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Climate of the Past
Discussions

Climatic subdivision of Heinrich Stadial 1 based on centennial-scale paleoenvironmental changes observed in the western Mediterranean area

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ABSTRACT

Heinrich Stadial 1 (HS1) is one of the most extreme climate periods of the last glacial cycle, generating extremely low sea surface temperatures (SST) and significant changes in terrestrial landscape (e.g., vegetation). Previous studies show that overall cold/dry conditions occurred during HS1, but the lack of high-resolution records precludes whether climate was stable or instead characterized by instability. A high-resolution paleoclimatic record from Padul (southern Iberian Peninsula), supported by a robust chronology, shows that climate during HS1 was non-stationary and centennial-

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Preprint. Discussion started: 6 November 2019

scale variability in moisture is superimposed on this overall cold climatic period. In this study we improve the resolution and suggest a novel subdivision of HS1 in 7 sub-phases, including: i) 3 sub-phases (a.1–a.3) during an arid early phase (HS1a; ~18.4–17.2 kyr BP), ii) a humid middle phase (HS1b; ~17.2–16.7 kyr BP), and iii) 3 sub-phases (c.1–c.3) during an arid late phase (HS1c; ~16.7–15.6 kyr BP). This climatic subdivision is regionally supported by SST oscillations from the Mediterranean Sea, suggesting a strong land-ocean relationship. A cyclostratigraphic analysis of our pollen data indicates that HS1 climate variability, and thus this subdivision, is characterized by ~2000 and ~800-yr periodicities, suggesting solar forcing controlling climate in this area.

INTRODUCTION

Understanding the background of natural climatic variability underlying abrupt anthropogenic climate change is a main goal in paleoclimate research. In this respect, deciphering rapid (e.g., millennial-scale) climate change and environmental impacts due to Dansgaard/Oeschger (D/O) and Heinrich-like climatic oscillations during the last glacial period and deglaciation have been the aim of ice, marine and terrestrial paleoclimate investigations (Cacho et al., 2006; Höbig et al., 2012; Panagiotopoulos et al., 2014).

Several paleoclimatic records evidenced the effect of especially cold and arid conditions recorded during Heinrich Stadials (HSs) in marine and terrestrial environments (Fletcher and Sánchez Goñi, 2008; Moreno et al., 2010; Martrat et al., 2014; Hodell et al., 2017). High-resolution paleoclimatic records also show that climate during HS1 was characterized by short-scale internal variability (Dupont et al., 2010; Stager et al., 2011; Escobar et al., 2012; Zhang et al., 2014; Stríkis et al., 2015). However, few studies focus on short-scale internal climate variability of HSs in southern Europe and the Mediterranean region, and in particular within HS1 (Fletcher and Sánchez Goñi, 2008).

https://doi.org/10.5194/cp-2019-130
Preprint. Discussion started: 6 November 2019

In this regard, a division of HS1 into two and three phases has previously been observed in very few marine records (Supplementary Information and Table S1). Nevertheless, the studies showing a three-phase division of HS1 disagree in the paleoenvironmental characterization of each phase (Table S1) and a complete knowledge of the variability within HS1 has yet to be achieved (Hodell et al., 2017).

Here, we present pollen and sedimentation data between 20 and 11 kyr BP from the new Padul-15-05 terrestrial sedimentary record (southern Iberian Peninsula; Fig. 1), registering regional and local paleoenvironmental responses to climate changes during HS1 and deglaciation, i.e., Bølling-Allerød (BA) and Younger Dryas (YD). The high-resolution data (~61-yr) from 18.4 to 15.6 kyr BP revealed centennial-scale variability during HS1, which is replicated in other Mediterranean paleoclimatic records and enables us to suggest, for the first time, an accurate internal climatic subdivision of HS1.

MATERIALS AND METHODS

In this study we used 10 AMS radiocarbon dates to obtain an accurate chronological control between 20 and 11 kyr BP from the Padul-15-05 record (Fig. 2a and Table S2; Supplementary Information for more precise methodology).

