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Reduced solar activity as a trigger for the start of the Younger Dryas?

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Abstract

It is generally assumed that changes in ocean circulation forced the abrupt climate changes during the Late Pleistocene, including the Younger Dryas event. Recently, however, it was proposed that variations in solar irradiance could have played a much more prominent role in forcing Pleistocene climate changes. For climate fluctuations during the Holocene the role of solar variability as an important forcing factor becomes more accepted. Furthermore, two physical mechanisms were recently published that explain how relatively small changes in solar irradiance could have had a strong impact on the climate system. We discuss the possibility that an abrupt reduction in solar irradiance triggered the start of the Younger Dryas and we argue that this is indeed supported by three observations: (1) the abrupt and strong increase in residual ^{14}C at the start of the Younger Dryas that seems to be too sharp to be caused by ocean circulation changes alone, (2) the Younger Dryas being part of an ~ 2500 year quasi-cycle — also found in the ^{14}C record — that is supposedly of solar origin, (3) the registration of the Younger Dryas in geological records in the tropics and the mid-latitudes of the Southern Hemisphere. Moreover, the proposed two physical mechanisms could possibly explain how the North Atlantic thermohaline circulation was perturbed through an increase in precipitation together with iceberg influxes. In addition, the full magnitude of the Younger Dryas cooling as evidenced by terrestrial records in Europe could be explained. We conclude that a solar triggering of the Younger Dryas is a valid option that should be studied in detail with climate models.

1. Introduction

The Younger Dryas (YD, 12.9–11.6 ka cal BP, Alley et al., 1993) was a cold event that interrupted the general warming trend during the last deglaciation. The YD was not unique, as it represents the last of a number of events during the Late Pleistocene, all characterised by rapid and intensive cooling in the North Atlantic region (e.g., Bond et al., 1993; Anderson, 1997). During these events, icebergs were common in the N Atlantic Ocean, as evidenced by ice-rafted sediments found in ocean cores. The most prominent of these episodes with ice rafting are known as Heinrich events (e.g., Bond et al., 1992, 1993; Andrews, 1998). A Heinrich-like event (H-0) was simultaneous with the YD (Andrews et al., 1995). Moreover, the YD seems to be part of a millennial-scale cycle of cool climatic events that extends into the Holocene (Denton and Karlén, 1973; Harvey, 1980; Magny and Ruffaldi, 1995; O'Brien et al., 1995; Bond et al., 1997). Based on analysis of the ^{14}C record from tree rings, Stuiver and Braziunas (1993) suggested that solar variability could be an important factor affecting climate variations during the Holocene (see also Magny, 1993, 1995a), possibly operating together with oceanic forcing. For the Late Pleistocene, however, it is generally assumed that the abrupt climate changes are predominantly forced by fluctuations in ocean circulation (e.g., Bond et al., 1997; Broecker, 1997, 1998). However, van Geel et al. (1999b) proposed that solar variability played a major role by triggering the abrupt Late Pleistocene climate shifts. In this paper, we extend this idea by discussing in detail the possibility that a reduced solar activity triggered the start of the YD. This discussion is important, since the exact

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mechanism causing the climate instability at the start of the YD is not sufficiently known. It is obvious that for a complete understanding of future climate change, it is crucial to know the sensitivity of the climate system to all possible forcing mechanisms.

2. Hypotheses on the cause of the Younger Dryas

The mechanism causing the YD is subject of a long-lasting debate. Since the 1980s, a number of causes for the YD have been suggested. In a review, Berger (1990) mentions three types of mechanisms: (1) an interplay of positive feedbacks within the climate system, possibly involving changes in ocean circulation, atmospheric CO_2 concentration and surface albedo, (2) the disturbance of an internal threshold feedback (e.g., collapse of ice sheets), and (3) forcings external to the climate system, such as solar radiation, volcanism, supernovae and cosmic dust. The complete picture may be very complex as some of these mechanisms may be both cause and effect to others (Berger, 1990). The most accepted hypothesis to explain the YD involves a perturbation of the thermohaline circulation (THC) in the N Atlantic ocean as a result of meltwater pulses.

The THC-hypothesis involved an on-and-off switching of N Atlantic deep water (NADW) formation and was first proposed by Broecker et al. (1985). The NADW formation is considered essential for driving the THC. In present climate, the THC is an important heat source for the N Atlantic region and, moreover, a shutdown during the YD would produce atmospheric cooling in agreement with reconstructions of European climate based on proxy records (e.g., Renssen, 1997; Renssen and Isarin, 1998). In addition, ocean modelling studies suggest that the thermohaline circulation may collapse as a result of small perturbations in the hydrological cycle (e.g., Maier-Reimer and Mikolajewicz, 1989; Rahmstorf, 1995; Schiller et al., 1997). Indeed, some ocean cores give evidence for a shutdown of the THC during the YD (Boyle and Keigwin, 1987). However, the THC shutdown hypothesis was contradicted by evidence from various other Atlantic ocean cores, showing that deep water was formed during YD time (Veum et al., 1992; Charles and Fairbanks, 1992; Sarnthein et al., 1994).

