field intensity [74–77]. In fact, compared with the rather muted changes reconstructed for the past few millennia [67], variations of the dipole moment were much larger over the past 200 kyr [77–81]. This geomagnetic modulation accounts quantitatively for most of the increase of atmospheric ^{14}C documented for the glacial period (see [70] for a review), which is incidentally not far from the value guessed by Suess [71].

In principle, ^{14}C variations can also be linked to internal causes such as changes in the carbon cycle [70]. Therefore, it is crucial to validate the production modulation hypothesis by considering other cosmogenic isotopes such as ^{10}Be and ^{36}Cl in polar ice cores. So far, a discrepancy remains concerning the general increase in ^{36}Cl fluxes between 40 and 25 kyr BP in the GRIP ice core [82], which is inconsistent with the almost invariant ^{10}Be fluxes in the GISP2 ice core for the same interval of time [52]. The studied core-sites are very close to each other on the Greenland Summit and should thus provide similar records. The observed discrepancies in ^{10}Be flux may be partly related to differences (i.e. biases) between the chronologies used for the GRIP and GISP2 cores, which have been dated independently.

Recently, Sharma revisited the issue and proposed that very large solar variations have modulated climate over the past 200 millennia [83]. This author claimed that the climatic evolution during the Late Pleistocene — with its pronounced 100 kyr cycle — was triggered by large changes in solar activity rather than being driven by variations in the Earth's orbital parameters. This hypothesis was proposed to resolve a problem that has puzzled climate researchers for a long time, i.e. the 100-kyr cycle, related to changes in the orbital eccentricity, generates very small changes in insolation that would be unable to directly produce the major glacial/interglacial terminations experienced by the Earth during the last million years. If confirmed, the alternative solar activity triggering would have a dramatic impact on our understanding of the factors driving climate in the past.

In proposing this mechanism, Sharma [83] used a reconstruction of the geomagnetic field intensity over the past 200 kyr based on a globally stacked paleointensity record derived from deep-sea sediment records [78,79]. This was combined with a reconstruction of the global cosmogenic nuclide production rate obtained from a stack of ^{10}Be deposition rates in deep-sea sediments covering the same interval of time [74,75]. Assuming that the ^{10}Be record contains both the geomagnetic and solar modulations, the residual signal between the two stacked curves was interpreted as the pure solar component. In other words, the largest discrepancies between the two records are interpreted as reflecting the largest variations in solar activity. The amplitude of the proposed variations in solar activity [83] is very large in comparison with the estimates for the past seven millennia [57].

In this contribution we critically evaluate the uncertainties of each of these stacks to obtain a realistic error on the residual between the stacks of geomagnetic paleointensity [78,79] and cosmogenic radionuclide production [74,75]. One of the main problems in calculating a residual between such independent stacks arises from discrepancies in the age models of the individual sediment cores. For example, the relatively large difference between the stacks between 42 and 30 kyr BP has been ascribed to a difference in the methods used to derive the age models for the deep-sea cores [74,75]. The chronology used for the cores of the paleointensity stack was derived using linearly interpolated sedimentation rates between the main Marine Isotope Stages (MIS) identified by $^{18}O/^{16}O$ stratigraphy. By contrast, a ^{230}Th-constant flux method was used for the ^{10}Be stack to derive higher resolution sedimentation rates also between the main MIS derived from $^{18}O/^{16}O$ stratigraphy. If we introduce only a slight adjustment of the chronologies within the given dating uncertainties for each core, the difference between the stacks from 42 to 30 kyr BP (i.e. the residual signal) completely disappears. A small error in age, for example, around 40 kyr BP, will be expressed as a huge difference in residual signals in cases where the variability in the stacks is large over short intervals of time.

To circumvent this problem, some paleomagnetic reconstructions (e.g. [80,81]) are based on the assumption that the sharpest minimum of field intensity observed in the records between 30 and 50 kyr BP should reflect the Laschamp Excursion that occurred around 41 kyr BP. Although realigning the paleomagnetic records has some advantages, we cannot be sure than an equivalent procedure would result in a fully compatible chronology when applied to ^{10}Be measured in different deep-sea cores. To avoid relying on ad hoc assumptions, the best approach is clearly to study paleomagnetic properties and ^{10}Be fluxes in the very same deep-sea cores. Unfortunately, this approach has rarely been adopted [e.g. 77,84], which is the reason why the chronologies of both stacks are not fully compatible.

