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Journal of Atmospheric and Solar-Terrestrial Physics 66 (2004) 313–322

Journal of ATMOSPHERIC AND SOLAR-TERRESTRIAL PHYSICS

www.elsevier.com/locate/jastp

Evidence for a link between the flux of galactic cosmic rays and Earth's climate during the past 200,000 years

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Received 24 April 2003; received in revised form 8 October 2003; accepted 10 December 2003

Abstract

The possibility that galactic cosmic rays (GCR) influence the Earth's cloud cover and therefore have an important impact on the Earth's radiative climate forcing has become a leading candidate to explain the observed sun–climate connection. A correlation between GCR and low cloud cover has been ascertained in models and observations over the past few years. The deposition of cosmogenic radionuclides in ice cores and deep sea sediments can be used as a proxy for the past GCR-flux and provides an important tool to study the supposed GCR–climate connection on glacial–interglacial timescales. In this study, a record of geomagnetic paleointensity based on ^{10}Be from deep sea sediments is used as proxy for GCR-flux over the past 200,000 years. It is compared with climate records from marine, terrestrial and ice core archives. Our results are consistent with the GCR–climate theory and suggest the existence of a GCR–climate connection over the past 200,000 years.

Keywords: Cosmic rays; Causality problem; Magnetic field; Speleothems; Orbital forcing; Paleoclimate

1. Introduction

There is little doubt that solar variability affects terrestrial climate on centennial and subcentennial timescales (Reid, 1997). For example, the so-called Little Ice Age between 1550 and 1850, during which temperatures were about 1°C colder than average, was most likely caused by reduced solar activity (Maunder and Dalton minimum) (Eddy, 1976). The presence of the solar 11-year Schwabe-cycle is seen in a wide range of tropospheric and stratospheric parameters (Labitzke and Van-Loon, 1993; Van-Loon and Labitzke, 1991).

In general, solar variability can be separated into two main components: the variation of electromagnetic (radiative) output and the modulation of the interplanetary magnetic field (IMF) via the solar open magnetic flux. Direct satellite-based observations of these two parameters exist only for the last few decades, and we have little knowledge of both the sun's long-term variability and the coupling between radiative solar output and open magnetic flux (Lean et al., 2002).

However, measured total solar irradiance only varies by about 0.1% (Fröhlich, 2000), so that a direct solar irradiance effect on climate is generally considered to be too small to cause the observed temperature change. A leading candidate to explain the link between relatively feeble solar fluctuations and climate is the effect of solar (magnetic) modulated galactic cosmic rays (GCR) on cloud formation (Editors of science, 2002). Although the contribution of clouds to the global radiative forcing is not well known, and the level of scientific understanding of cloud-forming tropospheric aerosols is very low, their contribution to the global radiative climate forcing is estimated to be about -28 W/m^2 (Hartmann, 1993). This is one order of magnitude larger than the radiative forcing caused by the anthropogenic

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1364-6826/$ - see front matter
doi:10.1016/j.jastp.2003.12.004

greenhouse gases (IPCC, 2001). Despite uncertainties understanding the microphysical processes, recent model calculations (Marsden and Lingenfelter, 2003; Yu, 2002) confirm the observed correlation between low cloud cover and GCR-flux (Marsh and Svensmark, 2000).

The Earth's magnetic field modulates the GCR-flux, impinging on the Earth's atmosphere, on a longer (millennial) timescale than the sun, but on the same order of magnitude (Masarik and Beer, 1999). If a link between solar-modulated GCR-flux and climate exists, it is expected to persist on longer (glacial/interglacial) timescales due to the long term variability of both the geomagnetic and the heliomagnetic field.

In this paper we show evidence that the suggested GCR–climate link possibly existed over the last 200,000 years. Because of the limited knowledge surrounding the microphysical details of the suggested link, our argumentation is rather qualitative and straightforward: a ^{10}Be-based record of geomagnetic paleointensity (GPI) (Christl et al., 2003) is used as a proxy for the GCR-flux over the past 200,000 years. To test the GCR–climate hypothesis this record is compared to climate records from speleothems and the Vostok ice core.

There are many problems and debates surrounding the synchronization of absolutely dated (Th/U-ages) terrestrial archives with orbitally tuned marine and ice core records (SPECMAP-chronology (Martinson et al., 1987; Muller and MacDonald, 1997)). As long as there is no consensus regarding the chronologies, this comparison has to remain qualitative and may be affected by dating uncertainties of the orbitally tuned SPECMAP age model. Nevertheless, this work provides important arguments for the suggested link between GCR and climate within the ongoing discussion about the impact of GCR on the Earth's climate.