The apparent contradiction between various records led to a refined hypothesis involving a separation between "lower" and "upper" NADW. Lehman and Keigwin (1992) suggested that the formation of "lower" NADW (LNADW), taking place between Norway and Iceland, could have been significantly reduced during YD time, whereas "upper" NADW (UNADW) formation in the Labrador Sea was not very different from the present. In addition, Marchitto et al. (1998) found evidence that deep-water formation was replaced by the formation of glacial N Atlantic intermediate water (NAIW). Both cases (formation of UNADW or NAIW) would result in a shallower THC and in surface cooling that would be less than in the case of a shutdown. This would be consistent with ocean core evidence for N Atlantic ventilation during the YD (Charles and Fairbanks, 1992) and with climate modelling (Rahmstorf, 1994). However, a shallower THC would mean less surface cooling and thus, this would be insufficient to explain the terrestrial geological evidence for intense cooling during the YD, i.e. a mean annual temperature of −1 to −8°C in W Europe (Renssen and Isarin, 1998; Isarin et al., 1998). Recently, Broecker (1997, 1998) suggested that, after the start of the YD, the weakening of the THC in the N Atlantic was accompanied by enhanced deep-water production in the Southern Ocean. In this situation, the climate in the Northern Hemisphere would be in anti-phase with the climate in the Southern Hemisphere.

Although acceptance of the shallower THC hypothesis may explain part of the geological evidence for the YD, the important question what the trigger for the THC weakening exactly was, remains to be answered. The timing of the meltwater pulses, being the proposed source of perturbation, causes a problem. The main late glacial meltwater pulse found by Fairbanks (1989) is dated at 14 ka cal BP, thus at least 1000 years before the start of the YD (Bard et al., 1996). Maybe, regional meltwater pulses, occurring near locations of NADW formation, could have perturbed the THC. However, ocean records near the mouth of the St Lawrence river suggest the opposite, giving evidence of a *reduced* meltwater outflow from the Laurentide ice sheet near the start of the YD (de Vernal et al., 1996). Also, the initial drainage of the Baltic ice lake (i.e. near the location of LNADW formation) occurred a few hundred years after the start of the YD (Bodén et al., 1997). In any case, ice rafting can be excluded as the trigger, since ocean cooling started before the ice rafting occurred (Bond, 1995). Moreover, the ice sheets in N America, Scandinavia and Iceland fluctuated coherently, thus implying that ice rafting was triggered by climate and not vice versa (Fronval et al., 1995; Bond and Lotti, 1995).

Geological evidence from various sites in the tropics and the Southern Hemisphere suggests a synchronous and global nature of the YD cooling (e.g., van Geel and van der Hammen, 1973; Roberts et al., 1993; Lowell et al., 1995; Thompson et al., 1995; Zhou et al., 1996). However, the global nature of the YD cooling is still debated, as others find no evidence for climate change in the Southern Hemisphere during the YD (e.g., Heine, 1993; Peteet, 1995). This issue is further complicated by Antarctic ice core records. Data from the Byrd and Vostok cores show the occurrence of a cool phase (named the Antarctic Cold Reversal) a thousand years *before* the start of the YD in the N Atlantic region, followed by a relative warm phase (Blunier et al., 1998). In contrast, the stable isotope record from the Taylor Dome ice core reveals a deglacial climate evolution synchronous with the Greenland ice cores (Steig et al., 1998). It has been argued that both these responses, i.e. relative cooling and warming during YD time in Antarctica, could follow from the THC-weakening hypothesis. The occurrence of Antarctic warming during YD time could imply that a reduced NADW formation could be accompanied by a compensating enhanced deep-water formation in the Southern Ocean (Broecker, 1998). On the other hand, an Antarctic cooling during YD time could be the result of reduced upwelling of relatively warm NADW near Antarctica, followed by an increase in sea ice and further cooling (Crowley and Parkinson, 1988). In some coupled atmosphere–ocean model experiments with a THC shutdown both these effects have been observed, resulting in both warming and cooling over Antarctica, depending on the location (e.g., Mikolajewicz et al., 1997; Schiller et al., 1997). However, the cooling in the tropics and the mid-latitudes of the Southern Hemisphere that is registered in various records (Roberts et al., 1993; Lowell et al., 1995; Thompson et al., 1995; Bard et al., 1997) is not reproduced in these THC-shutdown experiments. Thus, the THC-weakening hypothesis provides an answer for only a part of the global evidence for the YD.

The previous paragraphs show that the THC-weakening hypothesis alone is insufficient to explain all aspects of the YD, i.e. the extreme cooling in NW Europe and the registration in the tropics and the mid-latitudes of the Southern Hemisphere. This suggests that the mechanism forcing the YD may be more complicated and involves additional processes. Here we review the hypothesis that a reduction in solar irradiance triggered the start of the YD.

