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Rapid Communication

The role of solar forcing upon climate change

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Abstract

Evidence for millennial-scale climate changes during the last 60,000 years has been found in Greenland ice cores and North Atlantic ocean cores. Until now, the cause of these climate changes remained a matter of debate. We argue that variations in solar activity may have played a significant role in forcing these climate changes. We review the coincidence of variations in cosmogenic isotopes (^{14}C and ^{10}Be) with climate changes during the Holocene and the upper part of the last Glacial, and present two possible mechanisms (involving the role of solar UV variations and solar wind/cosmic rays) that may explain how small variations in solar activity are amplified to cause significant climate changes. Accepting the idea of solar forcing of Holocene and Glacial climatic shifts has major implications for our view of present and future climate. It implies that the climate system is far more sensitive to small variations in solar activity than generally believed. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

Recently, Bond *et al.* (1997) discovered that periodic ice-rafting events in the North Atlantic region were not restricted to the Last Glacial, but also occurred during the Holocene. They provide evidence that these events were simultaneous with climatic cooling phases. A number of those Holocene climate cooling phases coincide with events studied in detail by others and are most likely of a global nature (e.g. Magny, 1993; van Geel *et al.*, 1996; Alley *et al.*, 1997; Stager and Mayewski, 1997). As Bond *et al.* propose, the cooling phases seem to be part of a millennial-scale climatic cycle, operating independently of the glacial–interglacial cycles forced by orbital variations. The question remains, however, what is the driving mechanism behind these millennial-scale events. Answering this question is essential for our understanding of climate sensitivity and thus for estimating possible future climate changes. Bond *et al.* (1997) conclude that a solar forcing of the climatic cycle is unlikely and they suggest that the driving mechanism is to be found inside the atmosphere–ocean system. In contrast, we show here that there is mounting evidence suggesting that the variation in solar activity is a cause for millennial scale climate change. In Fig. 1 a schematic overview of the various factors in the relation between sun, cosmic rays and climate is shown. We emphasise the possibly important role of changing solar UV and solar wind, modulating cosmic ray intensity in the atmosphere (highlighted boxes in Fig. 1). Our ideas are based on existing records and new observations of the cosmogenic isotopes ^{14}C and ^{10}Be in various archives.

2. Solar activity and the cosmogenic isotopes ^{14}C and ^{10}Be

Variations in the cosmogenic isotopes ^{14}C and ^{10}Be are widely used to reconstruct solar variations of the past

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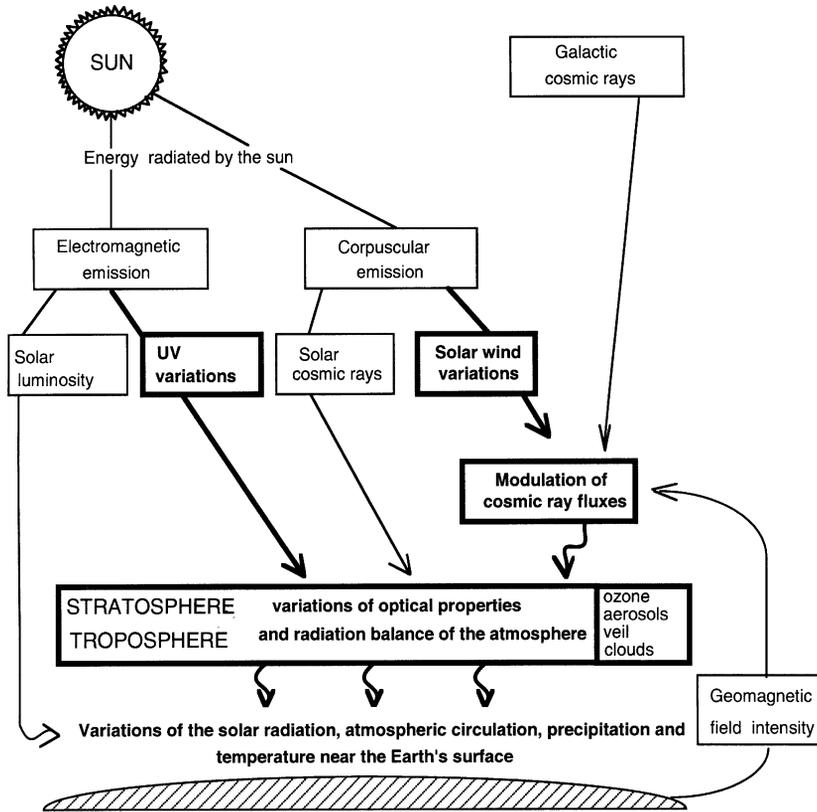*E-mail address*: vangeel@bio.uva.nl