2. Records of GPI, GCR and their comparison with Earth's climate

2.1. ^{10}Be-*based reconstruction of GPI and the GCR-flux over the last 200,000 years*

Cosmogenic radionuclides like ^{14}C and ^{10}Be are produced by GCR and deposited in ice cores and deep sea sediments. On a longer (millennial) timescale their production rate is assumed to vary inversely with the intensity of the Earth's magnetic field (Lal and Peters, 1967; Masarik and Reedy, 1995). The depositional flux of ^{10}Be in deep sea sediments has been used as a proxy for the reconstruction of GPI (Frank, 2000; Frank et al., 1997; Lao et al., 1992). However, a variation of the Earth's magnetic field is not the only factor influencing the deposition of ^{10}Be in deep sea sediments. Besides other factors, such as long-term solar magnetic variability (Sharma, 2002) and a variable GCR-source (Shaviv, 2002), it has been suggested that climatically induced oceanic transport signals potentially overprint the global production signal (Kok, 1999). Recently, Christl et al. (2003) illustrated that the transport of ^{10}Be in the ocean can be quantified. Their reconstruction of GPI is based on transport-corrected ^{10}Be-records and shows a good correlation with two recently developed high-resolution reconstructions based on natural-/anhysteretic remanence magnetization data (NRM/ARM) from North Atlantic sediment cores (Laj et al., 2000) and ^{36}Cl and ^{10}Be concentration in the GRIP ice core (Wagner et al., 2000). However, discrepancies exist between remanence- and cosmogenic radionuclide-based reconstructions of GPI. For example, in the time slice between about 110 and 150 kyr, unexplained deviations between two ^{10}Be-based GPI-reconstructions and the remanence-based stacked GPI-record (SINT 200-record) by Guyodo and Valet (1996) is reported by Christl et al. (2003) and Frank et al. (1997). This deviation might be explained by a long term magnetic variability of the sun and/or a variation of the GCR-source (see also end of Section 2.3).

2.2. *GPI and climate*

Numerous reconstructions of GPI from magnetic remanence measurements in sediment cores are available (Guyodo and Valet, 1996; Juarez and Tauxe, 2000; Laj et al., 2000; Meynadier et al., 1992; Stoner et al., 2000, 2002; Valet and Meynadier, 1993; Yamazaki and Ioka, 1994). The question whether large climatic changes during the last hundred of thousands of years may be associated with changes of the Earth's magnetic field has been subject to many investigations (Channell et al., 1998; Wollin et al., 1978; Worm, 1997; Yamazaki and Oda, 2002; Yokoyama and Yamazaki, 2000) but led to ambiguous results: Orbital frequencies that indicate a link between the Earth's magnetic field and climate have been found in several paleointensity (PI) records (e.g. Channell et al., 1998; Meynadier et al., 1992; Yamazaki and Ioka, 1994; Yamazaki and Oda, 2002). For the Ontong–Java Plateau, PI was found to correlate with temperature (Tauxe and Shackleton, 1994), and a correlation between PI and climate may be suspected. However, Worm (1997) rejected the suggested link because the discrepancy in results between the different records. For example, in the record of Valet and Meynadier (1993) GPI anticorrelates with δ^{18}O, and Kent and Carlut (2001) did not find any direct systematic relationship between geomagnetic reversals and orbital parameters. In contrast, a recent high-resolution study by St-Onge et al. (2003) suggests that a link between GPI, GCR and climate existed throughout the Holocene on centennial to millennial timescales.

The different results highlight the complications associated with the development of a reliable PI record based on magnetic remanence measurements. Besides the Earth's magnetic field, there are many other factors that also influence the intensity of the NRM-signal such as variations in mineralogy, grain size, concentration of magnetic remanence carriers, sedimentation rate, depositional environment, bioturbation, diagenesis, compaction, and coring or sampling-induced disturbance (Stoner et al., 2000). Therefore it is not yet clear if, for example, the existence of orbital frequencies in many GPI records are an indicator for climatically induced artificial remanence signals, or if this shows that these frequencies are field-immanent, which, if the GCR-hypothesis is true, might indicate a possible relation between the geomagnetic field and climate.

2.3. GCR-flux and climate

Generally, it is assumed that the Earth's magnetic field is the primary factor influencing the GCR-flux on longer (millennial) timescales. To test the GCR–climate-hypothesis, it appears reasonable to use a remanence-based PI-record as proxy for the GCR-flux and to compare it with climate records. However, the flux of GCR may also be influenced by long-term solar magnetic activity (Sharma, 2002), or by changes of the source of GCRs (Shaviv, 2002). The production of cosmogenic radionuclides is directly related with the GCR-flux to the Earth's atmosphere regardless of the cause of its variation while remanence-based records of GPI only reflect changes of the Earth's magnetic field. Consequently, records of cosmogenic radionuclides rather than remanence-based GPI-records should be used to test the GCR–climate-hypothesis.