An even more severe problem (discussed in [75] and also in [83]) is the presence of a potential residual climatic signal in the stacked records derived from marine sediment cores. Climatic residuals may originate from the fact that ^{10}Be is particle-reactive in the ocean, which means that climatically driven changes in biogenic or detrital particle fluxes have modulated its flux at particular locations, e.g. [85,86]. Moreover, changes in ocean circulation on glacial/interglacial time scales may have led to redistribution of ^{10}Be by advection. This can influence the average record because core locations included in the stack are not evenly distributed spatially. In the case of the relative paleointensity records based on magnetic parameters in marine sediments, the most important problem has been the correction for the influence of climatically induced changes in lithology of the deposited detrital particles. Magnetization processes in sediments are complex and still not fully understood. Advanced normalization techniques may help in correcting lithological signals (see [87] for a comprehensive overview).

Although great efforts had been made to eliminate climatic influences in the records of the original studies [74,75,78,79], Kok [88] showed that there still may be a small but significant residual climate signal in the ^{10}Be production record. By contrast, spectral analyses of the paleointensity stack [79] do not yield frequency maxima that are related to the Milankovich frequencies [88]. It is thus not too surprising that the residual between the two stacks shows frequency maxima related to orbital cyclicities, which probably originate from the small climatic signal left in the ^{10}Be-stack.

Therefore, the apparent orbital cyclicity in the calculated residual is probably not caused by solar modulation of the ^{10}Be production. In fact, calculating the residual between the two records amplifies the small climatic (probably orbital) signal. This would explain why the variability of solar modulation proposed in [83] is much larger than the variations reconstructed over the past five millennia.

Several independent reconstructions of past geomagnetic field intensity [78–81] and cosmogenic isotope

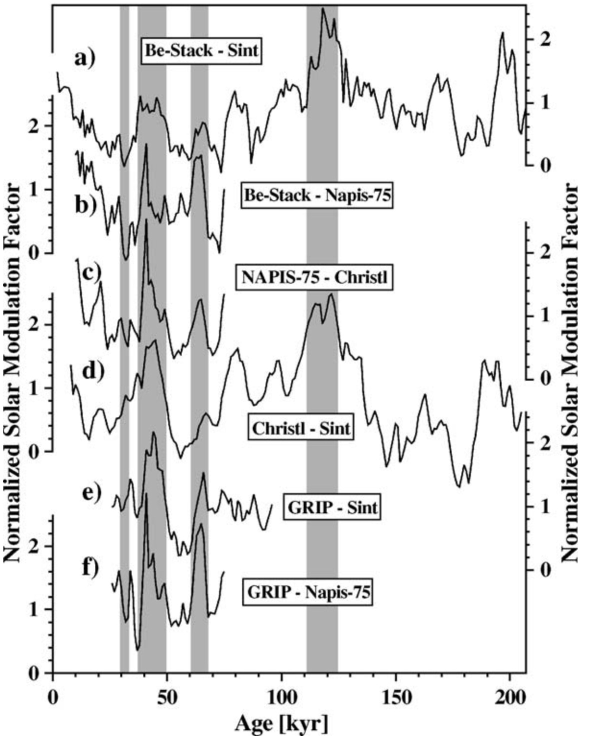

Fig. 7. Comparison of the normalized solar modulation factor (calculated as in [83]) from different available databases: a) from the Sint geomagnetic field intensity record [79] and the ^{10}Be production record of [75] (i.e. the reconstruction published in [83]), b) from a geomagnetic stack based on North Atlantic sediments (NAPIS-75, [80]) and the ^{10}Be production record of [75], c) from the NAPIS-75 curve [80] and the ^{10}Be production rates deduced from a stack of boundary scavenging-corrected ^{10}Be deposition rates [76], d) from the Sint curve [79] and the ^{10}Be production record of [76], e) from the Sint curve [79] and the ^{36}Cl flux record based on the GRIP ice core [82], f) from the NAPIS-75 curve [80] and the ^{36}Cl flux from GRIP [82]. For these calculations, we used the original chronology published for each of these different records. The grey bars mark periods during which the maxima and minima apparently coincide in most records.

production [74–77,82] have recently improved our knowledge of the evolution of both parameters over time. Different combinations of these records may be compiled to calculate residuals that can be expressed in terms of a normalized "solar modulation factor" (as calculated by [83]). Fig. 7 shows that the general pattern of the "solar modulation record" is reproduced by most of the combinations. Even when all the reconstructions are combined into one plot (Fig. 8), we are still able to recognize the general pattern (as given by the grey shading picking out all individual records).

However, a closer look reveals some highly significant discrepancies: around 31 kyr BP, the values range between 0 and 1.7. Similarly, for the period around 45 kyr BP, the range is between 0.9 and 2.9. In addition to the scattering between the residual records, we should take into account the statistical errors associated with each of the records of past geomagnetic field intensity and cosmogenic isotope production rate. By assuming the propagation of Gaussian errors, we obtain error bars for the solar modulation factor record that are similar to those calculated by the Monte Carlo simulation [83]. This error propagation was applied to all the other combinations of field intensity and nuclide production rate used to reconstruct the solar modulation curves (Fig. 7). In Fig. 8, the light grey area indicates the composite range of uncertainty defined by the error propagations of all reconstructions. It is clear that no statistically significant variation can be resolved.

