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Major $\Delta^{14}C$ excursions during the late glacial and early Holocene: changes in ocean ventilation or solar forcing of climate change?

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We dedicate this paper to Thomas van der Hammen, one of the pioneers in the study of climate change during the Late Glacial period

Abstract

The atmospheric ^{14}C record during the Late Glacial and the early Holocene shows sharp increases simultaneous with cold climatic phases. These increases in the atmospheric ^{14}C content are usually explained as the effect of reduced oceanic CO_2 ventilation after episodic outbursts of large meltwater reservoirs into the North Atlantic. In this hypothesis the stagnation of the thermohaline circulation is the cause of both climate change as well as an increase in atmospheric ^{14}C. As an alternative hypothesis we propose that changes in ^{14}C production give an indication for the cause of the recorded climate shifts: changes in solar activity cause fluctuations in the solar wind, which modulate the cosmic ray intensity and related ^{14}C production. Two possible mechanisms amplifying the changes in solar activity may result in climate change. In the case of a temporary decline in solar activity: (1) reduced solar UV intensity may cause a decline of stratospheric ozone production and cooling as a result of less absorption of sunlight. This might influence atmospheric circulation patterns (extension of Polar Cells and equatorward relocation of mid-latitude storm tracks), with effects on oceanic circulation, and (2) increased cosmic ray intensity may stimulate cloud formation and precipitation, while ^{14}C production increases.

1. Introduction

The period of the Late Glacial and the early Holocene in the north Atlantic region is characterised by alternations of marked cool phases and relatively warm periods. Rapid and intense cooling occurred at the start of the following cold phases: (1) the Older Dryas, (2) the Gerzensee/Killarney event (both occurring during the Bølling–Allerød warm phase), (3) the Younger Dryas (longest, most pronounced cold phase), (4) the cold phase of the so-called Preboreal oscillation during the early Holocene, and (5) the cold event of 8400–8000 years ago ('8.2 event'). In these five cases, the start of the rapid cooling is simultaneous with a temporary and steep rise of the cosmogenic isotope ^{14}C in the atmosphere. Moreover, two prominent warming phases coincided with abrupt decreases of atmospheric ^{14}C, i.e., the transitions from the Oldest Dryas to the Bølling, and from the Younger Dryas to the early Preboreal.

Major changes of atmospheric radiocarbon ($\Delta^{14}C$) during the Late Glacial and early Holocene are normally used as an indication of ocean ventilation changes related to deep water formation. In this "oceanocentric" hypothesis the changes in $\Delta^{14}C$ are thus considered as *effects* of climate change, because increases (decreases) in the release of oceanic CO_2 (with relatively low ^{14}C content) into the atmosphere would cause lowering (rising) of atmospheric $^{14}CO_2$ levels. Sudden meltwater inputs into the ocean after drainage of Laurentide and Scandinavian glacial lakes, are considered as the trigger for changes from relatively warm to cold climatic conditions (Broecker et al., 1985, 1990; Stuiver and Braziunas, 1993; Goslar et al., 1995; Bond et al., 1997; Broecker, 2000). The freshwater pulses should have decreased the salinity-driven formation of deep water in the northern parts of the Atlantic Ocean, thus reducing heat transport to the Northern Hemisphere. In this interpretation the possibility of solar forcing of climate change (reflected in a ^{14}C production rise during periods

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of low solar activity) is ignored because "the solar modulation alone is inadequate for the oscillations of the last deglaciation" (Björck et al., 1996). We do not consider this hypothesis as the only possible explanation. Based on Holocene evidence of climatic fluctuations in relation to changes of the atmospheric radiocarbon content (de Vries, 1958; Denton and Karlén, 1973; Magny, 1993; van Geel et al., 1998, 1999; van Geel and Renssen, 1998; Mauquoy et al., 2002), we come to an alternative hypothesis (compare Renssen et al., 2000) that is worthy of testing. Here we give a short overview of the evidence for climate change in the period concerned. Subsequently, we present our alternative hypothesis, in which changing solar activity (reflected in $\Delta^{14}C$ changes) is considered as the trigger for abrupt climate change.