In this study, a ^{10}Be-based reconstruction of GPI by Christl et al. (2003) (shown in the middle of Fig. 1) is used as a proxy for the GCR-flux over the past 200,000 years. The calculation of the GPI-record was based on the assumption that the observed variations in the transport corrected ^{10}Be-fluxes into deep sea sediments are solely caused by variations of the geomagnetic field. Consequently, the GPI-record was calculated under the assumption of a constant mean solar magnetic activity and a constant source of GCR-flux. If there is a long-term solar magnetic activity or any other cause influencing the ^{10}Be production, this would, in this case, be fully translated into geomagnetic variability (but it would be still present in the GPI-record). Thus, the ^{10}Be-based GPI-record shown in Fig. 1 can be used as a GCR-record over the past 200,000 years. If there is any other cause except for the geomagnetic field influencing the ^{10}Be-production on glacial/interglacial timescales, deviations between the ^{10}Be-based and the NRM-based reconstructions of GPI (e.g. the SINT 200 record, see Section 2.1) are expected.

In summary, for the qualitative comparison presented in this study the ^{10}Be-based reconstruction of GPI (Fig. 1) is interpreted as a record of GCR-flux at the Earth over the last 200,000 years, where low (solar- or geo-) magnetic fields denote high GCR- fluxes and stronger magnetic fields indicate less GCR reaching the Earth's atmosphere.

2.4. GCR–climate-hypothesis at maximum GCR-flux

A quantitative analysis of the relationship between geomagnetic field intensity and GCR-flux (assuming constant solar magnetic activity) reveals that a doubling of the present field intensity causes a reduction of GCR-flux by only 20%, whereas a reduction of the field by 10% of its present value almost leads to a doubling of the GCR-flux. The same would be expected if the influence of the solar magnetic field is analyzed (assuming constant geomagnetic activity). In case of constant mean solar activity, one would expect a large impact of GCR-flux on climate at a pronounced minimum of the Earth's magnetic field, a so-called global geomagnetic anomaly or event. Using this argument, Wagner et al. (2001) compared the flux of ^{10}Be and ^{36}Cl with climate proxies (δ^{18}O and CH_4) in the GRIP ice core during the Laschamp event, a minimum of Earth's magnetic field, dated between 36 and 41.5 kyr before present. In their study, they did not find a significant correlation between the GCR-flux and climate signals in the GRIP ice core, therefore they concluded that during this time period the GCR-flux had no influence on climate.

The Laschamp event at about 41 kyr occurs during Marine Oxygen Isotope Stage 3 (MIS 3: 59–29 kyr) during which temperatures in Greenland were already cold. During Stage 3 several cold events (Heinrich events), here particularly H4 at about 39 kyr (Heinrich, 1988) occurred around the North Atlantic, and were most probably associated with a breakdown in the thermohaline ocean circulation (Ganopolski and Rahmstorf, 2001; Paillard and Cortijo, 1999; Rahmstorf, 2002; Stocker and Wright, 1991). In Greenland, stadials have been equally cold with or without Heinrich events, whereas further south in the Atlantic region, Heinrich events clearly manifest themselves as cold intervals with even larger absolute temperature variation than observed during Dansgaard/Oeschger event warmings (Bard et al., 2000; Cacho et al., 1999; Rahmstorf, 2002). It seems that large climate changes (Heinrich events) in the North Atlantic region due to a breakdown in thermohaline circulation during stadial MIS 3 did not lead to further cooling in Greenland. Considering these results, it becomes questionable if the oxygen isotope signal in Greenland during MIS 3 would react sensitively to further cooling caused by high GCR fluxes during geomagnetic minima. A variable δ^{18}O—temperature relationship at high latitudes further constrains the use of δ^{18}O as proxy for global climate (Hendricks et al., 2000; Jouzel et al., 1997).

The methane concentration in the GRIP ice core probably reflects a more global climate signal than that one provided by the oxygen isotopes. Although the correlation with ^{10}Be and ^{36}Cl fluxes at GRIP ice core is higher than with the δ^{18}O-record, it is still not significant (Wagner et al., 2001). In contradiction to the results by Wagner et al. (2001), data from the southern hemisphere EPICA ice core show that there is some qualitative correlation between GCR-flux (^{10}Be-concentration) and climate (delta deuterium) (Raisbeck, 2002).

