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Rapid Communication

Spring-season changes during the Late Pleniglacial and Bølling/Allerød interstadial

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ABSTRACT

Earlier spring onset and the associated extension of the growing season in high latitudes belong to the most obvious consequences of global warming. The natural dynamics of growing-season properties during past climate shifts however, are extremely difficult to reconstruct since temperature reconstructions are hardly ever seasonally resolved and the applied proxies such as chirinomid or pollen analysis are mainly sensitive to summer temperatures. Here we apply a newly developed leaf cuticle-based proxy to reconstruct growing degree-days (GDD) in a quantitative way and to estimate changes in the timing of spring onset over the last deglaciation. Cuticle analyses of fossil birch leaves preserved in lake sediments from southern Germany reveal extremely low GDD values during the Late Pleniglacial, which are rapidly increasing at the onset of the Bølling/Allerød interstadial. While temperature and GDDs show a simultaneous warming during deglaciation, a GDD decline precedes lowering of summer temperatures during the Older Dryas cooling. Later bud-burst dates support the hypothesis of a shortening the growing season during this cool pulse.

1. Context and aim

Seasonality has been identified to be a major player in climate change, not only at present, where the significant lengthening of the growing season is a likely consequence of ongoing global warming (IPCC, 2007), but also during natural climate swings of the past. At the end of the last glacial, about 14,700 years ago, temperature shifts of 10 °C or more pushed the climate system within a few years to decades into the warm Bølling/Allerød interstadial (Steffensen et al., 2008). It is well accepted that these estimates, based on Greenland ice-core records, have to be separated into high amplitude changes during wintertime, and only moderate alterations of the summer temperatures (Isarin and Renssen, 1999; Denton et al., 2005, 2010; Wu et al., 2007). Greenlandic ice-core stable isotope records with seasonal resolution clearly demonstrate the importance of resolving sub-annual signals to understand mechanisms of climate change (Denton et al., 2005; Steffensen et al., 2008; Vinther et al., 2010). Outside Greenland, however, well-constrained quantification of seasonality remains a major challenge for palaeoclimatologists (Caseldine and Turney, 2010) because most climate proxies are usually responding to maximum summer or, to a lesser extent, minimum winter temperatures. Just recently, a new palaeobotanical approach has been introduced, using epidermal cell characteristics of dwarf birch leaves (*Betula nana*) to determine the amount of growing degree-days (GDD) (Wagner-Cremer et al., 2010). GDD, being the cumulative sum of degrees Celsius above a certain threshold value, are a combined measure for the total duration of the growing season as well as the mean daily temperature during the growing season. In today's subarctic biomes, the thermal properties of the growing season determine the duration of leaf growth, which produces detectable imprints on the leaf morphology. The high correlation between GDD_5 (cumulative temperature above 5 °C, the standard threshold temperature for subarctic biomes; growing season defined as May through September) and the shape of the epidermal cells allows to systematically infer GDD_5 values from fossil *B. nana* leaf remains often abundantly preserved in Quaternary sediments. Moreover, a significant correlation between cell shape and the date of bud-burst also allows for the very first time concomitant estimates of the timing of the phenological spring onset (Wagner-Cremer et al., 2010).

2. Evidence from modern and fossil leaves

A distinct correlation between epidermal cell morphology of modern *B. nana* and GDD_5 as well as bud-burst date has been described from annually-collected *B. nana* leaves from Kevo, Northern Finland (69.74°N, 27.14°E). Under subarctic conditions, spring onset in combination with GDD_5 determines the period available for leaf growth. Early spring onset, thus prolonged growth

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periods, stimulates epidermal cell wall undulation during leaf maturation, which can be expressed as the undulation index (UI) (Kürschner, 1997). The distinct imprint of GDD_5 on the cuticle morphology has been validated by studying *B. nana* leaf fragments from young peat deposits at the same site. Based on meteorological data from Kevo the modern and sub-fossil leaf material covers a GDD_5 range from 450 to 850 C°. This modern training set was used to develop inference models for GDD_5 and bud-burst date from UI values (Table 1). The response of the *B. nana* UI to GDD_5 from additional peat sections in Sweden and Finland has been validated by comparison with historical instrumental data from Scandinavia for the past 150 years (Wagner-Cremer et al., 2010).

In the present study we measured the UI of *B. nana* leaves preserved in 15.5–13.5 kyr BP old sediments from Schleinsee (Fig. 1), spanning the termination of the last glacial and the onset of the interstadial (i.e. the Bølling/Allerød warm phases). The age-assessment (Table 2) for the 70 cm Schleinsee sediment section presented here is based on the correlation of the bulk carbonate stable oxygen isotope ($\delta^{18}O$) record with that of the dated Greenland NGRIP $\delta^{18}O$ record (Andersen et al., 2004; Rasmussen et al., 2006). Moreover, an Accelerator Mass Spectronomy (AMS) ^{14}C date on *Dryas otopetala* leaves, calibrated with CALIB04 (Reimer et al., 2009) provided the basal age of the section. The chronology used for correlation of terrestrial and Greenlandic ice-core correlation is based on the INTIMATE event stratigraphy (Lowe et al., 2008). The high abundance and generally good preservation of *B. nana* macro remains in these calcareous lacustrine sediments have initially been described by Lang (1952), who tentatively ascribed the larger size of leaves from the interstadial to improved growing conditions. Systematic UI analysis performed on leaf fragments from new Schleinsee sediment cores (Fig. 2a) allow the quantification of both GDD_5 (Fig. 2b) and the date of bud-burst (Fig. 2c) on a (multi-)decadal scale.

