Timing and progression of the Last Interglacial derived from a high alpine stalagmite

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1. Introduction

The timing and duration of the Eemian interglacial climate has been extensively discussed [e.g., Shackleton et al., 2002]. According to the Milankovitch insolation curve, Marine Isotope Stage 5 (MIS 5) does not commence before 128 ka. In contrast, both marine and terrestrial datasets define the beginning of the Last Interglacial between 135 ka and 140 ka [Gallup et al., 2002; Henderson and Slowey, 2000; Spötl et al., 2002; Winograd et al., 1992]. The stability of the Eemian climate has been discussed controversially [Boettger et al., 2000; Frogley et al., 1999; Fromval and Jansen, 1996; Hearty and Neumann, 2001; Rioual et al., 2001]. Resolving these issues will lead to an improved theory of glacial-interglacial transitions. One major setback results from the lack of reliable absolute age determinations. Speleothems offer an important but yet underutilized source of information about the timing and progression of the Last Interglacial.

2. Geological and Climatic Setting

An ideal situation for paleoclimatic reconstruction would entail speleothem growth itself being an indicator of warm climate, as is the case in Spannagel Cave, located in the Austrian Alps, at an altitude of 2,500 m above sea level. At present the area above Spannagel Cave is ice-free, but was covered by the nearby Hintertux Glacier during glacial stages [Spötl et al., 2004]. Speleothems in Spannagel are able to grow despite the absence of soil overlying the cave owing to the presence of pyrite in the host rock, which under oxidizing conditions can transform into sulfuric acid. The acid dissolves the primary limestone, producing excess CO2, which results in the formation of supersaturated carbonate solutions and calcite precipitation. The interior cave temperature (at present +1.2 to +2.2°C, depending on the location within the 10 km cave system) shows no daily or seasonal variation and corresponds closely to the mean annual external air temperature [Spötl et al., 2004]. As speleothems can only develop above freezing point, growth of speleothems in Spannagel Cave is sensitive to temperature shifts.

3. Methods

22 subsamples along the growth axis of stalagmite SPA 50 were taken for U/Th age determination. U/Th measurements were performed on a thermal ionization mass spectrometer (Finnigan MAT 262 RPQ) with a double filament technique1. The detrital correction was performed using a factor of 3.8 [Wedepohl, 1995] for the mass ratio of 232Th and 238U in the detritus. The correction led to negligible age changes (<0.024 ka) owing to low 232Th concentration. All ages were calculated using half lives for 233U/236U double spike is 0.075%

4. Speleothem Growth Periods

The previously studied flowstone SPA 52 [Spötl et al., 2002] grew during MIS 7 and MIS 5. The beginning of the Last Interglacial was dated at 135.0 ± 1.2 ka (all errors reported are 2σ), and the Eemian lasted until 116.0 ± 1.9 ka. There are no indications of post-depositional U-leaching processes (such as deviations in δ234U or macroscopic pores), nor is it likely that older carbonate from MIS 7 section has
may be associated with a Younger Dryas-like cold spell occurring after a first warming of the Last Interglacial. Its existence has also been recorded in other climate archives [Esat et al., 1999; Sanchez Goni et al., 1999]. It might have been caused by freshwater pulses to the North Atlantic, reducing the formation of North Atlantic Deep Water and thus the heat transport to Northern Europe [Clark et al., 2001], as in the Younger Dryas, which also occurred within a period of maximum solar summer insolation. After the growth cessation, calcite deposition recommenced at 125.6 ± 0.9 ka (U4). The youngest available date for this growth phase was obtained at 118.2 ± 0.6 ka. One point with an age of 128.3 ± 1.3 ka from SPA 50 is interpreted as a mixing age due to the short distance from the hiatus and therefore was excluded from the following interpretation. U4 in stalagmite SPA 50 is represented by 19 dated points and shows two distinct jumps towards younger U/Th ages at around 123.8 ka and 120.5 ka, subdividing U4 into three subunits U4a, U4b, and U4c. Ages obtained from the upper section of the adjacent flowstone sample SPA 52 [Spötl et al., 2002] scatter around the values within U4b and U4c of SPA 50. In SPA 52, the two respective growth reductions are not visible, probably due to the lower temporal resolution in comparison to SPA 50. However, the youngest age of the Last Interglacial is recorded more reliably by SPA 52 at 116.0 ± 1.9 ka, because the uppermost part of stalagmite SPA 50 has a lower temporal resolution.

[7] Provided that the growth interruptions centered at around 123.8 ka and 120.5 ka recorded by the U/Th dates of SPA 50 are not the product of incidentally changed flowpaths of the drip waters, they are likely to represent cold spells when mean annual temperatures were at least 1° to 2°C lower than today. The duration of the interruptions cannot be determined precisely due to the dating uncertainty, but is in the order of 1 to 2 ka. A number of climate archives from various locations also show the existence of cooler, but not glacial periods at ~124 ka [Hearty and Neumann, 2001; Wilson et al., 1998] and at ~121 ka [Linsley, 1996; Stirling et al., 1998].

5. Oxygen Isotope Record

[8] In Figure 2 we show the growth periods and isotopic age profile of SPA 50. The age models for growth periods...
U3 and U4b are based on linear, error-weighted fits through the dated points, entailing growth rates of 48 mm/ka (U3) and 107 mm/ka (U4b), respectively. For U4a, the same growth rate as for U4b was assumed, owing to the broadly scattered ages of U4a, where a fit function would yield a negative growth rate. The growth rate of the youngest section of the stalagmite, U4c, was calculated by defining the two determined ages as the endpoints of the growth period U4c, resulting in a growth rate of 5.4 mm/ka, and not by extrapolating the growth rate to the end of the respective section, as it was performed in all the other growth phases; it therefore provides only a rough estimate.