The Mediterranean forest, xerophytes, Pollen Climate Index (PCI) and Precipitation Index (I_p) were used as pollen paleoclimatic proxies (Fig. 2c-f and Fig. 3a). The PCI is useful for temperature and precipitation related climate changes, whereas I_p is a proxy for precipitation reconstruction in this region. In addition, normalized silicon (Si_{norm}) data from XRF analysis (Fig. 2b) was used as indicator of the siliciclastic input from the Sierra Nevada into the wetland (Camuera et al., 2018) (Methods, Supplementary Information).

For the purpose of identifying cyclicities related to regional climate oscillations, a cyclostratigraphic spectral analysis using the REDFIT procedure under rectangular window function from (Schulz and Mudelsee, 2002) was performed on xerophyte and *Ip* data, which have been proven to be good proxies for regional moisture availability in this area (Pini et al., 2009; Fletcher et al., 2010). A spectral analysis was also run on raw GRIP ^{10}Be flux data between 18.6 and 11 kyr BP (Adolphi et al., 2014) in order to observe cyclicities related to solar activity (Fig. 4; Methods, Supplementary Information).

RESULTS AND DISCUSSION

Heinrich Stadial 1 (HS1)

The terrestrial paleoclimate record from Padul shows overall cold and arid conditions during HS1, deduced by the decrease in mesic forest and abundance of xerophytes between 18.4 and 15.6 kyr BP (Fig. 2c, d). Centennial-scale variability is also observed during HS1 that can be divided into 3 main climatic phases (i.e., HS1a from 18.4 to 17.2 kyr BP, HS1b from 17.2 to 16.7 kyr BP, and HS1c from 16.7 to 15.6 kyr BP) and a further subdivision in 7 smaller-scale phases within them (i.e., HS1a.1, HS1a.2, HS1a.3, HS1b, HS1c.1, HS1c.2 and HS1c.3) (Fig. 2e, f and Fig. 3a).

The first of the three main climatic phases in Padul, HS1a (early HS1; 18.4–17.2 kyr BP), is characterized by low temperatures with significant variability in precipitation but under generally arid conditions, deduced by high xerophytes and low PCI and *Ip* values (Fig. 2c, e, f). Especially cold/arid conditions during this early phase are confirmed by high Si_{norm} values, which show that high siliciclastic input from the Sierra Nevada range into the wetland are caused by enhanced erosion during decreased forest cover (Camuera et al., 2019). The general cold/arid conditions shown in Padul during the early HS1a were also documented in nearby marine records presenting the 3 main phases for HS1, such as the pollen records from NW Iberia (Naughton et al., 2016), or the pollen data, SST reconstructions and foraminifera/coccolithophore assemblages from Alboran Sea (Fletcher and Sánchez Goñi, 2008; Martrat et al., 2014; Bazzicalupo et al., 2018).

https://doi.org/10.5194/cp-2019-130
Preprint. Discussion started: 6 November 2019

HS1b (middle HS1; 17.2–16.7 kyr BP) is characterized in Padul by a moderate increase in temperature and precipitation, deduced by low xerophytes, and higher PCI and *Ip* values. This is further supported by low Si_{norm}, indicative of low erosion precluding siliciclastic input in the wetland (Fig. 2b, c, e, f). A similar slightly warmer climate during this phase was recorded in SST records from the Mediterranean (Cacho et al., 1999; 2006), and in particular, from Alboran Sea (Martrat et al., 2014) (Fig. 3b and c, subjected to age uncertainties for onset/ending of HS1). This warmer/wetter conditions agree with increases in temperate forest recorded in the Iberian margin (Daniau et al., 2007), and in runoff in Lake Estanya (NE Spain) (Morellón et al., 2009).

HS1c (late HS1; 16.7–15.6 kyr BP) was climatically similar to HS1a, characterized by cold/dry conditions. This is deduced by the observed increase in xerophytes and Si_{norm} and lowering in *Ip* between ~16.9 and 15.8 kyr BP, related with the decreasing moisture (Fig. 2b, c, e). The general cold/arid climate in Padul during this phase is concordant with low SST from Alboran Sea (Martrat et al., 2014) (Fig. 3a, b), and with increasing salinity and low lake level in Lake Estanya (Morellón et al., 2009).