2. Reconstruction of the changes in atmospheric ^{14}C

The atmospheric ^{14}C record (calibration curve and derived $\Delta^{14}C$ signal) of the Holocene is based on radiocarbon dates of dendrochronologically dated wood. From the present time back to ca. 11,800 years ago (cal BP) absolutely dated oak and floating pine trees were used. The presently recommended calibration curve is called INTCAL98 (Stuiver and van der Plicht, 1998). The part of INTCAL98 for the time preceding the record covered by the tree rings is based on marine varves (Hughen et al., 1998) and corals dated by both ^{14}C and U-series (Bard et al., 1998; Burr et al., 1998). In addition, changes in ^{14}C are measured from laminated lake sediments (Lotter et al., 1992; Hajdas et al., 1993; Goslar et al., 1995; Björck et al., 1996; Kitagawa and van der Plicht, 1998). These records are not incorporated in INTCAL98 because of questions concerning the "absolute" character of the laminations, but contain important information for ^{14}C reconstruction during the Glacial period. The time-control for the pre-tree ring period becomes more uncertain going back in time beyond the Holocene.

3. Relatively low $\Delta^{14}C$ values during warm periods and rising $\Delta^{14}C$ values during cold events; different interpretations

In this section we describe the most prominent phases of climate change, following the event stratigraphy and dating for the Late Glacial period as proposed by the INTIMATE group (Björck et al., 1998). In their terminology GS means Greenland Stadial, whereas GI stands for Greenland Interstadial. For practical reasons we also mention the old chronozones. The evidence as mentioned below comes from different studies of various lake deposits. Up to now there is no complete record (from one core) available, showing the Late Glacial and early Holocene climate changes as expressed in the vegetation development, in relation to a detailed ^{14}C record from the same core. The part of INTCAL98 for the time preceding the record covered by the tree rings is probably not detailed enough for ^{14}C wiggle matching. For those reasons we refrain from including an illustration here. The combination of a pollen record and a more detailed ^{14}C record from Lake Suigetsu (Kitagawa and van der Plicht, 1998) or such a combined record from a similar site elsewhere is urgently needed.

3.1. *Transition GS-2a/GI-1e (ice core age 14,700): transition Oldest Dryas/Bølling interstadial*

The transition from the Late Pleniglacial (Oldest Dryas) to the Bølling interstadial is characterised by a sharp decline of the atmospheric radiocarbon content, and the warmest phase of GI-1e, as evidenced by the oxygen isotope curves of Greenland ice cores, shows a deep $\Delta^{14}C$ minimum. The conventional interpretation for this phenomenon is that the start of the thermohaline circulation resulted in a strong increase in ocean ventilation (decline of atmospheric $^{14}CO_2$).

3.2. *GI-1d (ice core age 14,050–13,900): Older Dryas*

The Older Dryas event was a relatively cool episode during the warm Bølling/Allerød interstadial. Based on the evidence from Swiss lakes (Ammann and Lotter, 1989) and unpublished records, Björck et al. (1996) concluded that the atmospheric ^{14}C values rose during the Older Dryas, as a consequence of stagnation of ocean ventilation after a huge meltwater peak.

3.3. *GI-1b (ice core age 13,150–12,900): Gerzensee/Killarney event*

The amphi-Atlantic Gerzensee/Killarney cooling event, which started ca. 500 years before the onset of the cold Younger Dryas (Levesque et al., 1993) was accompanied by rising $\Delta^{14}C$ values (Björck et al., 1996 and references therein). Björck et al. (1996) interpret the rise in $\Delta^{14}C$ as an indication for a declining ocean ventilation caused by a temporary stagnation in the thermohaline circulation in the North Atlantic.

3.4. *GS-1 (ice core age 12,650–11,500): Younger Dryas*

The start of the cold Younger Dryas is characterised by a steep rise of $\Delta^{14}C$ (Goslar et al., 1995; Björck et al., 1996; Hajdas et al., 1998; Hughen et al., 1998). Björck et al. (1996) explain both the $\Delta^{14}C$ rise and the start of the cold period as the effect of a sudden stop of the thermohaline circulation after a meltwater peak into the North Atlantic Ocean.

3.5. Preboreal; Preboreal cooling phase

The Preboreal started around 11,500 years ago with rising temperatures (Friesland phase) during a period of declining ^{14}C values (^{14}C-plateau in the calibration curve). In the "oceanocentric" hypothesis this is an indication for good ocean ventilation (Björck et al., 1996).