It should be stressed that error bars calculated for the stacked curves probably underestimate the true size of the uncertainties. Indeed, both Guyodo and Valet [79] and Frank [75] calculated errors as the standard error of the mean (the observed scatter between core records divided by the square root of the number of cores). The bootstrap technique used in [80,81] to construct their geomagnetic stack leads to errors that are even smaller than those derived by Guyodo and Valet [79]. These statistical procedures imply that strict criteria should be satisfied by the sets of individual curves used to build the stacks. In reality, the uncertainty ranges are caused by variable errors in the chronologies of the individual records (i.e. errors on the x-axis) and by several sources of uncertainty in the approaches used to reconstruct the geomagnetic field intensities and cosmogenic nuclide production rates (i.e. errors on the y-axis). Finally, the overall error ranges would be even larger if the calculations took into account uncertainties in the relationships between geomagnetic intensity and cosmogenic nuclides ([89] used in [83]; see also [90,91] for different model calculations).

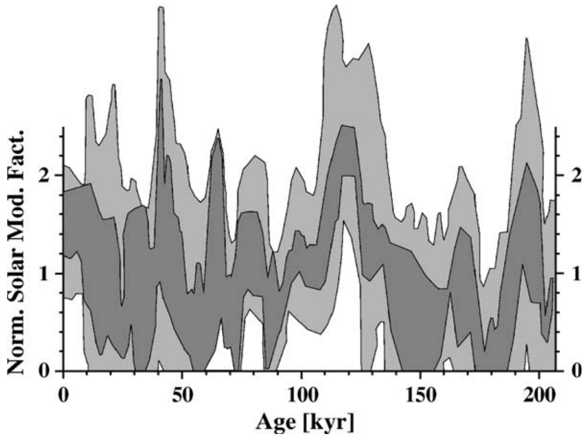

Fig. 8. Same records as in Fig. 7 but combined on the same graph. The dark grey area represents the range of all calculations. The light grey area marks the composite range of uncertainties obtained by propagating the errors published for each reconstruction. It is clear that in view of the cumulative uncertainties of the individually calculated records, no reliable reconstruction of the solar modulation can be achieved on the basis of the presently available datasets.

The above discussion clearly illustrates that, with the currently available reconstructions of field intensity and cosmogenic nuclide production over the past 200 kyr, it is not possible to extract a solar component with the precision required to draw meaningful conclusions. This approach should be viewed as a theoretical possibility, but, before applying it, we need more reliable reconstructions of past cosmogenic nuclide production and geomagnetic field intensity established over longer time scales.

6. Conclusions

Astrophysical data demonstrate that the Sun has been variable in activity and radiative output. Unfortunately, precise data are limited to the satellite era, i.e. after 1978. Looking at the solar variability over this short period only provides a small range of solar forcing, e.g. 1‰ of the total irradiance over the 11-yr activity cycle.

Conflicting views exist about a multi-decadal trend in irradiance and a possible link between solar activity and cloud cover. Acquiring data over the next solar minimum may contribute to answering both of these questions. Moreover, the hypothetical effect of cosmic rays on cloud formation is poorly understood and requires further research efforts.

Solar records are intrinsically incomplete for periods prior to the past three decades. Thus models are used to relate various proxies to the climatic forcing of the Sun. Several studies clearly suggest that solar output has varied on a time scale longer than the 11-yr sunspot cycle. It appears that solar fluctuations were involved in causing widespread but limited climatic changes, such as the Little Ice Age (1500–1800 A.D.) that followed the Medieval Warm Period (900–1400 A.D.).

Beyond the past four centuries of telescopic observations of the Sun, the main tool for evaluating solar activity is provided by cosmogenic nuclides. The production of these isotopes is modulated by the magnetic properties of the solar wind, which can be ultimately linked to solar activity. After their formation, cosmogenic isotopes are transported in the atmosphere and the ocean before being buried in various archives. These processes make the interpretation more complicated. Nevertheless, studies of cosmogenic isotopes generally agree in indicating numerous solar activity minima in the past, with the Sun passing a large part of its history in calm phases, conceivably with an irradiance several ‰ weaker than the present-day value.

Several recent studies have attempted to extract solar changes over periods of ten thousands [64] to hundreds of thousand years [83]. On such time scales, cosmogenic nuclide production is largely modulated by slow variations of the Earth's magnetic field. The currently available reconstructions of geomagnetic field intensity and cosmogenic nuclide production are still not sufficiently precise to extract a meaningful solar component. To apply this approach, we await more reliable and longer records of both cosmogenic nuclide production and geomagnetic field intensity of the past.

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