Hydrological change in Southern Europe responding to increasing North Atlantic overturning during Greenland Stadial 1

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Greenland Stadial 1 (GS-1) was the last of a long series of severe cooling episodes in the Northern Hemisphere during the last glacial period. Numerous North Atlantic and European records reveal the intense environmental impact of that stadial, whose origin is attributed to an intense weakening of the Atlantic Meridional Overturning Circulation in response to freshening of the North Atlantic. Recent high-resolution studies of European lakes revealed a mid-GS-1 transition in the climatic regimes. The geographical extension of such atmospheric changes and their potential coupling with ocean dynamics still remains unclear. Here we use a subdecadal resolved stalagmite record from the Northern Iberian Peninsula to further investigate the timing and forcing of this transition. A solid interpretation of the environmental changes detected in this new, accurately dated, stalagmite record is based on a parallel cave monitoring exercise. This record reveals a gradual transition from dry to wet conditions starting at 12,500 y before 2000 A.D. in parallel to a progressive warming of the subtropical Atlantic Ocean. The observed atmospheric changes are proposed to be led by a progressive resumption of the North Atlantic convection and highlight the complex regional signature of GS-1, very distinctive from previous stadial events.

speleothem | Iberia | Younger Dryas | stable isotopes | Greenland Stadial 1

The last deglacial warming was interrupted by a rapid cooling identified in Greenland ice cores as Greenland Stadial 1 (GS-1) at 12,846 y before 2000 A.D. [b2k, Greenland ice core chronology 2005 (GICC05)] (1), previously defined as Younger Dryas (YD) based on vegetation changes recorded in Europe (2). Although the forcing mechanism for this climate change is still under discussion (3), the most plausible trigger is related to catastrophic freshwater release into the North Atlantic and the consequent reduction in the Atlantic Meridional Overturning Circulation (AMOC) (4). Recently published high-resolution North European terrestrial records indicate two phases within GS-1, with the second phase characterized by rapid alternations between glacier advances and retreats (Lake Kråkenes, Norway) (5) and interpreted as a climatic amelioration based on an increase in detrital content and lamina thickness (Meerfelder Maar lake, Germany) (6) (Fig. 1). Records from the Atlantic Ocean, although of limited sampling resolution and not so well-constrained chronology, also indicate internal variability during GS-1, expressed as changes in sea surface salinity, temperature, and sea ice extension in parallel to modifications in the intensity and location of the North Atlantic deep overturning cells (5, 7–9) (Fig. 1). These marine sequences reveal rapid shifts between weak and strong modes of deep convection during the last deglaciation with potential consequences for European environments that need to be further assessed. The Northern Iberian Peninsula (IP), located within the polar front during the time of the coldest temperatures in GS-1

(10), is a very sensitive location to determine the exact sequence of temperature and hydrological changes in Southern Europe during this stadial, not yet well resolved due to the lack of high-resolution records (11–13). Here, we present the first stalagmite record, to our knowledge, that covers the entire GS-1 period in Southern Europe, providing an excellent and independent chronological framework and a high-resolution climate reconstruction of this event, allowing understanding of the climate mechanisms that caused the mid-GS-1 transition.

Seso Cave System (42°27'23.08"N, 0°02'23.18"E, 794 m above sea level; Fig. 1) in the Central Pyrenees provides an unusually direct record of temperature and moisture balance during GS-1 because the climate proxies in stalagmites can be directly calibrated to the instrumental record in actively growing modern stalagmites (see *Supporting Information*). Speleothem formation occurred during short intervals since 40 ka, and became more widespread during the Holocene. Today, the modern climatology of moderate rainfall (mean annual precipitation is 900 mm, concentrated in spring and fall) and mild temperatures (mean annual *ca.* 13 °C), together with a vegetation cover dominated by *Pinus sylvestris* and *Quercus ilex*, fuel speleothem growth. We present the record of SE09-6, a 160-mm-long stalagmite obtained in situ from the inner part of the cave where the temperature is constant throughout the

Significance

This study presents robust evidence of two hydrological phases within the Greenland Stadial 1 (GS-1) cold event (12.8–11.7 ka B.P.) in Southern Europe. We present a well-dated high-resolution speleothem record (Seso Cave, Central Pyrenees) where temperature and hydrological signals are independently reconstructed. Detailed interpretation of stable isotopes and trace elements allow characterizing a first dry period followed, after 12,500 y before 2000 A.D., by more humid conditions. Our findings point to the resumption of the Atlantic overturning circulation as the main mechanism behind the hydrological response in Europe during this mid-GS-1 transition. The second phase, cold in Greenland but humid in Western Europe, represents a new paradigm in the well-established model of dry, cold stadials during the last glacial period.

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along the GS-1 probably due to its high-latitude position, well within the zone of polar air masses.

Terrestrial records from North Europe also indicate the occurrence of some intra-GS-1 transition supporting our hypothesis (Fig. 3). An abrupt change is first detected in Meerfelder Maar (North Germany) at $12,240 \pm 40$ varve years proposed to reflect a climate amelioration led by a northward shift of the westerlies (6), which would be consistent with the northern location of the polar front indicated by the marine records. Farther north, the Kråkenes (South Norway) Ti record also supports two phases within GS-1, with an abrupt transition occurring slightly later, at 12,150 y b2k (Fig. 3). This change has been related to an increase in annual to decadal scale meltwater release from the nearby glacier, coincident with the incursion of warm waters into the Nordic Sea (5). This situation would lead to enhanced variability by the alternation of warm influx and meltwater fluxes, an instability also recorded in brine formation episodes in sediment cores south of Iceland (23). In such a context, Seso Cave represents the southernmost location where this mid-GS-1 transition is observed, and, coherently, it occurs before influencing northern records. In fact, this time-transgressive transition that occurred in Seso Cave at 12,500 b2k took about 350 y to migrate northward over more than 20 degrees of latitude. This intrastadial evolution in climate conditions over South Europe is further supported by recent Mediterranean marine records that detect warmer conditions by the second half of GS-1 (11), coherent with our hypothesis of a tight ocean–atmosphere coupling at this time-transgressive transition.