In this paper, we compare climate records (growth periods of speleothems in mid- and low-latitudes and the Vostok temperature record form Antarctica) with the flux

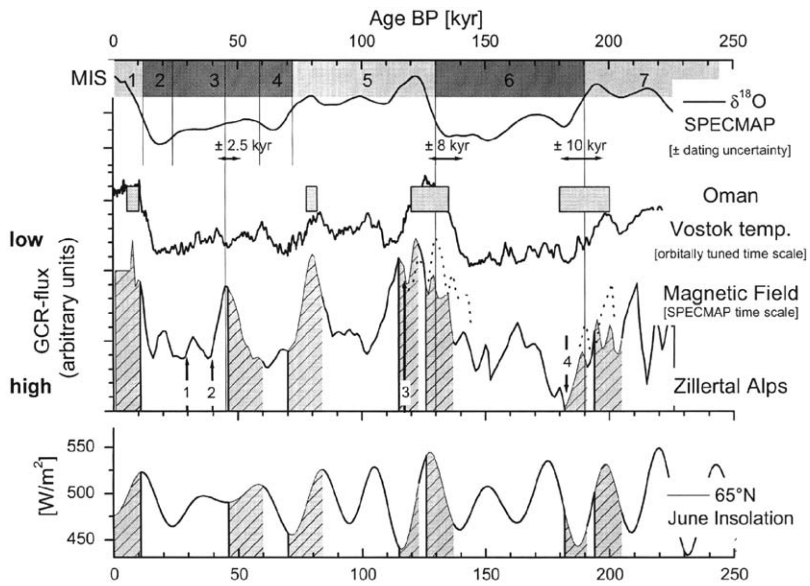

Fig. 1. From top to bottom: The marine oxygen isotope curve (SPECMAP Martinson et al. (1987) including its dating uncertainty (see text for details). The gray horizontal bar on the top indicates the marine isotope stages (MIS) 1 to 7 according to the SPECMAP- timescale. The shaded areas indicate growth periods of speleothems in Northern Oman (Burns et al., 2001) and in the Central Alps (Spötl and Mangini, 2002; Spötl et al., 2002) (see also Table 1). The temperature record from Vostok ice core on an orbitally tuned timescale (Waelbroeck et al., 1995). The reconstruction of GPI (Christl et al., 2003) interpreted as a record of GCR-flux over the last 200 kyr based on the SPECMAP chronology (see text). The dashed line shows the GCR-record on an adjusted timescale including the shift of the SPECMAP chronology as suggested in the text (+8 kyr around 130 kyr and −10 kyr around 190 kyr). The vertical arrows indicate maxima in the GCR-flux that are associated with global geomagnetic events: (1) Mono Lake (about 32 kyr), (2) Laschamp (about 40 kyr), (3) Blake (about 117 kyr), (4) Biwa I/Jamaica (about 187 kyr). The Blake event is not very pronounced in the ^{10}Be-based record due to the poor time resolution of the ^{10}Be stack. Because the relation between cosmic ray flux and the shielding magnetic fields is highly nonlinear, the scaling of the y-axis for this plot also is nonlinear. The lower part of the figure shows the curve of northern summer insolation (NSI). Details of the comparison of the GCR-flux with climate records are described in the text. The growth period between 47 and 57 kyr (recorded in the Central Alps) has no counterpart in Oman. It is possible that this period was missed during the sampling campaigns in Oman, where only a limited amount of specimens was sampled. Alternatively, the lack of speleothem growth in Northern Oman during this time period might indicate that temperature was not high enough for a northward shift of the ITCZ.

of GCR over the last 200,000 yr to extend the test of the GCR–climate hypothesis over much longer timescales (Fig. 1). Following this hypothesis, strong solar- and/or geomagnetic fields more effectively shield the GCR-flux reaching the Earth's atmosphere, so that, for example, cloud formation in the lower troposphere would be diminished, which consequently would lead to tropospheric heating. According to this hypothesis, warm periods should coincide with relative minima of GCR-flux, while maxima of GCR-flux should be related to periods of cold climate.

The growth of stalagmites at the two studied locations in the Central Alps and in Northern Oman indicates periods of warm climate. Consequently, these periods, as well as warm temperatures in Antarctica, should coincide with phases of low GCR-flux. Even if the climate response is expected to be less sensitive during phases of low GCR-fluxes than during phases of high GCR-fluxes, with the lack of knowledge about the nonlinear amplifying mechanisms of the climate system it is justified, to study the suggested GCR–climate connection during relative minima of GCR-flux. On the other hand, at both locations, speleothems should not grow during times of high GCR-flux that were associated with cold phases. Periods of high GCR-flux particularly appear during the so-called geomagnetic events. The four main geomagnetic events (Mono Lake, Laschamp, Blake, Biwa I/Jamaica) that occurred during the past 200,000 years, are marked by the arrows in Fig. 1. The Blake event is not well resolved in Fig. 1, probably due to the poor time resolution of the ^{10}Be-data.