[9] During growth phase U3 $\delta^{18}$O values in both samples range between $-13.0\%o$ and $-11.0\%o$, except for the older part of SPA 52 with fluctuations from $-10.7\%o$ to $-14\%o$. The beginning of U4 is marked by a significant increase of $\delta^{18}$O to values of around $-9.5\%o$ in both samples. It has been argued earlier that the difference of 2$\%o$ to 3$\%o$ in $\delta^{18}$O between sections U3 and U4 may not convincingly be explained by a temperature increase and is more likely to reflect a change in water sources [Spötl et al., 2002]. This means that the more negative isotopic values in U3 reflect a larger contribution of melt waters from the nearby glacier. The glacier retreat led to a stronger influence of precipitation on drip waters in the cave, leading to heavier $\delta^{18}$O values.

[10] The $\delta^{18}$O values of U4 correspond roughly with those of Holocene speleothems from Spannagel Cave, showing values around $-7.8\%o$, in equilibrium with $\delta^{18}$O of precipitation [Spötl et al., 2004]. The difference of about 1$\%o$ to 2$\%o$ in comparison to recent calcite would result in temperatures 4°C to 8°C higher than today [Friedman et al., 1997]. However, this difference may not solely be explained by temperature. Instead it may be ascribed to more negative $\delta^{18}$O values of precipitation or to a larger contribution of melt waters from the nearby glacier in comparison to the Holocene.

[11] During the Eemian, the profile of $\delta^{18}$O in U4a of SPA 50 increased from $-9.7\%o$ to $-9.1\%o$ and in U4b the $\delta^{18}$O values show a slight downward trend from $-8.8\%o$ to $-9.2\%o$. The boundary between U4b and U4c is marked by a negative spike in $\delta^{18}$O down to $-10.3\%o$, which may indicate a relapse to colder conditions with an increased contribution of glacial melt water in the cave. High amplitude variations of 1$\%o$ mark the uppermost part (U4c) before the growth ceased. Presuming that $\delta^{18}$O precipitation values remained constant during the Eemian, we can deduce from the 0.9$\%o$ difference in $\delta^{18}$O values that variations in the range of 4°C occurred, with higher temperatures at the beginning (U4a) of this period.

[12] The short term variations in $\delta^{18}$O of ±0.5$\%o$ in sections U4a, U4b, and U4c of stalagmite SPA 50 probably reflect both the fluctuations in temperature inside the cave, influencing the fractionation coefficient of calcite precipitation, as well as variations in the $\delta^{18}$O precipitation values. These may have been caused by any combination of the following factors: temperature, amount effect, changed seasonality of rainfall or alterations in storm and cloud tracks in the Central Alps. This latter effect has been investigated earlier [Florineth and Schlüchter, 2000], where it has been assumed that during colder periods the prevailing westerly circulation pattern over Central Europe was displaced by an enhanced southerly wind component from the Mediterranean. From our data it is not possible to deduce exact temperature shifts from the stable isotope variations nor to determine the quantitative contributions of the above mentioned processes. Additional investigations, such as fluid inclusion analyses and modeling of stable isotopes in precipitation will help to quantify the relative influences of the suggested processes.

6. Spectral Analysis

[13] In comparison to other Eemian climate records the uniquely high resolution of the $\delta^{18}$O profile in the growth interval U4b from SPA 50 allows to decipher hidden periodicities within the time series using spectral analysis (Figure 3). Three spectral peaks at 197, 109, and 21 years period, clearly exceed the 95% confidence bound. Considering the frequency resolution (6-dB bandwidth) and the additional uncertainty of the used age model, these peaks might well correspond to the Suess cycle (206 years period), Gleissberg cycle (89 years), and Hale cycle (22 years), which are well established solar signals found in climate archives over Holocene periods [Hoyt and Schatten, 1997; Stuiver and Braziunas, 1993].

[14] In the Holocene, North Atlantic marine sediments reveal a strong correlation between solar induced $^{10}$Be and $^{14}$C fluctuations and variations in surface winds and surface ocean hydrography on centennial to millennial timescales [Bond et al., 2001]. Two Holocene stalagmites from Sauerland, Central Germany, support the finding of a teleconnection between solar activity and climate in Central Europe: the $\delta^{18}$O records of stalagmites B7-7 and AH1 show a strong correlation with the solar induced delta $^{14}$C [Niggemann et al., 2002, 2003]. As the climate of Central Europe is predominantly influenced by the North Atlantic, our high-resolution record SPA 50 suggests that solar activity modulated the high alpine climate during the Eemian on decadal to centennial timescales in a similar fashion. The mechanism linking solar output variations to tropospheric...
climate oscillations is still uncertain. One possibility is that variations in the intensity of galactic cosmic rays in the atmosphere cause changes in cloudiness. Another mechanism suggests that UV irradiance variations affect ozone, which changes the temperature and wind pattern in the stratosphere, in turn altering tropospheric climate [Carslaw et al., 2002; Rind, 2002].

7. Conclusions

[15] Our high-resolution study of speleothems from the Central Alps reveals a warm phase prior to the classical Eemian from ~135 to 130 ka. The ambient temperature during the Eemian, from 125.7 ± 0.9 ka to 116.0 ± 1.9 ka, was at least as high as today in this region. This dataset provides a precise time frame for other continental climate archives for the duration of the Eemian. The growth reductions of stalagmite SPA 50 at about 123.8 ka and 120.5 ka could be the product of cold spells, during which the annual mean temperature was at least 1° to 2°C lower than today. Spectral analysis reveals solar forcing of the Eemian climate.

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References


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