A 150-year-long cooling, about 300 years after the start of the Preboreal, was associated with abruptly rising Δ^{14}C. Again, Björck et al. (1996, 1997) interpreted this as an ocean ventilation minimum.

3.6. '8200 years ago cold event'

A cold event of 8400–8000 years ago, as recorded in oxygen isotope records from Greenland ice (Alley et al., 1997) and in European lake sediments (von Grafenstein et al., 1998, 1999) is explained by Barber et al. (1999) as the effect of a drainage of Laurentide lakes into the North Atlantic. This freshwater perturbation should have caused reduced surface salinity and stagnation of the thermohaline circulation (reduced heat transport and thus reduced heat transfer from the ocean to the atmosphere) in the North Atlantic Ocean.

In summary, in the conventional hypothesis the major climatic changes during the Late Glacial and early Holocene are explained by variations in ocean ventilation. However, we argue that the strong variations in Δ^{14}C were caused by variations in solar activity (cf. van Geel et al., 1999; Renssen et al., 2000). In turn, these variations in solar activity could have triggered the observed climatic changes, most likely involving changes in ocean circulation. In the following section we discuss the mechanisms behind this "heliocentric" hypothesis. Moreover, we mention additional circumstantial evidence that supports this hypothesis.

4. The alternative hypothesis: solar forcing as the trigger for climate change?

Major atmospheric fluctuations of the cosmogenic isotope ^{14}C may largely have been caused by changes in solar activity and related fluctuations in cosmic ray intensity (Beer et al., 2000). The start of relatively cold periods during the Late Glacial and the early Holocene are characterised by sharp rises in Δ^{14}C and we hypothesise that this indicates that solar forcing was the trigger for these climate changes. So in our (heliocentric) hypothesis, the changes in Δ^{14}C are not in the first instance the *effect* of climate change (compare Björck et al., 1996), but they reflect the triggering factor of climate change, viz., changes in solar activity.

According to van Geel and Renssen (1998) there are two factors that might be involved in amplifying (relatively small) changes in solar activity. The first factor is the variation in solar UV radiation, which controls stratospheric ozone production and could trigger climate changes. The importance of UV radiation is suggested by the modeling studies of Haigh (1994, 1996), who performed simulations with climate models to study the relation between the 11-year solar activity cycles, ozone production, and climate change. She applied a chemical atmospheric model to show that a 1% increase in UV radiation at the maximum of a solar cycle generated 1–2% more ozone in the stratosphere. Moreover, this ozone surplus was used as an input in a climate model, which resulted in warming of the lower stratosphere by the absorption of more sunlight. Furthermore, a strengthening of the stratospheric winds and a poleward displacement of the tropospheric westerly jets was observed. The position of these jets determines the latitudinal extent of Hadley Cell circulation and, therefore, the poleward shift of the jets resulted in a similar displacement of the descending parts of the Hadley Cells. Ultimately, the change in circulation caused a poleward relocation of mid-latitude storm tracks. Recently, Shindell et al. (1999) confirmed the findings of Haigh (1996), with simulation experiments that were performed with an improved climate model. Changes in atmospheric circulation, related to the phenomena described by Haigh, may also have played a role in climate changes during the Late Glacial and the early Holocene (compare van Geel et al., 1998, 2000; Mauquoy et al., 2002 for late Holocene climate change). Reduced solar activity during the colder periods, as indicated by the observed strong increases of atmospheric radiocarbon, could have resulted in a reduction of stratospheric ozone. A decrease in latitudinal extent of the Hadley Cell circulation with equatorward relocation of mid-latitude storm tracks and an equatorward extension of the Polar Cells would follow in both hemispheres.

The second factor is the direct effect of an increase in cosmic ray flux, which may cause an extended global cloud cover. According to Pudovkin and Raspopov (1992) and Raspopov et al. (1998), ionisation by cosmic rays positively affects aerosol formation and cloud nucleation. An indication of the importance of this process was recorded by Svensmark and Friis-Christensen (1997), who found a strong correlation between the variation in cosmic ray flux and observed global cloud cover over the most recent solar cycle. An increase in global cloud cover is believed to cause cooling of the Earth, especially when low altitude clouds are involved, because more incoming radiation is reflected. Earlier, Friis-Christensen and Lassen (1991) analysed the historical period of 1861–1989 and found a similarity between the temperature record in the Northern Hemisphere and length of the solar cycle as an indicator of solar activity. Increases in cloudiness and precipitation and accompanying cooling during the relatively cold periods of the Late Glacial and early Holocene may have occurred under the influence of temporary increased cosmic ray intensities (also causing abrupt and steep increases of the cosmogenic isotope ^{14}C in the atmosphere).