2.5. Climate records from speleothems

The growth of stalagmites at two extremely different locations (Hoti Cave in Northern Oman and Spannagel Cave in the Central Alps) is used as an indicator of warm climate. It has been shown that the growth of stalagmites at these two key areas does not reflect local climate fluctuations but indicates global warming events, that is the northward shift of monsoon rain in Northern Oman (Burns et al., 2001; Neff et al., 2001) and the melting of alpine glaciers in the Central Alps, respectively (Spötl and Mangini, 2002; Spötl et al., 2002).

Monsoon rain events in northern Oman are caused by the northward shift of the inter tropical convergence zone (ITCZ) in summer. Hoti Cave in Northern Oman lies north of the present northernmost range of the ITCZ, so that the growth of speleothems in Hoti Cave reacts sensitively to a northward shift of the ITCZ. Growth of speleothems in Hoti Cave thus indicates periods which were warmer than today.

A second locality where the growth of speleothems reacts sensitively to global climate change is Spannagel Cave at 2500 m a.s.l. in the Zillertalalps in Central Europe. The mean air temperature in the cave is $1.5 \pm 1^{\circ}C$ (Spötl et al., 2002) where the speleothems cannot grow if the temperature is $2.5^{\circ}C$ lower than today, due to the formation of permafrost.

Although growth periods at both sites reflect global climate, the growth of speleothems at Hoti Cave only is possible if temperatures were higher than today, while speleothems in Spannagel Cave can grow if the mean annual air temperature is up to about $2^{\circ}C$ lower than today. This possibly explains why the growth period between 47 and 57 kyr (Fig. 1) recorded in the Central Alps has no counterpart in Oman (see also caption to Fig. 1).

Many stalagmites and flowstones from Spannagel Cave have been analyzed, where a high content of uranium (up to 120 ppm) allows extremely precise dating (Spötl et al., 2002). The growth period durations at Hoti Cave and Spannagel Cave are shown in Table 1 (together with the references to the original data). Table 1 additionally shows new data from flowstone SPA 59. In general, the speleothems from Spannagel Cave were analyzed and dated at a higher resolution than the samples from Hoti Cave.

2.6. Comparison of GCR-flux with climate records over the last 200,000 years

The periods of monsoon- and glacier-melt-induced stalagmite growth are displayed in Fig. 1 as gray shaded areas (labeled: Oman / Zillertal Alps). Fig. 1 additionally shows two important climate records from marine (SPECMAP $\delta^{18}O$) and ice core (Vostok temperature) archives. In contrast to the absolute Th/U-ages of the growth periods, these two records depend on orbitally tuned age models (Martinson et al., 1987; Waelbroeck et al., 1995). The horizontal arrows in Fig. 1 indicate the dating uncertainty associated with the SPECMAP curve. The average error of the SPECMAP age model is ± 5 kyr over the whole time period and about ± 2.5 kyr in the time slice around 50 kyr (Martinson et al., 1987). Recent Th/U dating of corals in marine sediments (Henderson and Slowey, 2000; Robinson et al., 2002) and coral reefs in Barbados (Gallup et al., 2002) shows that there is an additional (systematically) uncertainty concerning the timing of Termination II and the beginning of Marine Isotope Stage 6 (MIS 6). The horizontal arrows in Fig. 1 consider these additional errors.

Table 1
Growth phases of speleothems in Northern Oman and in the Central Alps (see also Fig. 1) and references to the original data

Location/ sample	Growth period (kyr)	References
SPA 12/70	0–9.7	Previously unpublished data
Hoti cave	6–10.5	Burns et al. (2001)
SPA 49	47–57	Spötl and Mangini (2002)
SPA 59	52–59	Previously unpublished data
SPA 59	71–83	Previously unpublished data
Hoti cave	78–82	Burns et al. (2001)
Hoti cave	113–119	Burns et al. (2001)
SPA 52	116–122	Spötl et al. (2002)
SPA 59	127–134	Previously unpublished data
SPA 52	127–136	Spötl et al. (2002)
Hoti cave	180–200	Burns et al. (2001)
SPA 52	183–190	Spötl et al. (2002)
SPA 59	Around 186.5	Previously unpublished data
SPA 52	195–204	Spötl et al. (2002)

The ^{10}Be-based record of GPI, interpreted as GCR-flux over the last 200,000 years, is also shown in Fig. 1. The age model of the GCR-record is based on the orbitally tuned SPECMAP curve and therefore reflects its dating uncertainties.

The curve of northern summer insolation (NSI) is displayed at the bottom of Fig. 1. In general this curve is considered as the major driving force for ice buildup and climate. Like the growth phases of speleothems, the NSI has an absolute timescale because it was calculated using the orbital parameters of the Earth.