Our high-resolution record also revealed shorter centennial-scale climatic variability during HS1a and HS1c with a further climatic subdivision of HS1 into 7 sub-phases (i.e., HS1a.1, HS1a.2, HS1a.3, HS1b, HS1c.1, HS1c.2 and HS1c.3):

HS1a.1 was characterized by a cold/arid phase between 18.4 and 17.8 kyr BP recorded by high xerophytes, and low PCI and *Ip* values. Climate changed towards more humidity in HS1a.2 sub-phase at 17.8–17.5 kyr BP, and returned to enhanced aridity during HS1a.3 between 17.5–17.2 kyr BP. This arid-humid-arid climatic pattern is further confirmed by oscillations in Si_{norm} (Fig. 2b, c, e, f and Fig. 3a).

HS1c also presents a three-phase subdivision, namely HS1c.1, HS1c.2 and HS1c.3. HS1c.1 was characterized by a decrease in precipitation and temperature (low *Ip* and lowest PCI values), registering the coldest conditions of HS1 at 16.7–16.4 kyr BP (Fig. 2f). Temperature and moisture conditions increased during HS1c.2 at 16.4–16 kyr BP, whereas similar temperatures but under more arid climate conditions are recorded during HS1c.3 at 16–15.6 kyr BP (Fig. 2c, e, f and Fig. 3a). This arid-humid-arid climatic pattern is similar to the earlier HS1a.

Environmental changes recorded in Padul represent centennial-scale climate oscillations during HS1, which can be correlated with other regional records. The centennial-scale arid-humid-arid trends recorded during HS1a and HS1c, and the increase in temperature/precipitation during HS1b, are also observed in the SST records from the Alboran Sea in western Mediterranean (Cacho et al., 1999; 2006; Martrat et al., 2014) and in the GISP2 ice core (Grootes et al., 1993) (Fig. 3a-d), suggesting a similar response in continental, marine and ice sheet environments to climatic forcing (see section below). The presented age offsets between records could be related with variations in reservoir ages of the Atlantic and Mediterranean promoted by thermohaline circulation collapse in both areas during HS1 (Sierro et al., 2005). In addition, the significant decrease in the atmospheric ^{14}C between 17.5 and 14.5 kyr also difficult age models during this period (Broecker and Barker, 2007), whereas dating on different foraminifera species can also produce large differences on radiocarbon ages, especially during HS1 (up to 1000 years) (Ausín et al., 2019). The asynchronicity and the early record of HS1 in Padul (18.4–15.6 kyr BP) with respect to the equivalent GS-2.1a cold event from Greenland ice-core records (17.5–14.7 kyr BP) is evident. This could be due to different environmental responses consequence of the different latitude and geographical features between high-latitude Greenland and mid-latitude Mediterranean and Iberian records. An early record of HS1 in the study area is supported by the well-dated paleoenvironmental records from our region. For instance, the growth interruption of the CAN speleothem (N Spain)

https://doi.org/10.5194/cp-2019-130
Preprint. Discussion started: 6 November 2019

Climate of the Past
Discussions
Open Access

occurred between 18.2 and 15.4 kyr BP (Moreno et al., 2010) supporting an early HS1 (or Mystery Interval in their study), the increasing moisture conditions in Lake Prespa (Macedonia, Albania, Greece) at 15.7 kyr BP indicating an early end of HS1 (Cvetkoska et al., 2015), and the pollen record from MD99-2331 (NW Iberian margin), which evidence HS1 between 18.8 and 15.8 kyr BP (Sánchez Goñi et al., 2018).

Despite the offsets of SST reconstructions from Mediterranean Sea, environmental oscillations in both areas should have been synchronous. Therefore, warming peaks recorded in Padul and in SST records during HS1 were coetaneous, result of the strong land-ocean interaction (Sánchez Goñi et al., 2018).