3. Indications for solar forcing of the start of the YD

So far, variations in solar irradiance have not been taken seriously as a trigger mechanism for climate change during the Late Pleistocene. Yet, for several climate change events during the Holocene variations in solar activity are considered as the forcing mechanism, for instance the Little Ice Age (e.g., Lean et al., 1995; Mann et al., 1998; van Geel et al., 1999a) and a global cooling event at 850 BC (van Geel et al., 1996, 1998; van Geel and Renssen, 1998). We discuss here the various lines of evidence for a triggering of the YD by an abrupt and strong reduction in solar activity.

3.1. Evidence for variations in solar activity derived from cosmogenic isotopes

Evidence for solar variations in the geological past may be inferred from cosmogenic isotope records (Hoyt and Schatten, 1997). The two most important of these isotopes are carbon-14 (^{14}C) and beryllium-10 (^{10}Be), both produced by the action of cosmic rays in the upper atmosphere. The intensity of cosmic rays reaching the earth depends on the strength of the interplanetary magnetic field, which in turn is modulated by variations in solar activity (Hoyt and Schatten, 1997). Carbon-14 enters the global carbon cycle via CO_2, whereas solid ^{10}Be precipitates with aerosols and is recorded in sediments and ice cores. This production scheme implies that records of ^{14}C and ^{10}Be may be considered as proxies for changes of solar activity in the past. However, variations in solar irradiance are not the only causes of changes in the ^{14}C and ^{10}Be records. The atmospheric ^{14}C and ^{10}Be production is also modulated by the strength of the geomagnetic field, since the latter affects the cosmic-ray flux reaching earth. In addition, the ^{14}C activity in the atmosphere also depends on the exchange with other ^{14}C reservoirs on earth, being the oceans and the biosphere. Moreover, fluctuations of ^{10}Be in Greenland ice are believed to reflect primarily changes in atmospheric circulation and precipitation and secondarily, variations in solar activity (McHargue and Damon, 1991; Yiou et al., 1997). Despite these different influences on the records of ^{14}C and ^{10}Be, it is interesting to ask the following question: what might the records of these two isotopes tell us about variations in solar irradiance around the start of the YD?

3.1.1. Carbon-14

Measurements of ^{14}C from absolutely (i.e. dendrochronologically) dated tree rings provide the ^{14}C calibration curve (Stuiver et al., 1998), reflecting fluctuations in the atmospheric ^{14}C content in the past. Beyond the tree-ring limit (~ 9900 BC), calibration information is known from corals dated by U/Th (Bard et al., 1998), and by laminated sediments (Goslar et al., 1995; Kitagawa and van der Plicht, 1998; Hughen et al., 1998). These data

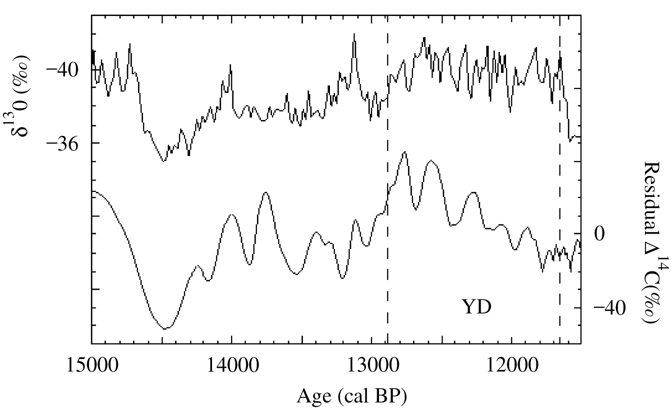

Fig. 1. The late glacial section of the $\Delta^{14}C$ record (lower curve and axis on the right) from INTCAL 98 (after Stuiver et al., 1998). Note the strong increase starting at 13,000 cal BP. For comparison, the GISP2 oxygen isotope ratio is also shown (upper curve and axis on the left, with bidecadal time separation, from Stuiver et al., 1995).

show major wiggles during the Late Glacial of which a prominent one occurs at the start of the YD (see Fig. 1). Estimates for the increase in $\Delta^{14}C$ at the start of the YD all demonstrate a strong and rapid rise: 40–70‰ within 300 years (Goslar et al., 1995), 30–60‰ in 70 years (Björck et al., 1996), 50– 80‰ in 200 years (Hughen et al., 1998) and 70‰ in 200 years (Hajdas et al., 1998). This change is apparently the largest increase of atmospheric ^{14}C known from late glacial and Holocene records (Goslar et al., 1995). Hajdas et al. (1998) used this sharp increase of atmospheric ^{14}C at the onset of the YD as a tool for time correlation between sites.