Fig. 1. Scheme showing various solar and cosmic factors relevant for the climate on Earth. The climate forcing effects of changes in UV and solar wind (modulating cosmic ray intensity) are highlighted in the figure and discussed in the text.

(Hoyt and Schatten, 1997). Both isotopes are produced in the upper atmosphere under the influence of cosmic rays of both galactic and solar origin. The production of these cosmogenic isotopes is subject to change due to fluctuations in the cosmic ray flux impinging the Earth. These fluctuations are mainly caused by changes of solar wind, which is a low-density ionised gas ejected from the sun, strongly influencing the magnetic field strength around the Earth. ^{14}C enters the global carbon cycle via CO_2, while solid ^{10}Be precipitates with aerosols and is recorded in sediments and ice cores. The ^{14}C calibration curve (Stuiver *et al.*, 1993) is based on ^{14}C measurements of dendrochronologically dated tree rings, and reflects the fluctuations of the atmospheric ^{14}C content in the past. When solar activity is high, the extended solar magnetic field sweeps through interplanetary space, thereby more effectively shielding the Earth from cosmic rays and reducing the production of ^{14}C. Low solar activity lets more cosmic rays enter the Earth's atmosphere, producing more ^{14}C. So the ^{14}C record is a good proxy for the solar radiant output (Bard *et al.*, 1997). However, explaining the observed changes in ^{14}C concentration by production-rate variations alone is too simple an assumption, the more so when rapid ^{14}C concentration changes appear to be coincident with significant changes in climate.

Climate changes can cause changes in the global carbon cycle. In the deep oceans, large quantities of 'old' carbon are stored with less ^{14}C than in the atmosphere. So, a decrease in ^{14}C concentration can either be explained by a lower production, or by an increase in upwelling deep ocean water, releasing large quantities of 'old' carbon with lower ^{14}C concentration into the atmosphere (Broecker, 1997). The choice between the two possibilities, viz. (1) was it lower solar activity leading to a cooler climate and higher ^{14}C or (2) was it cooling due to some other effect, leading to a change in the global carbon cycle and thereby increasing ^{14}C in the atmosphere, cannot be answered without additional information.