Bølling-Allerød (BA) and Younger Dryas (YD)

The BA recorded in Padul between 15.6 and 12.9 kyr BP is characterized by significant increase in the Mediterranean forest, and thus *Ip* and PCI values, indicating warmer/wetter climate than during HS1. In addition, Padul is one of the few continental records to detect the 5 centennial-scale sub-phases during the BA, similar to the GI-1e to GI-1a from Greenland ice cores (Johnsen et al., 1992; Grootes et al., 1993) (Fig. 2e, f and Fig. 3d).

Cold/arid climate during the YD stadial also affected the paleoenvironments in this area between 12.9–11.6 kyr BP. The YD is characterized by relatively arid conditions show by the mean xerophyte percentage of ~22%, whereas temperature seems to increase throughout the YD period, reflected by the increasing trend in the Mediterranean forest (Fig. 2c, d).

Climate variability and solar forcing in the Iberian Peninsula

Centennial- and millennial-scale climate variability have been recorded during HS1, BA and YD period in Padul. The spectral analysis on xerophytes and *Ip* presented ~2000, 800, 500 and 200-yr cycles (Fig. 4a-c). These climatic variabilities could be

https://doi.org/10.5194/cp-2019-130
Preprint. Discussion started: 6 November 2019

related to solar forcing, as similar cyclicities have been obtained analyzing solar activity with ^{14}C production rates (Damon and Jirikowic, 1992; Turney et al., 2005). Several studies have determined a relation between paleoenvironmental data oscillations linked to climate changes through variations in solar activity (Bond et al., 2001; Lüning and Vahrenholt, 2016). In particular, climate variability during the Last Glacial and Holocene periods was strongly controlled by solar activity, specifically during cold glacial phases, in which solar variability caused larger climate changes (van Geel et al., 1999). In addition, more recent temperature estimations showed that they also seem to be forced by solar variability (Soon et al., 2015).

The obtained ~2000-yr climatic cyclicity forced millennial-scale paleoenvironmental variability in Padul and permitted the three-phase division of HS1 (Fig. 5a, b). This cyclicity could be linked to D/O-like variability, which presents a 1–2 kyr periodicity during the last glaciation (Bond et al., 1999), such as the ~1.8-kyr cycle identified on the hematite-stained grain record from North Atlantic cores (Bond et al., 1999). Paleoclimatic records from the Equator and Southern Hemisphere also determined periodic surface temperature variations of around 2000 yrs in relation with solar irradiance (Bütikofer, 2007).

The ~800-yr cycle identified in Padul forced the centennial-scale climatic subdivision of HS1 in 7 sub-phases (Fig. 5a, c). A similar ~800 yr cyclicity characterizes the ^{10}Be flux data indicative of changes in solar activity (Adolphi et al., 2014) (Fig. 4d and Fig. 5d, e). Other global paleoclimatic studies also show similar frequencies caused by solar variability. For example, an ~800-yr cycle was observed in Irish oak tree chronologies (Turney et al., 2005) and in Mg/Ca SST from the Pacific Ocean (Marchitto et al., 2010), both records closely related to solar irradiance. A 890-yr cycle was also found in the $\delta^{18}O$ Holocene time series from Greenland and interpreted as linked to solar

https://doi.org/10.5194/cp-2019-130
Preprint. Discussion started: 6 November 2019

radiation (Schulz and Paul, 2002). Consequently, the ~800-yr cycle detected in Padul and in other worldwide records suggests a linkage between centennial-scale paleoenvironmental changes and solar activity.