What are the possible causes for this large increase in atmospheric ^{14}C? Geomagnetic variations are not a likely cause, since these generally act on a much longer time scale (i.e. millennia). Amongst others, Björck et al. (1996) and Goslar et al. (1999) postulate that the increase in ^{14}C at the start of the YD is caused by a decrease of the CO_2 exchange between the atmosphere and ocean, because of stagnation in ocean circulation (i.e. ^{14}C changes as an effect of climate change). If the deep-water formation would weaken or even cease, this would reduce the atmosphere–ocean exchange of CO_2, thus effectively increasing the atmospheric ^{14}C content.

Indeed, in modelling studies the ventilation change is considered as the mechanism responsible for the recorded $\Delta^{14}C$ change. For instance, Stocker and Wright (1996) used a 2D ocean–atmosphere-ice model to try to reproduce the main characteristics of the YD climate and the $\Delta^{14}C$ record. They perturbed their model with the main meltwater pulse of Fairbanks (1989), resulting — with one particular set of parameters — in a THC shutdown during 1500 years. A $\Delta^{14}C$ increase of 35‰ in about 1000 years was calculated at the start of this simulated YD-like event (their Fig. 7a). Similarly, Hughen et al. (1998) used a relatively simple geochemical box model and prescribed a THC shutdown in combination with various other processes, such as NAIW formation and Southern Ocean convection. The best scenario, with a THC shutdown together with increased Southern Ocean convection and doubled gas exchange rates, produces an ~ 45‰ $\Delta^{14}C$ increase in approximately 500 years (their Fig. 5d). Another example is provided by Goslar et al. (1999), who also utilised a global box model. Their best scenario, also with a drastic reduction in NADW formation, resulted in an ~ 40‰ $\Delta^{14}C$ increase in about 500 years (scenario S4 in their Fig. 6). Hence, the discussed modelled $\Delta^{14}C$ rises are slower and smaller than the measured $\Delta^{14}C$ increases at the YD onset (i.e. 50–80‰ $\Delta^{14}C$ increase in 200 years), and therefore, a THC weakening seems only to explain part of the recorded $\Delta^{14}C$ rise. Consequently, an additional mechanism is required to account for the remainder. As discussed below, such an additional mechanism can be provided by an abrupt decline in solar activity and related increase of cosmic-ray flux, which may cause (apart from a sharp rise in atmospheric ^{14}C) changes in climate through various strong positive feedbacks. Hence, unlike Hajdas et al. (1998) who used the $\Delta^{14}C$ increase at the YD onset only as a correlation tool between sites, we propose that this rapid and strong increase is also an indication for solar forcing of the start of the YD.

3.1.2. Beryllium-10

Although less extensive than the ^{14}C data, the ^{10}Be record also gives indications for an increase at the start of the YD. Recently, Finkel and Nishiizumi (1997) published a record of ^{10}Be concentrations from the GISP2 ice core for the period between 40 and 3 ka BP. This record shows that considerable shifts in ^{10}Be concentration occurred during the late glacial. At the start of the YD the concentration nearly doubles (Finkel and Nishiizumi, 1997). It is believed that fluctuations of ^{10}Be in Greenland ice reflect primarily changes in precipitation and secondarily variations in solar activity (McHargue and Damon, 1991; Yiou et al., 1997). Finkel and Nishiizumi (1997) used the ^{10}Be concentrations in ice to calculate the past atmospheric ^{10}Be content. During the last glacial the fluctuations in ^{10}Be concentration clearly parallel the so-called Dansgaard-Oeschger warm/cold cycles. Van Geel et al. (1999b) argue that these fluctuations were primarily caused by a periodically reduced solar activity. They point to the fact the fluctuations are also present in the ^{10}Be fluxes, which do not depend on the precipitation rate as is the case with ^{10}Be concentrations. Moreover, as discussed below, the precipitation rate itself may be modulated by changes in solar activity through the climate–cosmic-ray flux connection. Furthermore, recent new analyses on the GRIP core reveal that the variations in ^{10}Be are similar in shape to those of $\Delta^{14}C$ during the late glacial (Muscheler et al., 1999). This similarity indicates that the variations of these isotopes are primarily governed by changes in production, thus suggesting a strong influence of variations in solar activity.

3.2. Millennial-scale quasi-cycle in the ^{14}C record and other geological data

In the ^{14}C record of tree rings a quasi-cycle of ~ 2500 years was recognised that is supposedly of solar origin (Damon, 1986; Damon and Linick, 1986; Stuiver and Braziunas, 1989; Stuiver et al., 1991). This quasi-cycle was found as the reoccurrence of the so-called triple oscillations, defined by Stuiver and Braziunas (1989) as $\Delta^{14}C$ intervals during which at least two Spörer- and Maunder-type patterns (temporary sharp increases of $\Delta^{14}C$) occurred. The Spörer- and Maunder events were periods (1416–1534 AD and 1645–1715 AD, respectively) with a minimum number of sunspots (Eddy, 1976; Hoyt and Schatten, 1997), thus coinciding with a reduced solar activity (estimated at a 0.4% reduction) and with increases in atmospheric ^{14}C. Stuiver and Braziunas (1989) argue that such century-scale Δ^{14}C variations are best explained by variations in ^{14}C-production rate induced by solar change. This conclusion is partly based on the similarity of the ^{10}Be record and the atmospheric ^{14}C record during the last millennium (Siegenthaler and Oeschger, 1987; Beer et al., 1994). Apparently, the ~ 2500 year quasi-cycle of the triple oscillations reflects variations in solar activity.