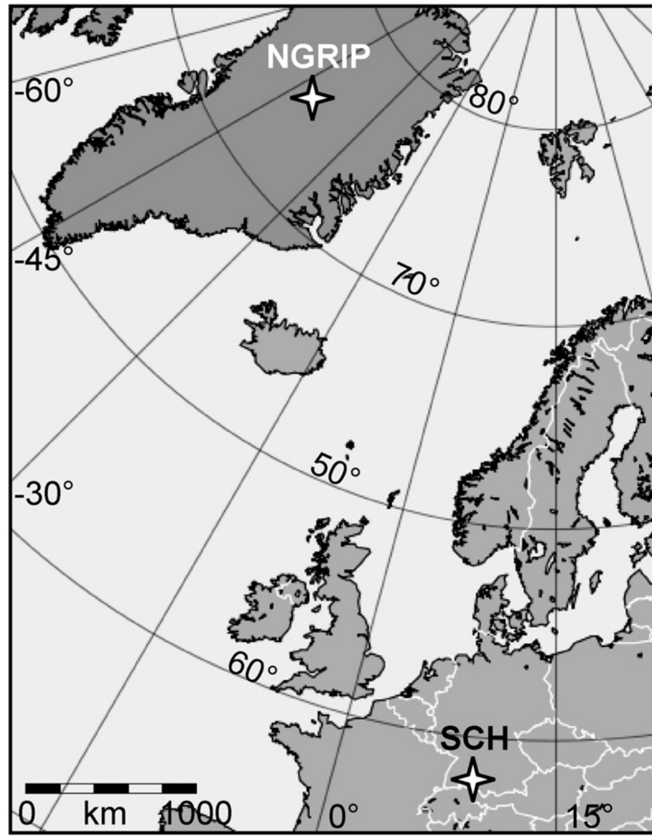

Fig. 1. Site map. Location of *Betula nana* leaf fragments-bearing Schleinsee (SCH) site in southern Germany (47.61°N, 9.63°E, 475 m a.s.l.) and Greenland NGRIP ice-core drill site (75.10°N, 42.43°W).

3. Growing season changes during the Pleniglacial/Bølling-Allerød

Lowest UI values (Fig. 2a) are recorded during the late Pleniglacial (GS-2) that translate into GDD_5 of ~500 °C (Fig. 2b). At the transition to the lateglacial interstadial GDD_5 start to increase, reaching maximum values of 750 °C in the early interstadial (GI-1e, Bølling). GDD_5 are constantly high for ~300 years before a decrease after 14.3 kyr BP indicates a prolonged phase of low GDD_5, lasting until 13.8 kyr BP. The youngest part of the record, from 13.8 to 13.6 kyr BP (GI-1c, Allerød) is again characterized by GDD_5 values of ~700 °C, but not reaching early interstadial (GI-1e) maximum levels any more. Inferred bud-burst dates (Fig. 2c) indicate an advance in spring onset by ~18 days, from day-of-year 167 in the late Pleniglacial (GS-2) to 149 in the early interstadial (GI-1e, Bølling), subsequently becoming successively later again with a second peak at 13.9 kyr BP, with inferred bud-burst at day-of-year 161.

Table 1
Correlation points and radiocarbon date for the Schleinsee chronology.

Core SCH05 II sample depth	NGRIP $\delta^{18}O$ age tie-points (b2k = years before A.D. 2000)	Age year BP	AMS^{14}C age	Calibrated age year BP (1 sigma)
491–490 cm POZ32706	–	–	13,020 ± 100 BP	15,215 –15,959 BP
470–469 cm	GS-2/GI-1: 14,700	14,650	–	–
435–434 cm	Onset GI-1d: 14,000	13,950	–	–

By correlating the $\delta^{18}O$ record of the mid-latitude Schleinsee site in Germany to the Greenland NGRIP $\delta^{18}O$ record, the GDD_5 and date of bud-burst data are directly comparable to the air temperature changes detected in the Greenland ice.

The extremely low GDD_5 values recorded in the Schleinsee leaf material during the Late Pleniglacial parallel the most negative $\delta^{18}O$ values, thus the coldest temperatures. The transition towards peak GDD_5 starts at 14.7 kyr BP, mirroring the transition from GS-2 to GI-1e. Due to the lack of *B. nana* leaves between 14.7 and 14.6 kyr BP the dynamics of the warming, however, are difficult to determine. Vegetation model-based estimates for the region north of the Alps predict 1500–2500 °C lower GDD_5 during the Last Glacial Maximum compared to present-day (Wu et al., 2007). In our reconstruction, the difference in GDD_5 between 15.4 kyr BP and present-day is approximately 1600 °C (2100 °C MJJAS GDD_5 for 2008, reference site Friedrichshafen, Germany), which agrees well with the model results.

A striking divergence between the GDD_5 and the NGRIP $\delta^{18}O$ record occurs during the second half of the Bølling (GI-1e), where a rapid decrease in GDD_5 values in combination with delayed bud-

Table 2
GDD_5 and bud-burst inference models. Inference models for GDD_5 and bud-burst based on modern training sets of *B. nana* UI values from Kevo, climate station data and phenological records from the same site (Wagner-Cremer et al., 2010).

GDD_5 inference model	$GDD_5 = 10^{(2.4355+5.5996(\log UI fossil))}$, $r^2 = 0.63$, $p=<0.001$, RMSE = 63 GDD_5
Bud-burst inference model	day-of-year $= 10^{(2.309-(-1.745(\log UI fossil))}$, $r^2 = 0.64$, $p = 0.002$, RMSE = 4.3 days