However, if we observe sudden, major ^{14}C increases like the ones starting at c. 850 cal. BC and at c. 1600 AD (about 20 per mil), it is hard to imagine any change in the global carbon cycle that can bring about such a drastic fast change, simply because there is no reservoir of carbon with higher ^{14}C concentration available anywhere on Earth. Even a sudden stop of the upwelling of old carbon-containing deep water could not cause the sudden (within decades) ^{14}C concentration increases that are documented in the dendrochronological records. So, if we observe that such a sudden ^{14}C increase, which must be caused by a production increase, is accompanied by indications for a change towards colder or wetter climate,
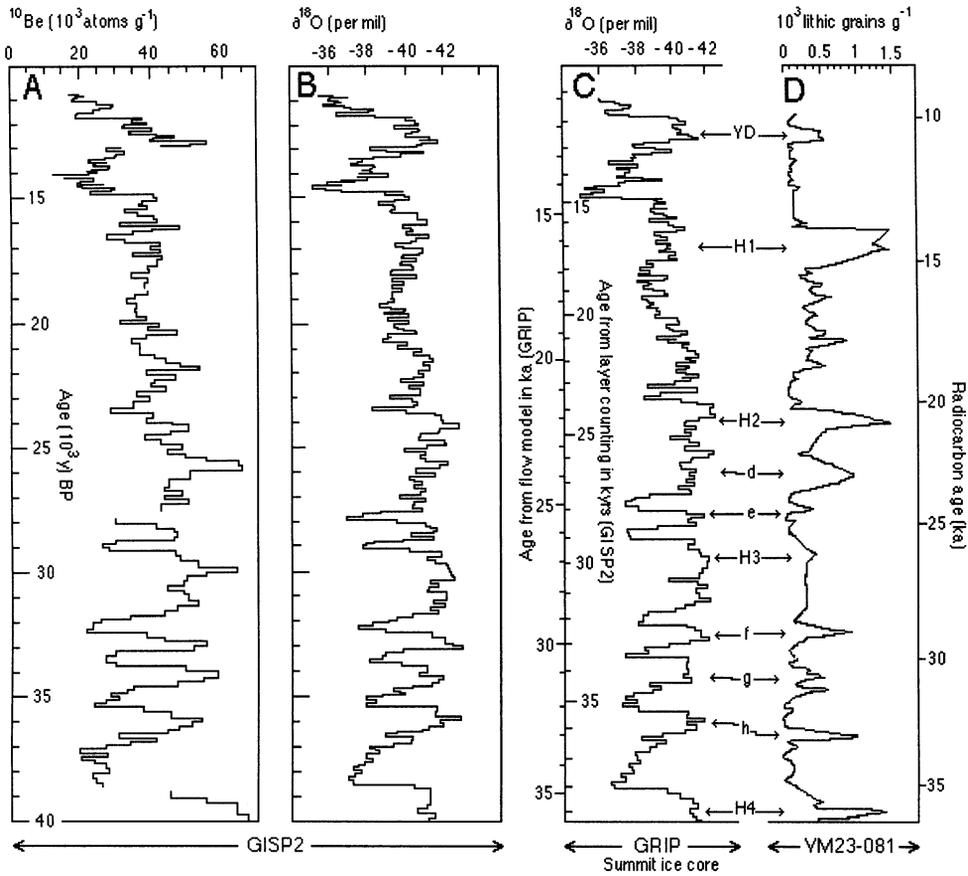
Fig. 2. (A) The GISP2 ^{10}Be record (according to Finkel and Nishiizumi, 1997) and, (B) the GISP2 ∂^{18}O record (Grootes *et al.*, 1993) in relation to the GRIP ∂^{18}O records (C; based on Dansgaard *et al.*, 1993) and ice-rafting events (D) in the North Atlantic as recorded by Bond and Lotti (1995) in core VM23-081. We conclude that solar forcing of climate change played an important role: periods of reduced solar activity and related increases of cosmic rays — as indicated by high ^{10}Be values — coincide with cold phases of the Dansgaard–Oeschger events as shown in the ∂^{18}O records.

this may indicate that solar forcing of the climate does exist. In theory, increased production of cosmogenic isotopes can also have a cause of cosmic origin such as a nearby supernova (Sonnett *et al.*, 1987). We consider this scenario unlikely, and note here that events such as the 850 cal. BC peak are present in the dendro-chronological curve with a periodicity of about 2400 years (Stuiver and Braziunas, 1989; see below).

By combining the ^{14}C record with measurements of an independent cosmogenic isotope, ^{10}Be, one can check the solar origin of variations in the ^{14}C/^{12}C ratio. The production of ^{10}Be occurs mainly in the lower stratosphere and upper troposphere at high latitudes as a result of nuclear reactions induced by cosmic rays. Deposition of ^{10}Be onto the Earth surface is predominantly through precipitation. For fluctuations of ^{10}Be in Greenland ice it is believed that they reflect primarily changes in precipitation and secondarily, variations in solar activity (McHargue and Damon, 1991; Yiou *et al.*, 1997). However, after comparing the records of ^{14}C and ^{10}Be, Bard *et al.* (1997) conclude that during the last millennium the variations in these isotopes are well explained by solar modulation. This implicates that, at least for the last

millennium, the variations in ^{10}Be are indicative for changes in solar activity and related cosmic ray intensity. Moreover, Finkel and Nishiizumi (1997) have shown parallels between ^{14}C and ^{10}Be records from 8000 to 5000 BP. In case a relationship between climate change and ^{10}Be concentrations in ice cores would exist further back in time, we suggest to consider solar forcing for climate change as an explanation.