The timing of the triple oscillations coincides with the timing of phases with a cool climate, recognised in Greenland ice cores (Dansgaard et al., 1984; O'Brien et al., 1995; Mayewski et al., 1997), but also in proxy data in Europe, N America and the Southern Hemisphere (Denton and Karlén, 1973; Harvey, 1980; Magny, 1993). Within the framework of this paper it is important that the YD fits into this cyclicity, and that the cycle may extend further back into the Pleistocene, as suggested by the findings of Bond and Lotti (1995). In later work it was reported that the YD forms part of a cyclicity of approximately 1500 years, for example in cores in the Atlantic (Bond et al., 1997) and the Indian Ocean (Sirocko et al., 1996), in lake sediments (Campbell et al., 1998) and in the GISP2 ice core (Stuiver et al., 1997). To study this ~ 1500 year cycle, Mayewski et al. (1997) compared the variability of the "polar circulation index" (derived from GISP2 glaciochemical series) of the last 11,500 years with that of the Δ^{14}C record derived from tree rings and corals by Stuiver and Braziunas (1993). Mayewski et al. (1997) found that both series contain a 1450 year periodicity and they conclude that this may suggest a link to climate–solar variability. It must be noted, however, that Stuiver et al. (1997) found no significant correlation between the GISP2 δ^{18}O and Δ^{14}C records spanning the Holocene. An exception is the climate of the last millennium, for which a solar forcing is considered a reasonable hypothesis by Stuiver et al. (1997). The YD is not the only cold event within these quasi-cycles with a possible global impact, as this is also recognised for an event at 850 BC (van Geel et al., 1998) and (some decades within) the Little Ice Age (1450–1850 AD, Bradley and Jones, 1992; Lean and Rind, 1999). The ~ 2500 year quasi-cycle is also recorded in European lake level data as an alternation of Holocene climatic changes (Magny, 1993, 1998; Magny et al., 1998). Fig. 2 (after Magny, 1999) illustrates the marked similarities in a variety of records during

