Timing and climatic impact of Greenland interstadials recorded in stalagmites from northern Turkey

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Received 14 July 2009; revised 17 August 2009; accepted 19 August 2009; published 6 October 2009.

A 50 kyr-long exceptionally well-dated and highly resolved stalagmite oxygen (δ18O) and carbon (δ13C) isotope record from Sofular Cave in northwestern Turkey helps to further improve the dating of Greenland Interstadials (GI) 1, and 3–12. Timing of most GI in the Sofular record is consistent within ±10 to 300 years with the “iconic” Hulu Cave record. Larger divergences (>500 years) between Sofular and Hulu are only observed for GI 4 and 7. The Sofular record differs from the most recent NGRIP chronology by up to several centuries, whereas age offsets do not increase systematically with depth. The Sofular record also reveals a rapid and sensitive climate and ecosystem response in the eastern Mediterranean to GI, whereas a phase lag of ~100 years between climate and full ecosystem response is evident. Finally, results of spectral analyses of the Sofular isotope records do not support a 1,470-year pacing response in the eastern Mediterranean to GI, whereas a 100-year phase lag of ~2.5% and highly resolved (~20 year resolution) δ18O and δ13C profiles allow us to assign precise ages to GI 1 (Bølling-Allerød (BA)), and 3–13.

Furthermore, the Sofular time series fills a large spatial gap of precisely-dated, highly-resolved and long terrestrial paleoclimate records in the northeastern Mediterranean, and provides unambiguous evidence for the climatic and environmental impact of GI in this area, where current key-paleoclimate time series, such as the Lago Grande di Monticchio, and Soreq Cave records from Southern Italy and Israel respectively [Allen et al., 1999; Bar-Matthews et al., 2003], do not show a well developed GI (Figure 1).

1. Introduction

The last glacial period is marked by rapid variations in climate termed Greenland interstadials (GI; also known as Dansgaard-Oeschger events). While the spatial extent and climatic impact of GI is well documented [Voelker, 2002], uncertainties with respect to their absolute timing exist. Uranium-series dated 230Th-dated stalagmites [Wang et al., 2001; Genty et al., 2003; Burns et al., 2003; Wang et al., 2006; Spötl et al., 2006] have been used to develop a more coherent and absolute chronology of GI. To date, the Hulu Cave stalagmite oxygen isotope record captures GI 1–21 in detail, though its resolution is rather coarse (50–200 years) and spacing of 230Th dates averages 1,600 years [Wang et al., 2001]. Other stalagmite records covering this period are discontinuous or do not show well-expressed GI in their isotopic profiles [e.g., Genty et al., 2003] (Figure 1). Additional 230Th-dated stalagmites are thus required for further validation and, if necessary, refinement of the Hulu record. This is of paramount importance as the Hulu time series is being used as a ‘reference record’ for other paleoclimate records [e.g., Svensson et al., 2008; Skinner, 2008], and even to constrain radiocarbon calibration [Weninger and Joris, 2008; Hughen et al., 2006]. Here we present a 50 kyr-long stalagmite oxygen (δ18O) and carbon (δ13C) isotope record from Sofular Cave located at the Black Sea in northwestern Turkey (Figure 1 and auxiliary material Text S1). A set of 98 230Th dates with very small errors of ~0.25–2.5% and highly resolved (~20 year resolution) δ18O and δ13C profiles allow us to assign precise ages to GI 1 (Bølling-Allerød (BA)), and 3–13.

2. Cave Location and Modern Climatology

Sofular (41°25′N, 31°56′E; So-1 and So-2) and Ovacik caves (41°46′N, 32°02′E; O-1) are located in northwestern Turkey. Precipitation in this region averages ~1,200 mm yr−1, with ~75% occurring between September and April (Figures S1 and S2). Moisture originates mainly from the Black Sea and, to lesser extent, from the Mediterranean and Marmara Sea. Climate in northwestern Turkey is strongly tied to the North Atlantic realm and representative for the northeastern part of the Mediterranean (Text S1 and Figure S3). Vegetation above both caves is marginally affected by human activity and consists of trees, shrubs and, to a lesser extent, grass (Figure S4).

3. Methods and Sample Description

Three large active stalagmites, ranging between 1–1.75 m in height, were collected from Sofular Cave (stalagmites So-1 and So-2) and Ovacik Cave (stalagmite O-1) A total of 121 230Th dates and 5,485 stable isotope measurements were performed, although the main focus was on stalagmite So-1.


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0094-8276/09/2009GL040050S05.00
Th dating of stalagmite So-1 was made on a multi-collector inductively coupled plasma mass spectrometer (MC-ICP-MS, Thermo-Finnigan-Neptune) at the Minnesota Isotope Laboratory, University of Minnesota (Table S1). Further \(^{230}\)Th dating on all stalagmites was done on a Nu Instruments’ MC-ICP-MS at the Geological Institute, University of Bern (Table S2). Detailed information on analytical procedures is provided in Texts S2 and S3 accompanying this article.