The data from Padul display a good correlation between environmental changes in the southern Iberian Peninsula and Mediterranean SSTs during HS1 (Fig. 3a-c), suggesting a close land-ocean relationship in response to solar variability. The Mediterranean SST could have been affected by solar activity, similar to the North Atlantic cooling episodes linked to reduced solar irradiance (Bond et al., 2001). In addition, observed variations in the Padul data suggest a southward shift of the North Atlantic polar front during HS1 (Repschläger et al., 2015), which could have produced a penetration of colder Atlantic surface waters into the Mediterranean (Cacho et al., 1999; Sierro et al., 2005). These conditions, along with the southward displacement of the North Atlantic atmospheric polar front, could have produced a low land-ocean temperature contrast and weak moisture advection between both environments, and therefore, increasing aridity in the western Mediterranean during cold sub-phases HS1a.1, HS1a.3, HS1c.1 and HS1c.3. Similar conditions linked to weak moisture advection were interpreted in the eastern Mediterranean during HS1 and HS2 (Kwiecien et al., 2009) and in the Corchia Cave during HS11 (Drysdale et al., 2009). In contrast, during warmer sub-phases in Padul (i.e., HS1a.2, HS1b and HS1c.2) and in Mediterranean SSTs, enhanced marine evaporation and moisture advection toward the continent could have provoked wetter climate conditions in southern Iberian Peninsula.

CONCLUSIONS

The high-resolution analysis of the Padul-15-05 continental record for the 20–11 kyr BP interval shows that:

1) Centennial-scale climate oscillations affected southern Iberian Peninsula during HS1, with three main phases HS1a (18.4–17.2 kyr BP), HS1b (17.2–16.7 kyr BP) and HS1c (16.7–15.6 kyr BP) characterized by general arid(cold), humid(cool) and arid(cold) climate, respectively.
2) We suggest for the first time a further subdivision within these 3 main climatic phases of HS1 in 7 sub-phases: 3 sub-phases (a.1–a.3) during HS1a, HS1b, and 3 sub-phases (c.1–c.3) during HS1c. The climatic variability is also identified in Mediterranean SST records, confirming this climatic pattern at regional-scale.
3) The main periodicities obtained for climatic oscillations of ~2000 and ~800 yrs within HS1, BA and YD seem to be related to solar forcing. Variations in solar activity could have influenced latitudinal shifts of the North Atlantic and atmospheric polar fronts, affecting the land-ocean temperature contrast, marine evaporation and moisture advection toward the continent.

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DATA AVAILABILITY

The paleoclimatic pollen data from Padul-15-05 can be found in the PANGAEA data repository (https://doi.pangaea.de/10.1594/PANGAEA.904053, dataset *in review*).

https://doi.org/10.5194/cp-2019-130
Preprint. Discussion started: 6 November 2019

Climate of the Past Discussions

AUTHOR CONTRIBUTIONS

J.C. performed the pollen, XRF and spectral analyses, interpreted the data and wrote the manuscript. G.J.-M. discussed data and interpretations and wrote the manuscript. M.J.R.-R. performed the XRF analysis, discussed data and interpretations and contributed to the writing of the manuscript. A.G.-A., J.L.T., R.S.A., F.J.E. and C.W. discussed data and interpretations and contributed to the writing of the manuscript.

COMPETING INTEREST

The authors declare no financial and non-financial competing interests.

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Climate of the Past Discussions

FIGURES AND FIGURE CAPTIONS

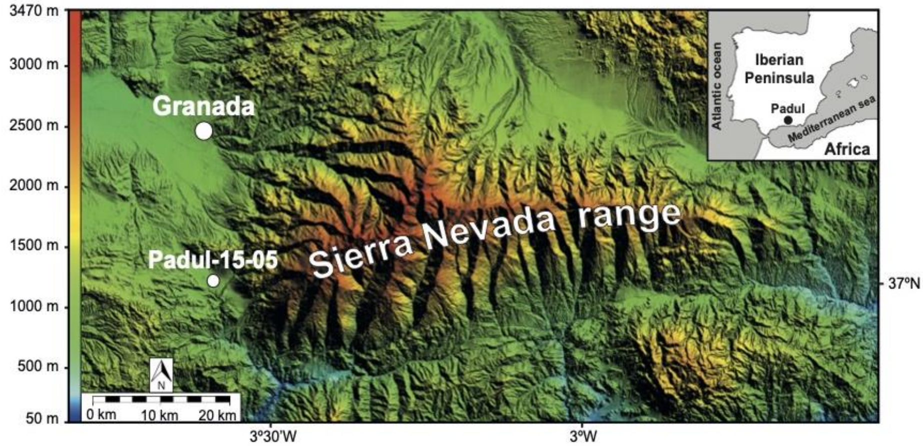

Figure 1. Geographical location of the Padul-15-05 record in the western margin of Sierra Nevada range and south of Granada city (southern Iberian Peninsula) (modified from Camuera et al., 2018).