In Fig. 2a we show the ^{10}Be concentration data (Finkel and Nishiizumi, 1997) for the period of 40,000–11,000 years ago. These data show strong fluctuations parallel-ing the ∂^{18}O record (with so-called Dansgaard–Oeschger cycles) of the same ice core (see Fig. 2B). We note here that these fluctuations in the ^{10}Be concentration, at least for the period 40,000 to c. 16,000 years ago, are also present in the ^{10}Be flux, and in the calculated model atmospheric concentration (see Fig. 2 of Finkel and Nishiizumi, 1997). The ^{10}Be concentration depends on the precipitation rate, the ^{10}Be flux does not; both how-ever still show the fluctuations paralleling ∂^{18}O. We discuss below that also the precipitation in itself may depend on the cosmic ray flux, which is modulated by changes in solar wind.

3. Coincidences of ^{14}C and [10]Be changes and climate change

It is well documented that periods of decreased solar activity, as reconstructed with ^{14}C and [10]Be, often coincide with climatic change. The best known example is the Maunder Minimum (1645–1715), a solar event that is coinciding with one of the coldest phases of the Little Ice Age (Eddy, 1976; see also van Geel et al., 1998b). The Maunder Minimum is characterised by a minimum in sunspots, as recorded by observers. According to Lean et al. (1992) the sun during the Maunder Minimum was 0.25% less bright than it was during the solar minimum of 1985–1986. Climate model experiments indicate that such a decrease in solar irradiance is capable of causing a global cooling of about 0.5°C (Rind and Overpeck, 1993). Moreover, Stuiver et al. (1997) have stressed that a substantial part of the climatic perturbations of the current millennium is compatible with a solar interpreted Δ^{14}C record.

Another example is the period around 850 cal. BC. Kilian et al. (1995) analysed NW-European peat deposits and found evidence for climatic cooling around this time, simultaneous with a sharp and considerable rise of the atmospheric ^{14}C level. As observed in ice cores (Beer et al., 1988), the [10]Be record shows also an increase around this time. Based on archaeological, paleoecological and geological/geomorphological evidence, van Geel et al. (1996, 1998a) concluded that climate change around 850 BC occurred in both hemispheres. They compiled evidence for a change from a relatively warm climate to cool and wet conditions in the middle latitudes of the N. Hemisphere (Europe, N. America, Japan) and the S. Hemisphere (S. America, New Zealand), being synchronous with a shift to drier conditions in the tropics (Africa, Caribbean). The 850 cal. BC event can very well have been caused by a reduction of solar energy output, comparable to the situation during the Maunder Minimum. Maunder-type minima show up in the ^{14}C calibration curve throughout the Holocene with a periodicity of about 2400 years (Stuiver and Braziunas, 1989). The association between climate (palaeowinds in varved sediments) and solar activity (radiocarbon content of tree-rings) was established by Anderson (1992) in sediments formed between 7300 and 5300 years ago. The wind record is preserved as changes in the thickness of varved sediments related to changes in cyclonic activity and tropospheric winds. This time interval is characterised by a weak magnetic field and abrupt changes of the ^{14}C content. Cross-correlation had a coefficient that is significant at the 95% confidence level.

Evidence for an earlier Holocene example of global climate change, viz. between 8200 and 7800 years ago, is described recently by Stager and Mayewski (1997). They infer that during this early-to-mid-Holocene transition (EMHT) a climatic reorganisation took place, leading to weakened summer monsoons in the Indian ocean, decreased tropical precipitation, precipitation changes at mid-latitudes and cooling at the poles (Alley et al., 1997).

