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

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[1] 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 gap of precisely-dated, highly-resolved (20 year resolution) δ18O and δ13C profiles allows us to assign precise ages to GI 1 (Bølling-Allerød (BA)), and 3–13.

[2] 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).

2. Cave Location and Modern Climatology

[4] 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

[5] 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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The 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‰ (1σ-error) respectively.

Uranium concentrations of ~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
Comparison between Sofular Cave isotope dominated vegetation above aridic zones indicative of more C/C₄ plants (trees and shrubs) and denser Kotthoff % are characteristic for C/L19707/C₀ plants; Figure 2) and in plants and higher soil productivity Kotthoff et al. are in enhanced input of isotopically depleted melt water (MW). Figure S6 and Table S3). Combined δ¹⁸O and δ¹³C measurements hold further information on climate and ecosystem coupling at the transition into a GI. The So-1 δ¹³C 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 δ¹⁸O 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 δ¹⁸O and δ¹³C time series, the slightly slower transition into GI in the So-1 δ¹³C 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.

5. Ecosystem Response to GI

Between 50.3 and 14.6 kyr BP So-1 δ¹³C values of around ~8% are indicative of more C₄ plants, lower plant density and soil microbial activity due to colder and drier climatic conditions. This observation agrees with pollen evidence for enhanced steppe (C₄ 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 δ¹³C within a few decades to centuries (transition times were calculated by ramp regressions) (Figure S6 and Table S3), and reveal a greater proportion of C₃ 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].

6. Timing of GI

The rapid decrease of So-1 δ¹³C 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 (C₃ plants). This observation supports the presumption that parts of the Black Sea Mountains were glacial refugia for temperate trees [Bottema, 1995; Bottema et al., 1997], which facilitated their rapid re-advance at the onset of the BA and Holocene. Overall, the So-1 δ¹³C 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.
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 δ¹⁸O 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) δ¹⁸O records reveals small age offsets for GI 1 (Δ₈⁰⁰Hulu-So = −13 yrs), 3 (Δ₈⁰⁰Hulu-So = −75 yrs), 5 (Δ₈⁰⁰Hulu-So = 112 yrs), 6 (Δ₈⁰⁰Hulu-So = 134 yrs), 8 (Δ₈⁰⁰Hulu-So = −321 yrs), 9 (Δ₈⁰⁰Hulu-So = −166 yrs), 10 (Δ₈⁰⁰Hulu-So = 252 yrs), 11 (Δ₈⁰⁰Hulu-So = −195 yrs) and 12 (Δ₈⁰⁰Hulu-So = −9 yrs), all of them are within dating uncertainties (Figure 3b and Table S5). Higher divergences are only observed for GI 4 (Δ₈⁰⁰Hulu-So = 524 yrs) and 7 (Δ₈⁰⁰Hulu-So = −554 yrs), and likely a combination of (1) ²³⁰Th 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 δ¹⁸O, 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 (Δ₈⁰⁰Hulu-Bo = 613 yrs), but is in good agreement with Sofular (Δ₈⁰⁰So-Bo = 89 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 (Δ₈⁰⁰NGRIP-So = −586 yrs), 7 (Δ₈⁰⁰NGRIP-So = −493 yrs), 11 (Δ₈⁰⁰NGRIP-So = −839 yrs), and 12 (Δ₈⁰⁰NGRIP-So = −855 yrs) (Figure 3c). NGRIP-Hulu age offsets are similar, GI 11 (Δ₈⁰⁰NGRIP-Hu = −644 yrs) and 12 (Δ₈⁰⁰NGRIP-Hu = −846 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 (Δ₈⁰⁰GISP2-So = −553 yrs; Δ₈⁰⁰GISP2-Hu = −806 yrs), 11 (Δ₈⁰⁰GISP2-So = 1636 yrs; Δ₈⁰⁰GISP2-Hu = −1441 yrs), and 12 (Δ₈⁰⁰GISP2-So = −2303 yrs; Δ₈⁰⁰GISP2-Hu = −2294 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 δ¹⁸O and δ¹³C 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].

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References