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Preprint. Discussion started: 6 November 2019

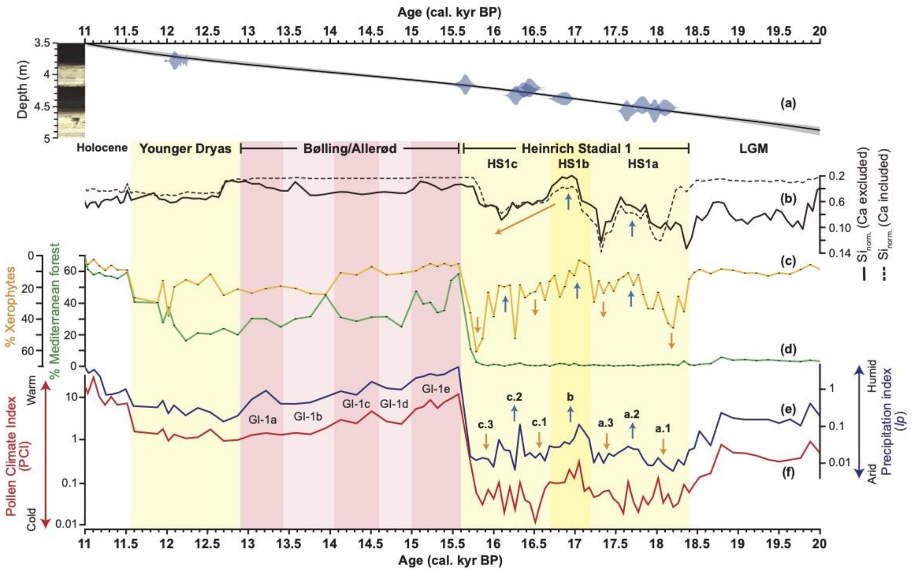

Figure 2. Paleoclimatic raw data from the Padul-15-05 sediment core for the time period between 20 and 11 kyr BP: (a) Photograph and age-depth model. (b) Normalized silicon values, with calcium excluded (continuous line) and included (dashed line) from total counts (values inverted) (Methods, Supplementary Information). (c) Percentage of xerophytes (values inverted). (d) Percentage of Mediterranean forest. (e) Precipitation Index (*Ip*). (f) Pollen Climate Index (PCI). Yellow shadings show the Younger Dryas (YD) and Heirich Stadial 1 (HS1). Dark yellow shading within HS1 indicates the slightly warmer/wetter middle phase (HS1b). Red and pink shadings show the Bølling-Allerød (BA). In particular, red shadings correspond to the warmer/wetter Greenland Interstadials 1a, 1c and 1e, and pink shadings to the colder/more arid Greenland Interstadial 1b and 1d. Blue arrows indicate moderately warmer/wetter sub-phases within HS1, whereas orange arrows show colder/more arid sub-phases.

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Preprint. Discussion started: 6 November 2019