During the Holocene, speleothem growth is observed in Northern Oman and in the Central Alps. Speleothems in the Central Alps still grow under current conditions, whilst growth ceased in Northern Oman around 6 kyr. The flux of GCR began to decrease at about 16 kyr ago. The increase of NSI started at around 22 kyr, reached its maximum at about 11 kyr, and has decreased since then. Both the decrease of the GCR-flux and the increase of NSI commenced before the onset of the deglaciation, therefore it is not possible to decide whether the NSI, the GCR-flux or a combination of both was the driving force for climate at Termination I.

The second growth period of speleothems in the Central Alps is recorded between 47 and 59 kyr ago. Because this period has no counterpart in Oman, it most likely indicates that temperatures did not rise enough to initiate the growth of speleothems at Hoti Cave. The age of this warmer interval corresponds to a sea level high stand which is only 30–60 m below the present sea level between

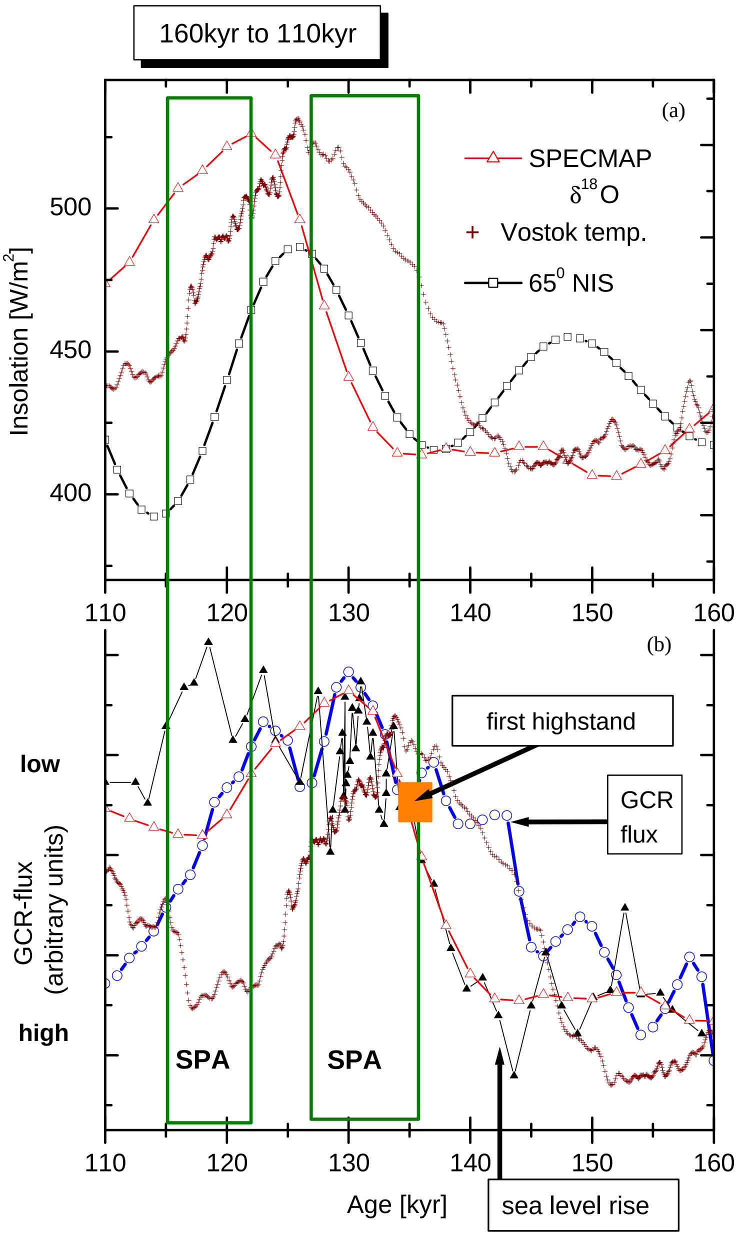

Fig. 2. The time slice between 160 and 110 kyr: (a) shows the growth phase of speleothems in the Central Alps (SPA, large green squares), the curve of northern summer insolation (NSI; black curve, open squares), the SPECMAP-stack (red line, open triangles), and the temperature record from Vostok ice core (brown crosses) on an absolute (SPA and NSI) or orbitally tuned (SPECMAP and Vostok) time scales, respectively. The comparison of SPA with NSI shows that speleothem growth at Termination II could not have been caused by NSI; (b) shows the rise of the sea level during Termination II (based on δ^{18}O-isotope data; black curve, filled triangles), that was absolutely dated by Henderson and Slowey (2000), together with the SPA growth phases. At Termination II the SPECMAP record was shifted to match the time scale of the absolutely dated δ^{18}O record by Henderson and Slowey (2000). Consequently, the Vostok temperature reconstruction and the GCR-record (blue curve, open circles) must also be shifted (8 kyr towards older ages). In Fig. 2b the absolute and orbitally tuned time scales are synchronized, so that the different records can be compared directly during this time slice: The beginning of the sea level rise follows the declining flux of GCR but is out of phase with the maximum NSI (shown in Fig. 2a). The first growth period of stalagmite SPA 52 at 135 ± 1.2 kyr (Spötl et al., 2002) indicates that the glacier above the cave already was retreating and that temperatures in the cave were above the freezing point (that is within 1.5°C of the present day temperatures in the cave; see text). This correlates well with the dating of a terrace on Barbados presented by Gallup et al. (2002), which shows that the sea level was at about 20% below the maximum value at 135.8 ± 0.8 kyr (small filled orange square).This data is consistent with the GCR–climate theory but it is not consistent with the theory of NSI as the major climate force.