Maunder-type oscillations, linked to reoccurrence of cold climatic phases have also been found in Greenland ice cores (Dansgaard et al., 1984; O'Brien et al., 1995) and in terrestrial records from Europe, North America and the Southern Hemisphere (Harvey, 1980). Bond and Lotti (1995) showed that during the Last Glaciation nearly synchronous increases in rates of iceberg discharges occurred at the edges of Icelandic and NE-American ice caps. This phenomenon occurred every 2000–3000 years, suggesting that those icebergs were discharged when air temperatures dropped below a critical threshold. Bond and Lotti do not give a possible cause, but they made a comparison between these cyclic iceberg discharges and the evidence for regular climatic fluctuations during the Holocene as given by Denton and Karlen (1973) and Magny (1993). Moreover, Finkel and Nishiizumi (1997) present a detailed record of [10]Be in the GISP2 Greenland Ice core for the period 40,000–3,000 years BP. Fluctuations in the [10]Be values during the last Glacial evidently parallel the so-called Dansgaard–Oeschger warm/cold cycles (D–O events; Dansgaard et al., 1993) in the ∂^{18}O record from the same ice core: relatively warm phases show low [10]Be values and peaks in the [10]Be record occur during the cold phases. Although these variations in [10]Be are thought to reflect changes in snow accumulation rates (Yiou et al., 1997) and in production and long-distance transport (Grootes and Stuiver, 1997), the effect of solar variability on these variations may be substantial.

4. Mechanisms for amplification of changing solar activity

Solar/cosmic ray forcing of global climatic change, as may be inferred from the above records, is controversial among physicists and climatologists. Attempting to explain a physical link on the basis of the relationship 'solar wind–magnetosphere–ionosphere–atmosphere' is difficult because of a very large difference of the solar wind energy and the energy of the atmospheric processes (4 orders of magnitude). Thus, it is necessary to develop another approach in the problem solution: the solar irradiance remains the main source of the energy affecting the atmosphere, but some agents controlled by solar activity must act directly on the atmosphere and change the amount of the solar energy reaching the Earth surface. Clearly a positive feedback mechanism is needed, explaining how relatively small variations in solar activity can cause significant climate changes. Two possible processes for solar forcing of climate change are considered here that may operate alone or in concert.

The first mechanism involves variations in UV radiation, accompanying changes in solar activity that may cause significant shifts in the atmospheric circulation and climate through the stratospheric ozone production (Haigh, 1996 and references therein). In this respect Hoyt and Schatten (1997) note that UV variations are an excellent candidate for solar variability influences on climate, not only because solar spectral irradiance fluctuations are proportionally larger at short wavelengths, but also because they carry a significant fraction of the total solar energy variability (about 20% below 300 nm according to Lean (1991)). In a climate model experiment, Haigh (1996) analysed the response of the atmosphere to the 11-year solar activity cycle. In this simulation, a small increase in UV radiation caused substantial stratospheric heating, as the excess in ozone absorbed more sunlight in the lower stratosphere. In addition, the stratospheric winds were also strengthened and the tropospheric subtropical jet streams were displaced poleward. The location of these westerly jets determines the latitudinal extent of the Hadley cells and, therefore, the poleward shift resulted in a similar displacement of the descending limbs of the Hadley cells. This ultimately led to a poleward relocation of the mid-latitude storm tracks.

Temperature changes in the model result were very similar, although smaller in magnitude, to observations made by van Loon and Labitzke (1994). Moreover, recently the results of Haigh (1996) were supported by an analysis of Christoforou and Hameed (1997), showing a close correlation between solar activity, as expressed by mean annual sunspot numbers, and the intensity and locations of low- and high-pressure centres in the North Pacific area. Although considering a different time scale, van Geel and Renssen (1998) inferred that an opposite process to the one found by Haigh (1996), i.e. the result of a decrease in UV radiation and stratospheric ozone content, explains the evidence for global climatic change around 850 BC very well (van Geel et al., 1996, 1998a). Indeed, the cooler and wetter conditions in the mid-latitudes and the drier tropics are in agreement with a contraction of the Hadley cells, possible weakening of the monsoons, an equatorward shift of the mid-latitude storm tracks and an expansion of the polar cells.