Stable isotope analyses were performed on a Finnigan Delta V Advantage mass spectrometer equipped with an automated carbonate preparation system (Gas Bench-II) at the Institute of Geological Sciences, University of Bern. Precision of \(\delta^{13}\)C and \(\delta^{18}\)O measurements is 0.06\% and 0.07\% (1\(\sigma\)-error) respectively.

Uranium concentrations of \(\sim 0.5\) ppm and low common thorium (\(^{232}\)Th) result in especially precise \(^{230}\)Th ages for So-1; almost all of them are in stratigraphic order (Figure S5). Age models of stalagmites So-1 and O-1 are based on linear interpolation between \(^{230}\)Th dates. Chronology of So-2 was adjusted within age uncertainties to the more precisely dated stalagmite So-1, which grew nearly continuously over the last 50.3 kyr before present (BP, “present” is defined as 1950 AD), except of a hiatus between 21.2 and 24.8 kyr BP.

4. Interpretation of Stable Isotope Profiles

Isotope profiles of all stalagmites are very similar, indicating that So-1 \(\delta^{18}\)O and \(\delta^{13}\)C values are not biased by
negative $\delta^{13}C$ calcite values. Thus, stalagmite $\delta^{13}C$ values are sensitive proxies for climate-driven changes of the local ecosystem. Modern stalagmite $\delta^{13}C$ values of $-10\%$ are in good agreement with the $C_3$ dominated vegetation above Sofular and Ovacik caves.

5. Ecosystem Response to GI

[11] Between 50.3 and 14.6 kyr BP So-1 $\delta^{13}C$ values of around $-8\%$ are indicative of more $C_4$ plants, lower plant density and soil microbial activity due to colder and drier climatic conditions. This observation agrees with pollen evidence for enhanced steppe ($C_4$ plants; Figure 2) and reduced arboreal vegetation in the central and eastern Mediterranean [Bottema, 1995; Allen et al., 1999; Kotthoff et al., 2008]. In the Sofular time series GI 1 and 3–13 are characterized by negative shifts of 1–3‰ in $\delta^{13}C$ within a few decades to centuries (transition times were calculated by ramp regressions) (Figure S6 and Table S3), and reveal a greater proportion of $C_3$ plants and higher soil productivity due to increasing temperatures and effective moisture. Such rapid changes in vegetation have been also observed in pollen assemblages from southern Italy (Figure 1h) and Greece, although identification of GI is difficult in both records [Allen et al., 1999; Tzedakis et al., 2002]. Combined $\delta^{18}O$ and $\delta^{13}C$ measurements hold further information on climate and eco-system coupling at the transition into a GI. In the So-1 $\delta^{13}C$ time series, the full transition into GI takes place within 252 ± 87 years (GI 8 not included), slower compared to 121 ± 99 years in the So-1 $\delta^{18}O$ record, and 62 ± 14 years in NGRIP (values derive from the mean and standard deviation of all transitions in So-1 and NGRIP; Figure 3a and Table S3). While the onset of GI is almost simultaneous in the So-1 $\delta^{18}O$ and $\delta^{13}C$ time series, the slightly slower transition into GI in the So-1 $\delta^{13}C$ record suggests that the ecosystem reached a kind of equilibrium with climate within ~250 years, if the equilibrium was reached at all during shorter GI.

[12] Another interesting feature of So-1 is the nature of Termination I. In contrast to pollen records from the eastern Mediterranean [Bottema, 1995; Kotthoff et al., 2008], the So-1 $\delta^{13}C$ record does not exhibit a time lag of several hundreds to thousands of years between climate and vegetation at the onset of the BA and early Holocene (Figure 2). Rather, the rapid decrease of So-1 $\delta^{13}C$ values at the onset of the BA (~14.6 kyr B.P.) and the Holocene (~10.5 kyr B.P.) suggest a fast re-vegetation with trees and shrubs ($C_3$ plants). This observation supports the presumption that parts of the Black Sea Mountains were glacial refugia for temperate trees [Leroy and Arpe, 2007], which facilitated their rapid re-advance at the onset of the BA and Holocene. Overall, the So-1 $\delta^{13}C$ time series complements and extends pollen records from the eastern Mediterranean much further back in time, and provides, due to its precise chronology and high resolution, clear evidence for a rapid ecosystem response to GI.