The enhanced humid conditions detected in our new Seso record after 12,500 y b2k, while temperatures were still low in Greenland, contrasts with the previous inference of uniformly cold, dry glacial stadials over Iberia (25). These findings would indicate that cold dry stadial conditions during GS-1 would have lasted for only a few centuries (12,900–12,500 y b2k) previous to a long transition to interstadial conditions. Further examination at high resolution of other glacial stadials will be needed to distinguish if these are also multiphase, or if GS-1 represents a distinctive type of stadial response observed during the deglaciation, and potentially transitional to the type of perturbations observed in the Holocene in Southern Europe (26). Future work on atmospheric mechanism will be required to resolve why the mid-GS-1 oceanic reorganization mostly affected regions located southward of polar air masses, with little variation recorded in Greenland.

Conclusion

The analysis of SE09-6 stalagmite from Seso Cave (Central Pyrenees) provides robust evidence of the existence of two different phases in GS-1 in terms of the hydrological response of terrestrial environments. The first phase, characterized by high values of $\delta^{13}\text{C}$ and Mg/Ca together with slow growth rates, is interpreted as a dry period with decreased infiltration into the cave resulting from lower precipitation–evaporation balance in the region. The chronological model based on 17 U/Th dates indicates the transition to a more humid period took place gradually, starting at 12,500 y b2k, well ahead of other terrestrial sequences in Northern Europe, such as Meerfelder Maar and Kråkenes Lake. This time-transgressive transition took about 350 y

from its record in Seso Cave to influence Northern European regions. Overall, there is a good correlation between the NGRIP temperature record and the $\delta^{18}\text{O}$ profile from Seso stalagmite that, supported by recent stalagmites from the same cave that overlap with the instrumental period, allows the extraction of a temperature signal. However, competing influences of the amount effect and temperature variation in the $\delta^{18}\text{O}$ signal controlled the second phase of GS-1, characterized by humid conditions while there were still cold atmospheric temperatures. This phase demands a new model for the well-established, archetypical, dry, cold stadials of the last glacial period. After comparison with marine sequences from the Atlantic Ocean, we conclude that the resumption of the Atlantic overturning circulation is the main mechanism behind the hydrological response in Europe during this mid-GS-1 transition. Therefore, a rapid coupling among terrestrial (atmospheric) and oceanic systems is evidenced at mid-GS-1 transition at a European scale.

Methods

Samples for isotopic ($\delta^{18}\text{O}$, $\delta^{13}\text{C}$) and trace element analyses were microdrilled at 1-mm resolution along the growth axis (SI Appendix, Fig. S1 and Dataset S1). One part of the isotopic analyses was performed at the University of Barcelona using a Finnigan-MAT 252 mass spectrometer, linked to a Kiel Carbonate Device III, with a reproducibility of 0.02‰ for $\delta^{13}\text{C}$ and 0.06‰ for $\delta^{18}\text{O}$. A second part of the samples was analyzed at the University of Innsbruck using a ThermoFisher DeltaPlusXL isotope ratio mass spectrometer coupled to a ThermoFisher Gas-Bench II. The long-term precision of the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values is 0.08 and 0.06‰ (1 sigma), respectively. In both laboratories, the results are reported relative to the Vienna Pee Dee Belemnite (VPDB) standard. Five Hendy tests were performed and showed no correlation between $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ (SI Appendix, Fig. S5). Trace elements were analyzed at the University of Oviedo using a Thermo inductively coupled plasma optical emission spectrometer. Samples were dissolved in 1.5 mL of dilute nitric acid (Tracepur) immediately before analysis and were introduced with a microflow nebulizer (0.2 mL/min), which permitted two replicate analyses. Mg was measured at 280.3 nm, in axial mode. Calibration was performed offline using the intensity ratio method (27).

A total of 17 U/Th ages were analyzed at the University of Minnesota (SI Appendix, Table S1) and at the University of Melbourne (SI Appendix, Table S1) following standard procedures (28). The calcite powder (150–200 mg) was dissolved in nitric acid, a mixed $^{229}\text{Th}/^{233}\text{U}/^{236}\text{U}$ tracer was added, and the sample was dried. After the addition of an iron chloride solution, NH_4OH was added drop by drop until the iron precipitated. The sample was then centrifuged to separate the iron from the rest of the solution, and the overlying liquid was removed. After loading the sample into columns containing anion resin, HCl was added to elute thorium and water was added to elute uranium. With the uranium and thorium separated, each sample was dried down, and dilute nitric acid was added. Analyses were conducted using a multicollector inductively coupled plasma mass spectrometer (Neptune Thermo Finnigan) and final ages are given as years before 2000 A.D. (b2k). The depth–age model was calculated with R (version 3.0.2) (29) using StalAge (30) (SI Appendix, Fig. S2). A reduction in the growth rate occurred at 120–110 mm (distance from the base), but no evidence of hiatus was observed in thin sections.

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