Extended climatic cooling induced by one or both of these amplifying mechanisms is possible from the atmosphere–ocean interaction proposed by Bjerknes (1965). This interaction is the result of the anomalous atmospheric circulation that creates sea surface temperature anomalies through changes in windstress heat transport. In turn, the pattern of ocean surface temperature anomalies favours the persistence of the triggering anomalous atmospheric circulation. Consequently, an ocean–atmosphere feedback cycle is created that may last for several decades or centuries. Regional differences in the intensity and duration of the feedback cycle may exist due to differences in the geometry and depths of the oceans.

In our hypothesis we do not deny positive feedback mechanisms related to the reaction of the ocean to solar forced changes in atmospheric circulation patterns (Stuiver and Braziunas, 1993). Increased precipitation after a change in the position and intensity of storm tracks and/or by an increase in cloud cover, could well have disturbed the thermohaline circulation in the North Atlantic (van Geel and Renssen, 1998). It is important to realise that the "oceanocentric" and "heliocentric" hypotheses imply different geographical distributions of the climatic changes. The "oceanocentric" hypothesis implies a strong regional effect in the N Atlantic region that is possibly transported over the Northern Hemisphere mid-latitudes. In contrast, our "heliocentric" hypothesis implies global climate change with significant effects at all latitudes in both hemispheres. In other words, if evidence for the climatic changes discussed in this paper is found outside the Northern Hemisphere mid-latitudes, this would argue in favour or our "heliocentric" hypothesis.

It is important to note that all of the cooling phases mentioned coincide with ice-rafting events as recognised in N Atlantic Ocean sediments (Bond et al., 1997). These ice-rafting events occurred throughout the last glacial and Holocene with a cyclicity close to 1470 ± 500 years. Two characteristics of this cyclicity should be mentioned here: (1) the cyclicity is similar in both glacial and interglacial climatic records (Bond et al., 1997), (2) the cyclicity has been recognised in proxy records from all latitudes (e.g. Heusser and Sirocko, 1997; Campbell et al., 1998). It may be argued that these characteristics point to a forcing mechanism external to the earth (most likely variations in solar output), since it is extremely difficult to come up with an internal mechanism that has a global effect on climate and that operates on similar time-scales under all conditions.

It is evident that the use of both cosmogenic isotopes (^{14}C,^{10}Be) in the reconstruction of solar forcing of climate change is valuable but complicated, as the record cannot be interpreted in a straightforward way. Atmospheric radiocarbon fluctuations do not only depend on the variable cosmic ray intensity (modulated by solar wind). Some reservoirs in the carbon cycle (biosphere, ocean) also play a role, and may influence the atmospheric record of ^{14}C as present in tree rings, peat deposits and lake deposits. Beryllium-10 does not have reservoirs. However, the ^{10}Be record in Greenland ice cores is not a direct reflection of cosmic ray intensity and solar activity. Before ^{10}Be is embedded in ice, variable wind-transport may change the amount which is deposited, and thus the ^{10}Be record itself can be climate-modulated. The combination of detailed ^{14}C and ^{10}Be data (Beer et al., 2000) will certainly throw more light on the question about solar forcing of the Late Glacial and early Holocene climate changes. Detailed ^{14}C AMS records from annually laminated lake sediments—in combination with palynological studies, stable isotope records and geochemical studies from the same cores—are of crucial importance to understand the mechanisms of climate change and to build up a fine-resolution chronology of the recorded events.

5. Conclusion

Temporary sharp fluctuations of the atmospheric ^{14}C content during the Late Glacial and early Holocene may well, like middle and late Holocene atmospheric ^{14}C shifts, reflect solar forcing of climate change in the first place. Reactions of the ocean circulation (stagnation of the thermohaline circulation) in the North Atlantic, triggered by solar forced changes in atmospheric circulation (increased precipitation?), may have amplified both increases in atmospheric ^{14}C (by reduced ocean ventilation), and climate change to colder conditions. Future research may provide support for this hypothesis by: (1) a strong correlation between the ^{14}C record and global ^{10}Be data, and (2) a global distribution of the discussed climatic changes.

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