about 45 and 55 kyr. This is seen in several data sets providing strong evidence for a markedly reduced continental ice volume during parts of Marine Isotope Stage 3 (Cabioch and Ayliffe (2001) and Siddall et al. (2003) and references therein). For comparison: sea level during the last glacial maximum, at about 24 kyr before present, was 120 m lower than today, whilst around 65 kyr it was about 100 m lower than during the Holocene (Siddall et al., 2003). The temperature record in Antarctica only shows a marginal increase during this time. The record of GCR-flux displays a relative minimum between about 60 and 40 kyr. It seems that Stalagmites began to grow around 60 kyr when the GCR-flux still was high, while growth ceased around 47 kyr when the GCR-flux reached its minimum. Some of this discrepancy may rely on the different timescales used: the SPECMAP chronology for the GCR-record and absolute U/Th calendar ages for the speleothems. The dating uncertainty of the SPECMAP stack is at least 2–3 kyr in the time slice around 50 kyr (Martinson et al., 1987) and even the high resolution oxygen isotope records from the GRIP and GISP2 ice cores disagree with each other during this time slice. Furthermore, the chronologies of the ice core records have to be shifted by about 2–3 kyr (in the time slice around 50 kyr) to match the absolute (U/Th) timescales of the speleothem records (Burns et al., 2003; Spötl and Mangini, 2002). In Fig. 1 the match between the growth phases and the GCR-flux improves if the dating uncertainties of the different records are taken into account. The curve of NSI increases by less than 10% during this time which is only half the increase of that at the maximum at 128 kyr. The upper result does not contradict the theory of NSI as the major climate force, although it seems to be unlikely that the slightly increased Insolation caused the observed warming around 50 kyr. Again, it is difficult to decide what was the driving force for climate during this time, and again it might have been a combination of both NSI and GCR-flux.

The third stalagmite growth phase is recorded between 71 and 82 kyr before present in Northern Oman and in the Central Alps coinciding with an increase of temperatures in Antarctica. At the same time (between 85 and 75 kyr), the flux of GCR was markedly decreased, while the NSI curve shows a maximum at 84 kyr followed by minimum at 71 kyr. Similar to the previous results, it is not clear if a decreased GCR-flux and/or an increased NSI caused the observed warming.

The most extended growth period of speleothems was recorded between about 115 and 135 kyr before present. The fact that growth in the Central Alps began at 135 $\pm$ 1.2 kyr corroborates Henderson and Slowey's data (2000) which suggests that warming was already in progress at 135$\pm$2.5 kyr. Moreover, this contradicts the SPECMAP age model that places Termination II at 128 kyr (the maximum of the NSI curve, Fig. 2a). The disagreement between the orbitally tuned SPECMAP age model and the absolutely dated Th/U time scale at Termination II is well known (Gallup et al., 2002; Henderson and Slowey, 2000) and leads to the so-called causality problem with the theory of orbital climate forcing (Muller and MacDonald, 1997): Whilst the curve of NSI shows a minimum at 140 kyr, the warming had already started in Antarctica (Fig. 2a). Stalagmites began to grow in low and mid-latitudes and sea level was already high at about 135 kyr, a time when NSI was still very low (Fig. 2b). In contrast, there is no causality problem with the GCR–climate theory: The flux of GCR decreased steadily between 146 and 122 kyr and therefore may have caused the observed warming (Fig. 1).