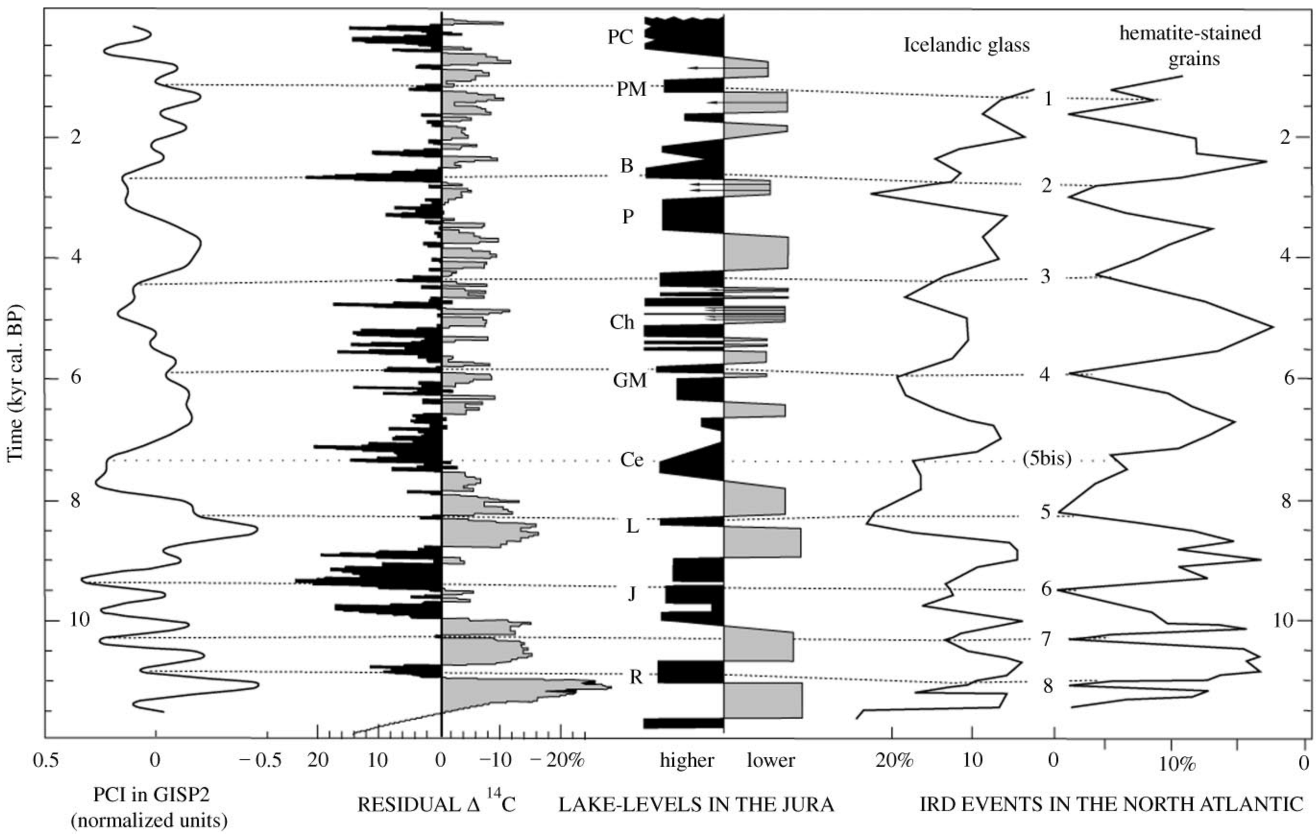

Fig. 2. (After Magny, 1999): Holocene records of the Polar Circulation Index (PCI, positive values indicate relatively cold climate) at GISP2 (Mayewski et al., 1997), the residual Δ^{14}C variations (Stuiver and Braziunas, 1993), lake-level fluctuations in the Jura mountains (Magny, 1995b, 1999) and the ice-rafting (IRD) events marked by Icelandic glass and hematite-stained grains in core VM-29-191 in the North Atlantic (Bond et al., 1997). The PCI curve represents the sum of the energy of the band-pass component covering 2300 + 1400 + 512 yr frequencies. The names of the high lake-level phases are indicated by: R: Remoray, J: Jouz, L: Le Locle, Ce: Cerin, GM: Grand Maclu, Ch: Chalain, P: Pluvis, B: Boruget, PM: Petit Maclu, PC: Petit Clairvaux. For methodology, see explanation in Magny (1998).

the Holocene: the residual $\Delta^{14}C$ record (Stuiver and Braziunas, 1993), ice-rafting events in the N Atlantic (Bond et al., 1997), lake levels in the Jura mountains (Magny, 1998, 1999) and the polar circulation index derived from the GISP2 ice core (Mayewski et al., 1997).

3.3. Summary of evidence

The combination of cosmogenic isotope records and other geological data gives three indications for a triggering of the YD by a reduction in solar irradiance. First, strong increases in the $\Delta^{14}C$ record and to a lesser extent in ^{10}Be measurements support the idea of a reduced solar activity at the start of the YD. Second, the correlation between the $\Delta^{14}C$ triple oscillation and the ~ 2500 year quasi-cycle of cold periods (including the YD) provides further support for the idea that a sudden decline in solar activity could be involved in triggering the YD. Third, an indirect indication is provided by the registration of the YD in records in the tropics and mid-latitudes of the Southern Hemisphere, which could not be explained with the THC-weakening hypothesis alone and suggests the involvement of a larger global-scale climate forcing mechanism. Solar forcing is an important candidate because its expected effect has a global impact (see e.g., Rind and Overpeck, 1993). It must be noted, however, that solar forcing of global climatic change 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 in energy between solar wind and atmospheric processes (four orders of magnitude). Therefore, a strong positive feedback mechanism is required that explains how relatively small variations in solar activity can cause significant climate changes.

4. Mechanisms explaining triggering of climate change by a reduced solar activity

Van Geel and Renssen (1998) proposed two possible scenarios (which do not exclude each other), explaining how a small reduction in solar radiation and a simultaneous increase in cosmic-ray flux may have caused significant climate changes such as the YD (see Fig. 3).

According to the *first scenario,* variations in solar ultraviolet radiation alter the stratospheric ozone production in a way that the latter process could trigger climate change. Such a link is suggested by climate model simulations that were performed by Haigh (1994, 1996) to study the relation between the 11 yr solar activity cycles, ozone production and climate change. First, Haigh (1994) showed with a chemical atmospheric model that