6. Timing of GI

[13] GI and the Younger Dryas (YD) are clearly discernible in both So-1 isotope profiles and more explicit than in the Hulu and Villars caves records (Figure 1). This is important, as the more closely Sofular resembles NGRIP [Svensson et al., 2008] and GISIP2 [Meese et al., 1997], the
better GI can be dated and synchronized. Midpoints of isotopic transitions into GI 1–12 (referred as midpoints hereinafter) were determined by statistical ramp function regression for the Hulu and Sofular $\delta^{18}O$ records; provided that the transition was defined by sufficiently many data points [Mudelsee, 2000] (Figures 1 and S6 and Table S4). The Villars record was not used because of its weakly expressed GI (Figure 1f). The comparison between Hulu-Sofular (Hu-So) $\delta^{18}O$ records reveals small age offsets for GI 1 ($\Delta_{\text{Hu-So}} = -75 \text{ yrs}$), 3 ($\Delta_{\text{Hu-So}} = -112 \text{ yrs}$), 6 ($\Delta_{\text{Hu-So}} = 134 \text{ yrs}$), 8 ($\Delta_{\text{Hu-So}} = -321 \text{ yrs}$), 9 ($\Delta_{\text{Hu-So}} = -166 \text{ yrs}$), 10 ($\Delta_{\text{Hu-So}} = 252 \text{ yrs}$), 11 ($\Delta_{\text{Hu-So}} = -195 \text{ yrs}$), and 12 ($\Delta_{\text{Hu-So}} = -9 \text{ yrs}$), all of them are within dating uncertainties (Figure 3b and Table S5). Higher divergences are only observed for GI 4 ($\Delta_{\text{Hu-So}} = 524 \text{ yrs}$) and 7 ($\Delta_{\text{Hu-So}} = -554 \text{ yrs}$), and likely a combination of (1) $^{230}$Th dating uncertainties, (2) lower temporal resolution of Hulu, and (3) errors introduced by age model construction. In Hulu GI 4 is characterized by a broad peak in $\delta^{18}O$, which is in contrast to the relatively narrow nature of this event in Sofular, NGRIP, and GISP2. Age estimate for the midpoint of GI 4 in the Botuvera (Bo) Cave record from Brazil [Wang et al., 2006] (Figure 1g), differs also from Hulu ($\Delta_{\text{Hu-Bo}} = 613 \text{ yrs}$), but is in good agreement with Sofular ($\Delta_{\text{So-Bo}} = 89 \text{ yrs}$) (Figure 3b). However, the So-1 chronology seems to have an anomalous GI 7 timing, which is older as compared to Hulu and Botuvera (Figure 3b). Overall, the timing of most GI is broadly consistent between the Sofular, Hulu, and Botuvera caves records.

Another important aspect of this study is the evaluation of the most recent NGRIP (GICC05) chronology [Svensson et al., 2008]. The NGRIP-Sofular comparison shows non-systematic age offsets (Figure 3c). While age estimates for the midpoints of GI, are synchronous within stated 1σ-age uncertainties of the NGRIP GICC05 chronology, larger age differences are observed for GI 4 ($\Delta_{\text{NGRIP-So}} = -586 \text{ yrs}$), 7 ($\Delta_{\text{NGRIP-So}} = -493 \text{ yrs}$), 11 ($\Delta_{\text{NGRIP-So}} = -839 \text{ yrs}$), and 12 ($\Delta_{\text{NGRIP-So}} = -855 \text{ yrs}$) (Figure 3c). NGRIP-Hulu age offsets are similar, GI 11 ($\Delta_{\text{NGRIP-Hu}} = -644 \text{ yrs}$) and 12 ($\Delta_{\text{NGRIP-Hu}} = -846 \text{ yrs}$) seem to be too young in NGRIP (Figure 3c). Even larger discrepancies are observed between GISP2-Sofular and GISP2-Hulu (Figure 3d), particularly for GI 10 ($\Delta_{\text{GISP2-So}} = -553 \text{ yrs}$; $\Delta_{\text{GISP2-Hu}} = -806 \text{ yrs}$), 11 ($\Delta_{\text{GISP2-So}} = 1636 \text{ yrs}$; $\Delta_{\text{GISP2-Hu}} = -1441 \text{ yrs}$), and 12 ($\Delta_{\text{GISP2-So}} = -2294 \text{ yrs}$). Overall, ice core chronologies seem to be consistently too young, whereas age offsets of GI between the Greenland ice cores and Hulu and Sofular do not increase systematically with depth. GI 7-9 seem to deviate from the general trend of generally younger ages in NGRIP and GISP2 relative to the cave records, though the reason for this deviation is yet unknown.

7. Conclusions

Based on the best fit between absolutely dated stalagmites from Sofular, Hulu and Botuvera, a more robust chronological framework for GI 1, 3–12 can now be provided. This is one prerequisite for an improved radiocarbon age scale beyond 24 kyr BP [Hughen et al., 2006; Weninger and Joris, 2008], improvement of chronologies of ice core and sediment records, and determination of the pacing of GI. Whether GI follow an underlying cycle of ~1,500 years is controversially discussed [You et al., 1997; Rahmstorf, 2003]. Spectral analysis of the So-1 $\delta^{18}O$ and $\delta^{13}C$ time series do not show a significant peak around 1,500 years (Figure S7) and, thus, point to a rather stochastic forcing of GI [Ditlevsen et al., 2005]. Finally, the Sofular Cave record shows, for the first time, unequivocal evidence for a rapid and sensitive climate and ecosystem response in the eastern Mediterranean to GI, and thus bears important climatic information for the Black Sea area which has been a stronghold for Neanderthal populations during the late Pleistocene [Finlayson, 2008].
References


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