To better compare the absolute ages of speleothem growth periods with the orbitally tuned ^{10}Be-derived record of GCR at Termination II (around 135 kyr) it is necessary to synchronize the chronologies. The ^{10}Be timescale was originally based on the orbitally tuned SPECMAP chronology (Fig. 1). However, this can be synchronized to an absolute chronology by fitting the δ^{18}O SPECMAP curve to the absolute dated (U/Th) δ^{18}O time scale of the Bahamas (black curve in Fig. 1, Henderson and Slowey, 2000). At Termination II this results in an 8 kyr shift to older ages of the SPECMAP chronology and thus an equivalent shift in time scales for the Vostok temperature and the ^{10}Be-derived GCR record (Fig. 2b).

Fig. 2b shows that the sea level highstand at 135 kyr (Gallup et al., 2002) caused by the warming could be associated with a minimum GCR-flux whereas NSI is very low at that time. Obviously, the beginning of the sea level rise at about 142 kyr (Henderson and Slowey, 2000) could not have been triggered by NSI, but it may have been a consequence of the declining GCR-flux. However, the second growth period of speleothems recorded between 122 and 115 kyr could be a result of the NSI-maximum at 128 kyr.

The growth phase between 200 and about 183 kyr appears to start during a phase of medium GCR-flux and ends with a GCR-flux maximum. A comparison with the NSI-curve also leads to ambiguous results: the first growth phase between 204 and 195 kyr occurred during a NSI maximum, whereas the second phase corresponds to an insolation minimum.

An independent calibration of the SPECMAP timescale at the end of stage MIS 7 (δ^{18}O in aragonite rich sediments off Bahamas dated via Th/U-ages (Robinson et al., 2002)) yields ages as young as 178.4 kyr for the end of MIS 7, about 10 kyr later than was suggested by the SPECMAP chronology. The results from sediment cores off Bahamas are in good agreement with the data from speleothems: The end of MIS 7 was dated at 182.9$\pm$2.6 kyr in sample SPA 52 from the Central Alps (Spötl et al., 2002), while in Northern Oman the end of MIS 7 was dated at 180 $\pm$ 12.8 kyr (see Table 1). These data suggests that the SPECMAP chronology and therefore the time scale of the GCR-flux and the Vostok temperature record at the end of MIS 7 probably may be shifted towards younger ages by up to 10 kyr. The shift of the orbitally tuned time scale leads to an even better agreement of the stalagmite growth periods with GCR-flux and the temperature-record in Antarctica (the dashed line in Fig. 1 indicates the time-shifted GCR-flux). However, speleothem data presented by Bard et al. (2002) show that sea level was falling rapidly around 190 kyr which is in full agreement with the SPECMAP chronology. These discrepant results show that the timing of the end of MIS 7 is complex and not well understood, making it difficult to test the GCR–climate hypothesis during this time slice.

3. Conclusion

Despite the uncertainty in the synchronization of timescales, we observe growth of speleothems during four periods of low GCR-flux: during the Holocene, at about 50 kyr, at 78 kyr, and between 110 and 130 kyr, three of which are coincident at both localities, in Oman and in the Central Alps. Furthermore, speleothems did not grow during the Mono Lake, Laschamp and Jamaica event, characterized by high GCR-fluxes, indicated by the arrows in Fig. 1.

The comparison of growth periods with the timing of the NSI curve shows that the growth periods only partly coincide with the maxima of the NSI. They either follow the insolation maximum (during the Holocene, at about 50 kyr, and at about 78 kyr), or precede (leading to the causality problem) the maximum (at about 135 and 200 kyr), or coincide with minima of insolation (180–190 kyr). Therefore, it is difficult to explain the onset of speleothem growth particularly at 135 kyr and between 180 and 190 kyr only as a result of increased NSI. For the growth periods at 78, 50 kyr, and during the Holocene our results do not contradict the theory of orbital climate forcing, but it is not clear why the growth of stalagmites only occurred during five of nine maxima of NSI over the last 200,000 years.

During the past 150,000 years the four growth periods of speleothems in Northern Oman and the Central Alps all coincide with the four relative minima of GCR–flux. No growth of speleothems is recorded during maxima of GCR-flux. The correlation with the GCR-flux improves and extends over the last 200,000 years if the dating uncertainty of the orbitally tuned SPECMAP age model is taken into account. These results support the GCR–climate theory that predicts warm climate during periods of low GCR-flux and vice versa. Although the observed correlation of relative minima of GCR-flux with growth periods of stalagmites is only qualitative, it suggests that a link between GCR-flux and climate existed over the last 200,000 years. Our results do not preclude the theory of orbital climate forcing and whilst it is clear that NSI has an important influence on Earth's climate, it is perhaps not the only trigger of the observed climate changes over the past 200,000 years.

Acknowledgements

We thank Holger Braun and Petya Blumbach for corrections and discussions. We also want to thank two anonymous reviewers for their constructive comments that helped to improve the manuscript.

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