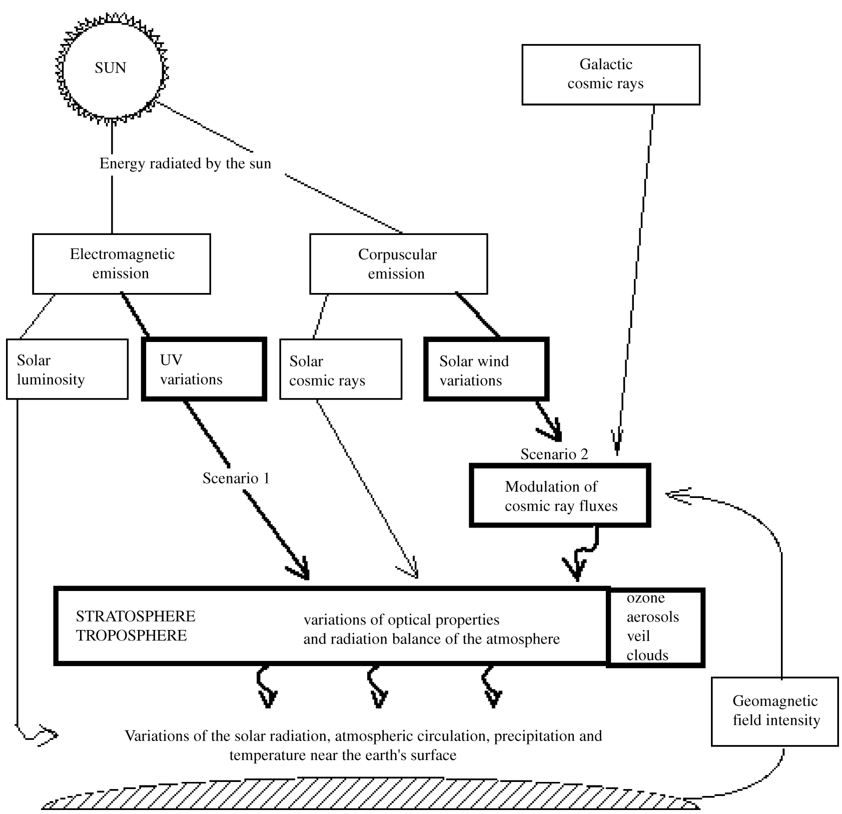

Fig. 3. Scheme showing various solar and cosmic factors relevant to the climate system. The effects of variations in UV and solar wind (i.e. scenario 1 and 2 in bold) are discussed in the text (after van Geel et al., 1999b).

a 1% increase in UV radiation at the maximum of a solar activity cycle generated 1–2% more ozone in the stratosphere. Subsequently, this increase in the stratospheric ozone content was used as input in a climate model experiment (Haigh, 1996), resulting in warming of the lower stratosphere by the absorption of more sunlight. In addition, the stratospheric winds were strengthened and the tropospheric westerly jets were displaced poleward. This poleward shift resulted in a similar displacement of the descending parts of the Hadley Cells, because the position of the westerly jets determines the latitudinal extent of the Hadley cells. Ultimately, this change in atmospheric circulation caused a poleward relocation of the mid-latitude storm tracks. These simulation results of Haigh (1996) were similar (though smaller in magnitude) to observations made by van Loon and Labitzke (1994). Various other modelling studies have confirmed that the solar UV radiation could very well play a significant role in amplifying the effects of the solar cycle from the stratosphere down to the earth surface (Rind and Balachandran, 1995; Lean and Rind, 1998; Shindell et al., 1999; Haigh, 1999).

Although Haigh's experiments focus on a decadal time scale, van Geel and Renssen (1998) proposed that the (opposite) effect may have also played a role in climate changes on a century time scale. For instance at the start of the YD, a reduced solar activity, as indicated by the observed strong increases of atmospheric ^{14}C, could have resulted in a decrease in the stratospheric ozone content. A decrease of the latitudinal extent of the Hadley Cell circulation and an equatorward relocation of the mid-latitude storm tracks in both hemispheres could be the result. The changes described could imply cooling in mid-to-high latitudes in both hemispheres through the expansion of the polar cells. Moreover, the change in the position of the storm tracks would also mean a shift in the main precipitation belts. In addition, this could have affected the stability of the ice sheets in N America and N Europe, possibly leading to an increase in the number of icebergs. The melting of these icebergs together with the relocation of the storm tracks would mean a change in the fresh-water flux to the N Atlantic Ocean. Possibly, this resulted in a perturbation of the THC, since ocean modelling studies show that the THC is very sensitive to changes in the fresh-water input (e.g., Rahmstorf, 1995).

The *second scenario* is based on the idea that an enhanced cosmic-ray flux may directly result in an increase in global cloud cover. A direct link may exist through ionisation by cosmic rays, since this promotes aerosol formation and cloud nucleation. Svensmark and Friis-Christensen (1997) argued that this process is important, as they found an excellent correlation between the variation in cosmic-ray flux and the observed global cloud cover for the most recent solar cycle. An increase in global cloud cover could increase reflection of incoming radiation, thereby cooling the Earth. These inferences are consistent with the findings of Friis-Christensen and Lassen (1991). They found for the period 1861–1989 a good correlation between the length of the solar cycle (as an indicator of solar activity) and the Northern Hemisphere temperature record. Again, one may argue that an increase in cloud cover may indicate a more vigorous hydrological cycle, having a strong impact on precipitation and the fresh-water flux into the Atlantic Ocean.