Climate of the Past
Discussions

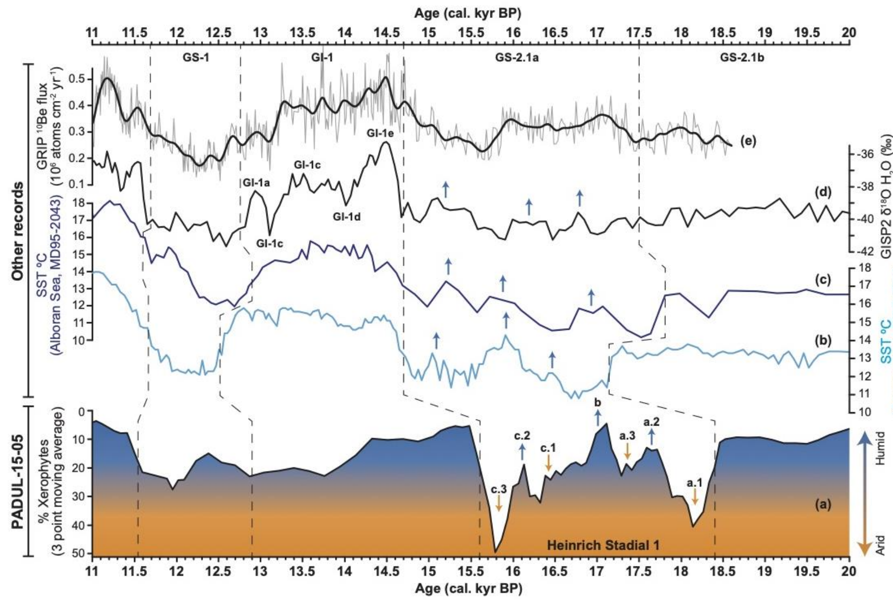

Figure 3. Paleoclimatic proxy data from Padul, Mediterranean Sea and Greenland ice-cores for the time period between 20 and 11 kyr BP: (a) Xerophyte data from Padul-15-05 with three-point moving average (values inverted). (b) SST (degrees Celsius) from ODP-976 record of Alboran Sea (Martrat et al., 2014). (c) SST (degrees Celsius) from MD95-2043 record of Alboran Sea (Cacho et al., 1999; 2006). (d) Raw $\delta^{18}O$ H_2O values (‰) from GISP2 (Grootes et al., 1993). (e) Raw ^{10}Be flux values (10^6 atoms cm^{-2} yr^{-1}) (grey line) and smoothed data (black line) from GRIP (Adolphi et al., 2014). Within HS1, blue and orange arrows in the Padul record show the humid and arid phases, respectively. In the SSTs from Alboran Sea and the Greenland record during HS1, blue arrows marked the warmer temperatures in relation with the relatively more humid phases from Padul for this period (HS1a.2, HS1b and HS1c.2). Vertical dashed lines show transitions between LGM-HS1 (GS-2.1b – GS-2.1a), HS1-BA (GS-2.1a – GI-1), BA-YD (GI-1 – GS-1) and YD-Holocene for each study.

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Preprint. Discussion started: 6 November 2019

Climate of the Past
Discussions

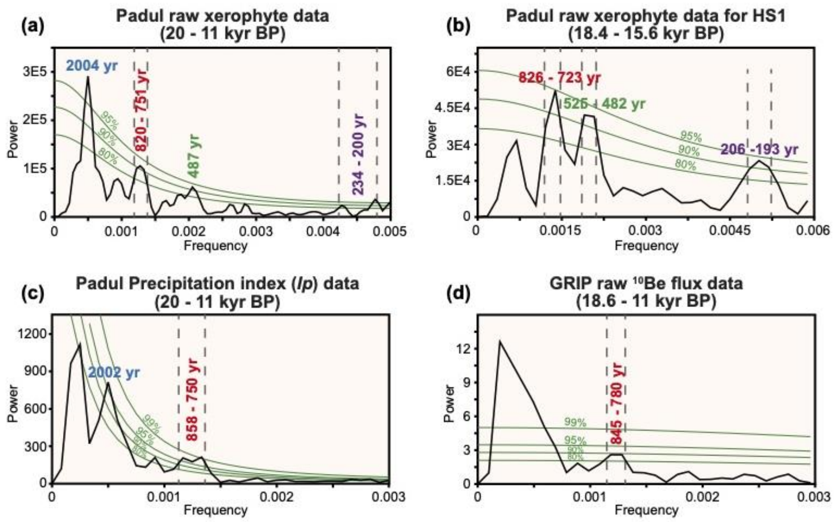

Figure 4. Cyclostratigraphic analysis of the Padul-15-05 pollen data and Greenland ice-core record during HS1. Spectral analysis run on: (a) Raw xerophyte percentages from the Padul-15-05 record for the age range between 20 and 11 kyr BP. (b) Raw xerophyte percentages for HS1 (18.4 – 15.6 kyr BP). (c) *Ip* data for the age period between 20 and 11 kyr BP. (d) GRIP ^{10}Be flux data between 18.6 – 11 kyr BP. Note that the spectral peak of the GRIP ^{10}Be between 0.0001973 and 0.0005919 frequencies (a cycle with a periodicity between 5068 and 1689 years) seems to be an artefact, as the longer periodicity cycles (closer to 5 kyr) cannot be significant in a time series of data spanning 7600 years.