According to the second mechanism, variations in cosmic ray flux, related to changes of solar wind, cause climate change through amplification of changing solar radiation. Such a mechanism was proposed by Ney (1959) and studied by Pudovkin and Raspopov (1992) and Raspopov et al. (1998). The main idea is that a variation of cosmic ray flux may change the optical parameters and radiation balance of the atmosphere (Fig. 1). Galactic and solar cosmic ray fluxes penetrate into the stratosphere and troposphere and cause physical–chemical reactions. These fluxes are modulated by solar activity. During the 11-years solar cycle the change of galactic cosmic ray fluxes could be about 10% on the Earth surface and about 50% in the stratosphere. Even larger changes in cosmic ray intensity could be expected during secular cycles of solar activity, like the Maunder minimum and the period between 850 and 760 cal. BC as discussed by van Geel et al. (1996).

Recent experimental data support this second physical mechanism proposed. These data demonstrate the change of the ozone layer density, the development of cloudiness, the formation of an aerosol layer in the stratosphere and an atmospheric veil during periods of increased cosmic ray fluxes in the stratosphere. Shumilov et al. (1992, 1995), Stephenson and Scourfield (1992) and Kodama et al. (1992) showed that solar proton events (known as SPE), which generate the solar cosmic rays, may produce ozone 'mini-holes' at the high latitudes (the decrease of the total ozone content is about 10–15%) and these are accompanied by a decrease of the temperature in the stratosphere of 2.4°C. Pudovkin and Veretenenko (1992, 1995) found a relation between the intensity of cosmic rays and cloudiness. Svensmark and Friis-Christensen (1997) used cloudiness data on the temporal scale of the solar cycle and found that variations in cloudiness parallel changes in cosmic ray intensity. Shumilov et al. (1996) showed that after SPE the development of an aerosol layer is observed in the atmosphere at the altitude from 12 to 18 km. Schuurmans (1991) reported that after SPE a decrease of the atmospheric temperature (about 1.4°C) was observed at altitudes between 5.5 and 11.7 km during 10 days. This effect is apparently associated with the development of clouds and aerosols. The data mentioned above concerning the changes of optical and thermodynamical properties of the atmosphere related to cosmic ray flux variations in the atmosphere permitted Raspopov et al. (1997a, b, 1998) to estimate the possible decrease of the Earth surface temperature during the Maunder minimum of solar activity. The estimation was 0.6–0.7°C, which corresponds with the temperature change observed in reality (Lean et al., 1992). With the physical mechanism proposed, it is possible to explain the physical link between the solar cycle length and the global Earth surface temperature (Raspopov et al., 1997b). At the same time the proposed mechanism explains the decrease of the Earth surface temperature during excursions, inversions, and low-value periods of the main geomagnetic field (Raspopov et al., 1997a).

5. Discussion and conclusion

Bond et al. (1997) found evidence for ice-rafting events during the Holocene at 1400, 2800, 4200, 5900, 8100, 9400, 10,300 and 11,100 cal. BP and during the Last Glacial at a similar timing as the Dansgaard–Oeschger events. They identified that these climatic shifts occurred with a cyclicity of 1470 years, and conclude that solar