5. Discussion and conclusion

Recently, van Geel et al. (1999b) postulated that the discussed mechanisms (one or in concert), which could amplify relatively small changes in solar activity, caused climate change during the Holocene and Late Pleistocene. They argued that these scenarios triggered — periodically — sudden and strong increases of cloudiness, precipitation and declining temperatures. These changes could have played a crucial role in producing the regularly occurring iceberg discharges during the Late Pleistocene and Holocene, as recorded in N Atlantic deep-sea cores (Bond et al., 1997). The change in atmospheric circulation and precipitation at the end of the Allerød period, together with the fresh-water input due to melting of icebergs, could have weakened the THC, thus implying a positive feedback that culminated in the YD. Evidence for a sudden and strong increase in precipitation is found in lake levels in Europe. This is illustrated by Fig. 4 (Magny and Richoz, 2000), which shows a steep rise in lake level in Switzerland that was simultaneous with the cooling at the onset of the YD as depicted in the stable isotope record from Greenland.

In summary, we found the following indications that an abrupt reduction in solar irradiance possibly triggered the YD onset:

(1) the large and sharp increase in Δ^{14}C that cannot convincingly be understood on the basis of the THC-weakening mechanism alone,
(2) the YD being one of a number of cold events that fall in an $\sim$2500 year quasi-cycle that is supposedly of solar origin, and
(3) the possible global signature of the YD. Cooling in the tropics and mid-latitudes of the Southern Hemisphere does not follow from the "traditional" hypothesis to explain the YD, i.e. a THC perturbation. This global signature implies a global-scale climate forcing mechanism, for which solar forcing is a likely candidate.

Moreover, the discussed scenarios provide a mechanism to weaken the THC without the necessity of the occurrence of a prominent meltwater pulse. The main deglacial meltwater pulse occurred 1000 years before the YD onset (Fairbanks, 1989; Bard et al., 1996) and could not have

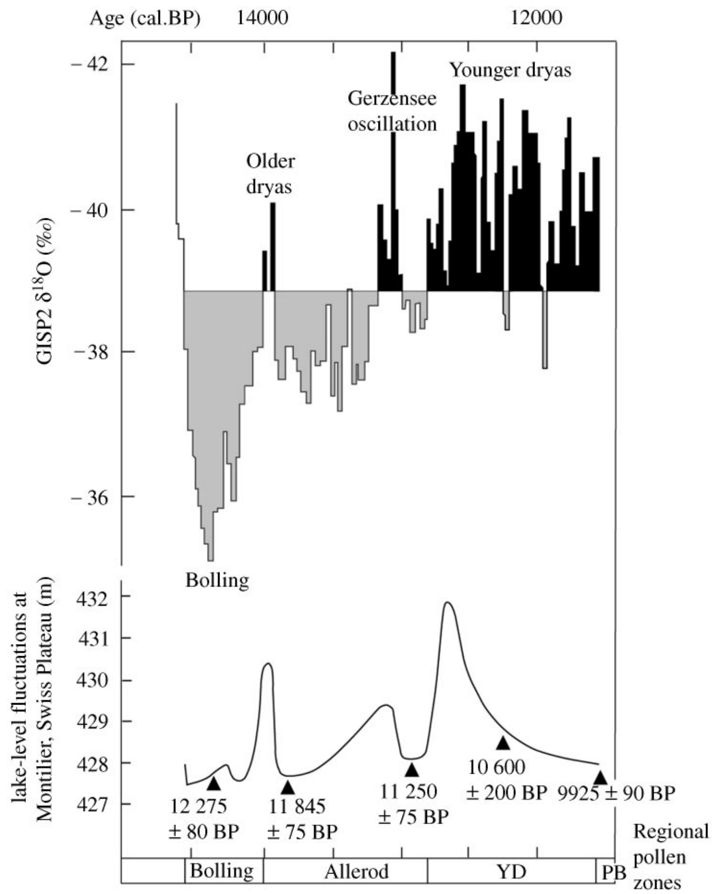

Fig. 4. (After Magny and Richoz, 2000): Late glacial lake-level fluctuations from Lake Morat, Switzerland, correlated with the $\delta^{18}O$ record from the GISP2 Greenland ice core (Stuiver et al., 1995). The lake-level curve is reconstructed using sediment and pollen evidence. Note the strong and rapid rise in lake level right at the beginning of the YD. The marked coincidence of two other cold events, i.e. the Older Dryas and the Gerzensee oscillation, with high lake levels and distinct increases in the $\Delta^{14}C$ record (see Fig. 1) at $\sim$ 14.0 and $\sim$ 13.2 ka cal BP, indicates that a reduced solar activity may also have played a role in forcing these events.

caused the THC weakening. Furthermore, a reduced solar activity in combination with a THC weakening could account for the full magnitude of YD cooling as evidenced in terrestrial records in Europe.

Still, a number of uncertainties remain. Therefore it is of crucial importance that sensitive climate models should be applied to test if the inferred sudden reduction in solar activity could indeed lead to the sequence of processes being part of the discussed scenarios. In addition, the global signature of the YD is still debated and therefore, additional high-resolution records from the Southern Hemisphere are required. Moreover, ^{10}Be measurements in these records could also shed light on the question to what extent shifts in the atmospheric ^{14}C content reflect solar variability.

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