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Preprint. Discussion started: 6 November 2019

Climate of the Past
Discussions

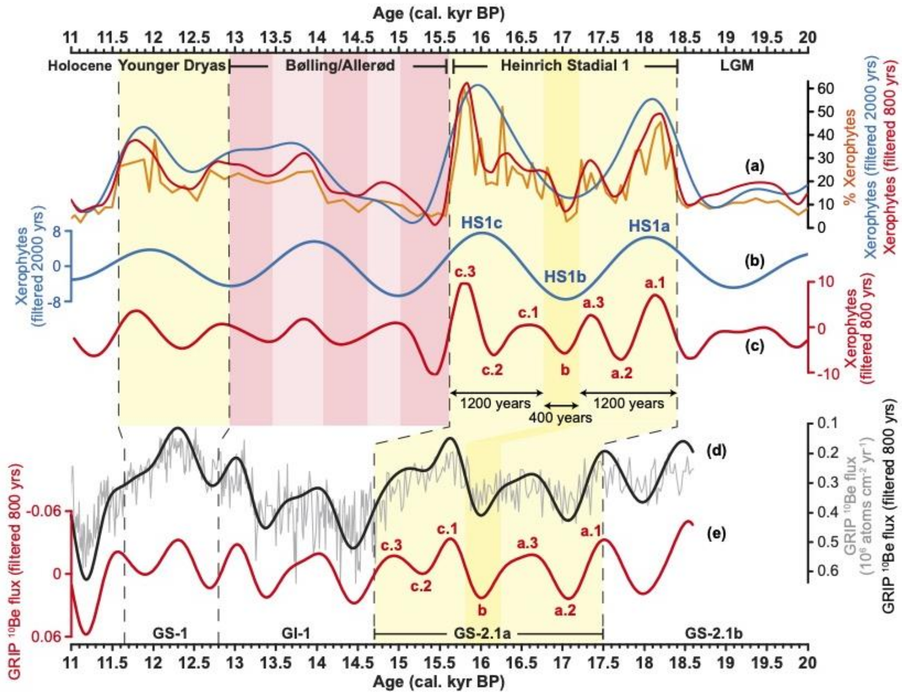

Figure 5. (a) Raw percentages of xerophyte taxa (orange line) along with the filtered xerophyte taxa based on the obtained ~2000-yr cycle (blue line) and the ~800-yr cycle (red line) (see spectral analysis from Figure 4a and b). (b) Xerophyte data filtered using a bandwidth parameter of 0.0001 for the ~2000-yr cycle (blue line). (c) Xerophyte data filtered using a bandwidth parameter of 0.0006 for the ~800-yr cycle (red line). Note that the 3 main phases (HS1a, HS1b and HS1c) are marked within HS1 in relation with the ~2000-yr cycle, and the internal sub-phases (a.1-a.3, b, and c.1-c.3) in relation with the ~800-yr cycle. The length of the HS1a, HS1b and HS1c have also been marked. (d) GRIP ^{10}Be flux data (10^6 atoms cm^{-2} yr^{-1}; values inverted) (grey line) filtered to the obtained cyclicity of ~800 yr (black line) (see spectral analysis from Figure 4d). (G) GRIP ^{10}Be flux data filtered using a bandwidth parameter of 0.0006 for the ~800-yr cycle. Vertical dashed lines have been marked according to the Greenland Stadials (GS-2.1b, GS-2.1a, GS-1) and Interstadial (GI-1) delimitations (Rasmussen et al., 2014).