forcing of these cyclic events is 'highly controversial', as 'no evidence has been found of a solar cycle in the range 1400–1500 years'. Instead, they favour a driving process from within the atmosphere–ocean system, most likely related to the North Atlantic thermohaline circulation. However, Mayewski et al. (1997) showed that a 1450 periodicity is present in the band pass component of both the $\Delta^{14}C$ residual series derived from tree rings and glaciochemical series from the GISP2 ice core, believed to reflect changes in the polar atmospheric circulation. As these authors conclude, this may indeed suggest a link to climate–solar variability. Moreover, the GISP2 ^{10}Be record presented by Finkel and Nishiizumi (1997; see Fig. 2) shows (in our opinion) that periods of reduced solar activity, as possibly indicated by high ^{10}Be values, coincide with cold phases of the D–O events. In addition, at least two of the recognised Holocene ice-rafting events, viz. the ones around 8100 and 2800, as well as the Little Ice Age event, are known to coincide with periods of reduced solar activity as reconstructed with the aid of ^{14}C and ^{10}Be records (viz. EMHT and 850 cal. BC events). This evidence, in combination with the study of Holocene lake-level fluctuations related to the atmospheric ^{14}C record (Magny, 1993), strongly points to solar forcing of global climatic shifts.

The amplitudes of the ^{10}Be fluctuations during the period 40,000–16,000 years ago are surprisingly large, especially when compared with the fluctuations during the Holocene. It is generally accepted that during the glacial period climatic perturbations were amplified compared to the Holocene, probably due to the existence of large ice sheets (e.g. Mayewski et al., 1997). Thus, the glacial climate appears to have been much more unstable than the interglacial climate, so that a relatively small trigger is sufficient to cause substantial climate changes. Consequently, the same variations in solar activity may have caused larger climatic changes (temperature, precipitation) during the Pleistocene than during the Holocene. Accompanying these climate changes, shifts in atmospheric circulation occurred, that may have altered the ^{10}Be concentrations in the ice cores through considerable precipitation rate changes (maxima and minima of ^{10}Be more pronounced than during the Holocene).

Substantial geological and paleoecological evidence point to a global distribution of climate change during Holocene events (e.g. Harvey 1980, van Geel et al., 1996; Alley et al., 1997; Stager and Mayewski, 1997). If these shifts were forced by variations in the Atlantic thermohaline circulation, as suggested by Bond et al. (1997), one would expect the climate changes to occur primarily downwind of areas of deepwater formation (Rind and Overpeck, 1993). Moreover, in our view the identification of a 1470-cycle is not a convincing argument to reject a reduced solar activity as the ultimate cause of the ice-rafting events. A 1450 year periodicity is also identi-

fied in the $\delta^{14}C$ record by Mayewski et al. (1997) and Stuiver et al. (1997). We note here that Bond and Lotti (1995), without further explanation or discussion, concluded earlier that ice-rafting events occurred every 2000–3000 years. The latter periodicity is in agreement with the cycle of about 2600 year in North Atlantic climate shifts as deduced from analyses in Greenland ice cores (Dansgaard et al., 1984; O'Brien et al., 1995). Furthermore, this cycle is close to the 2400-year cycle, believed to be of heliomagnetic origin, known from the ^{14}C record in tree rings (Stuiver and Braziunas, 1989). We therefore postulate, that — periodically — sudden and strong increases of cloudiness, precipitation (snow) and declining temperatures as a consequence of solar/cosmic ray forcing have played a crucial role in the regularly occurring iceberg discharges as recorded in North Atlantic deep sea cores and the synchronous events in the Southern Hemisphere. These changes in climate can be explained by the two mechanisms, operating alone or simultaneously, as discussed in the present paper. Accepting the idea of solar forcing of Holocene and Glacial climatic shifts has major implications for our view of present and future climate. It implies that the climate system is far more sensitive to small variations in solar activity than generally believed. For instance, it could mean that the global temperature fluctuations during the last decades are partly, or completely explained by small changes in solar radiation, as postulated by Friis-Christensen and Lassen (1991) and Svensmark and Friis-Christensen (1997). In order to fully understand how sensitive climate really is for variations in solar activity, we need to look for additional evidence, and to quantify such evidence, both in paleorecords and in observations of present climate. Moreover, there is a challenge for climatologists to include this sensitivity of climate in their models, as these models are important tools for estimating climate change in the future.

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